A Study On Antenna Polarization Plane for UL/DL Drone Access Network

Takuma Okada
Dept. Electrical and Electronic Engineering
Tokyo Institute of Technology
2-12-1 Ookayama, Meguro-ku, Tokyo
E-mail: okada@mobile.ee.titech.ac.jp

Gia Khanh Tran
Dept. Electrical and Electronic Engineering
Tokyo Institute of Technology
2-12-1 Ookayama, Meguro-ku, Tokyo
E-mail: khanhtg@mobile.ee.titech.ac.jp

Abstract— Drones are deployed as aerial base stations in areas where ground base stations are not available, such as disaster areas, to provide services to users. However, when multiple drones are deployed, the SIR (Signal-to-Interference Ratio) is degraded by the ground reflection in the environment where UL (UpLink) and DL (DownLink) concurrently exist. In this paper, circular polarization, whose polarization plane characteristics change before and after the ground reflection, is applied to the communication link between the drone and the user to improve the SIR. Numerical evaluation shows the effectiveness of the proposed method.

Keywords—Aerial base station; Multiple drones; Circular polarization; Two-ray model

I. INTRODUCTION

Drones are a type of unmanned aircraft achieving significant attention in recent years for both civilian and commercial applications due to their hovering capability, flight capacity, ease of deployment, low operation and maintenance costs. Drones have many use cases since it has been used in a wide range of applications such as disaster rescue operations, smart agriculture, emergency medical services, and aerial photography [1]. In addition, recent advances in drone technology have made it possible to widely deploy drones for wireless communication. This allows drones to be used as aerial base stations to support the connection of existing terrestrial wireless networks such as cell phones and broadband networks.

Unlike conventional ground base stations, aerial base stations have the advantage that they can adjust their flight altitude and avoid obstacles to increase the possibility of connecting with ground users by establishing LoS (Line-of-Sight). The LoS connection can improve coverage and data rate performance. In addition, it is possible to construct the network flexibly because it can be freely deployed in the air. On the other hand, wireless data communication has exploded in the last few years due to the rapid spread of the IoT (Internet of Things) and their various new applications. However, conventional wireless drone networks operate in the microwave frequency band below 6 GHz, where the spectrum resources are already heavily utilized. Despite the rapid increase in the demand for data capacity, there is a growing concern that the available spectrum is limited. Several techniques have been proposed to improve the network capacity and to achieve high frequency efficiency in future cellular systems. For example, MIMO (Multiple-Input and Multiple-Output), NOMA (Non-Orthogonal Multiple Access), and cooperative relaying. However, these technological advances do not provide a solution to solve the spectrum scarcity problem. Therefore, a solution may be to expand using higher frequencies in the radio spectrum. In this paper, communication links between user and drone, and between drone and drone are considered using millimeter wave communication. The expanding in using millimeter-wave frequencies can provide multiple gigabit data transmission rates by ensuring a wide range of available spectrum resources [2]. Hence, millimeter-wave communication should be leveraged in 5G wireless communication systems that requires very high data throughput, wide bandwidth, high communication speed, and low latency. In addition to the sufficient bandwidth, the short wavelength of millimeter-wave communication makes it possible to design physically small circuits and antennas. Moreover, it is easy to achieve sharper directivity by miniaturizing the antenna. On the other hand, millimeter wave communications suffer from large free space attenuation. In addition to the expected application of drone to wireless networks, the possibility of transmitting multiple gigabits of data using 5G millimeter-wave communications has led to the idea of combining wireless network support by drone with millimeter-wave communications [3].

In this paper, we propose a scenario for a disaster area where ground base stations are out of service. In fact, during the Great East Japan Earthquake in 2011, about 29,000 cell phone base stations and PHS (Personal Handy-phone System) base stations of five major companies, NTT docomo, KDDI, Softbank Mobile, EMOBILE, and WILLCOM, were out of service [4]. The first 72 hours after a disaster occurs are considered the most critical, and it is necessary to deploy wireless networks quickly to restore communication connectivity in order to aid rescue teams in the disaster area. Establishing a wireless network using drones in the damaged area where ground base stations are malfunctioned is an effective and fast method to support different rescue operations at the disaster area. One of the current problems is that when multiple drones communicate with the user, the UL that sends data from the user to the aerial base station and the DL that sends data from the aerial base station to the user cause interference. In this paper, we investigate the improvement of SIR by using the characteristics of circular polarization whose rotation direction changes before and after the ground reflection. For the propagation model, we apply the two-ray model to calculate the received power and SIR, and show the effectiveness of the proposed method.

The rest of this paper is organized as follows. In Section II, we present the related work about our research and the overall architecture of our research. In Section III, we show the system model and the proposed method with the circular polarization. Finally, Section IV concludes our paper and works in the future.

II. Related Research

The overall architecture of this research is shown in Fig. 1. The roles of drones are assumed to be divided into the access-drones and the backhaul-drones to provide data to users. The access-drones communicates directly with the user, while the backhaul-drones acts as a relay between the access-drones and the ground base station. By relaying the backhaul-drones, the communication distance between drones becomes shorter. This reduces the effect of distance attenuation and rainfall attenuation, which are concerns in millimeter-wave communication. On the other hand, since the access-drones provide data directly to users, it is important to know how to deploy these drones. If drones are efficiently deployed, it is expected to provide LoS communication to the ground users, which is important in millimeter-wave communications, and to expand the coverage with fewer base stations.

Authors in [5] show the minimum transmit power required to have a certain coverage radius as a function of the altitude of the drones. At lower altitudes, the shadowing effect reduces the probability of LoS connection between the transmitter and the receiver, resulting in a decrease in the coverage radius. On the other hand, at high altitudes, the probability of LoS connection is high. However, due to the large distance between the transmitter and the receiver, the path loss increases and as a result, the coverage performance decreases. In [6], the optimal deployment of multiple drones equipped with directional antennas as aerial base stations is investigated. Based on the circle packing theory, an efficient placement method is proposed in which each drone can obtain the maximum coverage with the minimum transmission power. As a result, the optimal altitude and position of drones are determined based on the number of available drones, antenna gain and beamwidth. In [7], a deployment method that combines the K-means method with the minimum envelope problem is considered to maximize the data rate that can be provided to users in DL. There have been many studies of deployment methods that give priority to DL connections, but few studies have been conducted in environments where DL and UL concurrently exist. In this paper, we propose a method to reduce the interference to UL caused by DL in the communication between an access-drone and a user.

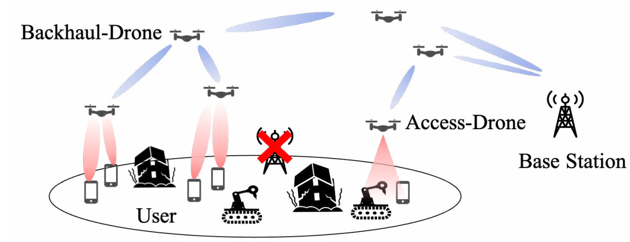

Fig. 1. Overall architecture.

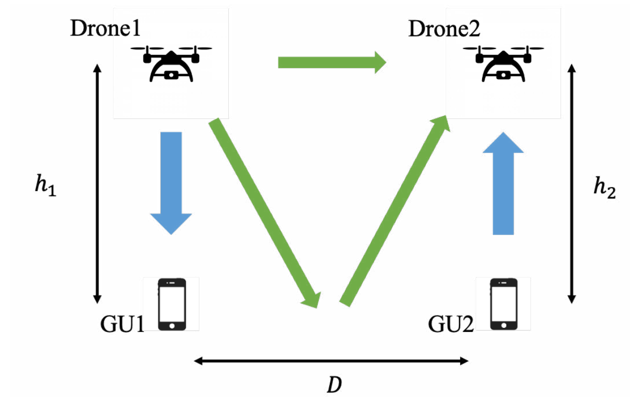

Fig. 2. System model.

III. System Model and Proposed Method

In this section, we describe the system model and the proposed method considered in this research. For simplicity, we consider an UL-DL pair system as shown in Fig. 2. The structure of this section is as follows. Section A describes the initial arrangement of the drone and the user. In section B, we apply the two-ray model without adopting the circular polarization in the system model and show the calculation results of the received power. In section C, we show the effectiveness of the proposed method by introducing the circular polarization in the system model.

A. System Model

Figure 2 shows the system model used in this research. Here, h_1 is the height of Drone 1 from the ground surface, h_2 is the height of Drone 2 from the ground surface, and D is the distance between Drone 1 and Drone 2 (GU1 and GU2). The blue signal represents the desired signal, the green signal represents the interference signal. We considered an environment in which the user and the drone are communicating one-to-one. The communication between Drone 1 and GU1 is assumed to be DL, and that between Drone 2 and GU2 is assumed to be UL. It is assumed that the communication between Drone 1-GU1 and Drone 2-GU2 is DL and that the communication between Drone 1-GU1 and Drone 2-GU2 is UL. Considering the receiving power of Drone 2, the signal transmitted from GU2 can be treated as a desired signal, and the other signals are treated as interference signals. During the communication between Drone 1 and GU1, a part of the radio wave transmitted from Drone 1 is reflected from the ground and is received by Drone 2 as an interference component. It is considered that the shorter D is, the larger the influence of the ground reflection. The direct wave from Drone 1 without ground reflection is also received by Drone 2 as an interference component.

B. Case without circular polarization

In this section, we apply the two-ray model to the system model described in Section A, and calculate the received power and SIR from Friis's formula. The received signal in Drone 2 consists of two components, i.e. the direct wave transmitted from Drone 1 through free space and the reflected wave from the ground. The distance of the direct wave and the reflected wave is shown as follows.

$$D_d = \sqrt{D^2 + |h_1 - h_2|^2} \tag{1}$$

$$D_r = \sqrt{D^2 + (h_1 + h_2)^2} \tag{2}$$

The phase difference φ between the direct wave and the reflected wave is shown as follows.

$$\varphi = \frac{2\pi(D_r - D_d)}{\lambda} \tag{3}$$

The received power, which is the interference signal at Drone 2, is shown as follows by applying the two-ray model.

$$P_{Iuav} = P_{tuav}\left(\frac{\lambda}{4\pi}\right)^2 \left|\frac{\sqrt{G_{dir}}}{D_d} + R\frac{\sqrt{G_{ref}}e^{-j\Delta\varphi}}{D_r}\right|^2 \tag{4}$$

$$\sqrt{G_{dir}} = \sqrt{G_b G_d} \tag{5}$$

$$\sqrt{G_{ref}} = \sqrt{G_a G_c} \tag{6}$$

where P_{tuav} denotes the transmit power of Drone 1, R denotes the reflection coefficient, $\sqrt{G_{dir}}$ denotes the product of the antenna field patterns along the LoS direction, $\sqrt{G_{ref}}$ denotes the product of the antenna field patterns along the reflected path. The antenna model is based on the following equation.

$$G(\theta) = 10^{G_0 - 3.01\frac{2\theta}{\theta_B}}\left(-\frac{\theta_{ml}}{2} \le \theta \le \frac{\theta_{ml}}{2}\right) \tag{7}$$

$$= 10^{-0.411\ln\theta_B - 10.6}\left(0 < -\frac{\theta_{ml}}{2}, \frac{\theta_{ml}}{2} < \theta\right) \tag{8}$$

$$G_0 = 20\log_{10}\left(\frac{1.62}{\sin\frac{\frac{\pi}{180}\theta_B}{2}}\right) \tag{9}$$

$$\theta_{ml} = 2.58\theta_B \tag{10}$$

where θ_B denotes the half-width angle, θ_{ml} denotes the main lobe width, G_0 denotes the antenna gain.

The power of the desired signal transmitted from GU2 is shown as follows.

$$P_{up} = P_t\left(\frac{\lambda}{4\pi}\right)^2 \frac{G_t G_0}{{h_2}^2} \tag{11}$$

where P_t denotes the terminal ground power, G_t denotes the terminal antenna gain. From the above, SIR can be shown as follows.

$$\text{SIR} = \frac{P_{up}}{P_{Iuav}} \tag{12}$$

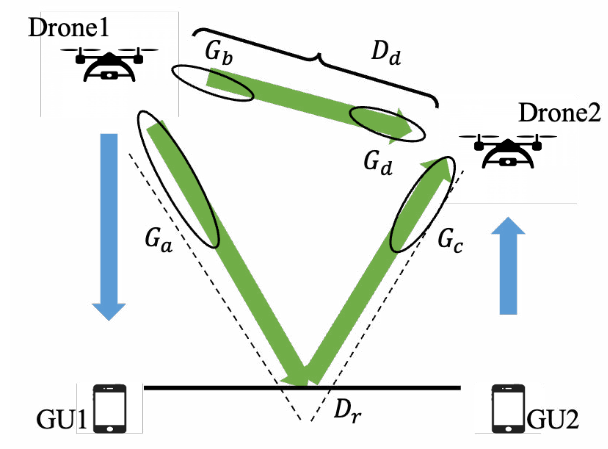

Fig. 3. Two-ray model.

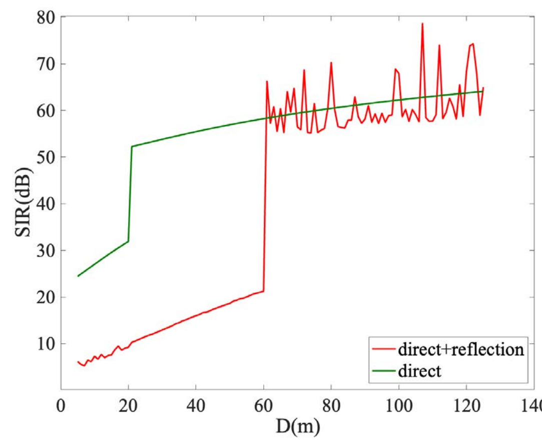

Fig. 4. SIR performance in conventional method.

where P_{up} denotes the desired power received from GU2 to Drone 2 and P_{Iuav} denotes the interference power received from Drone 1 to Drone 2. Figure 4 shows the SIR when D is varied from 5m to 125m in the system model with h_1 =50m and h_2 =25m. The green curve shows the SIR of the direct wave only, and the red curve shows the SIR of the two-ray model that combines the direct and reflected waves. From the figure, we can see that the red curve is less than 30 dB for the range from 5 m to 60 m, which is affected by the ground reflection. The closer the distance between the drones, the stronger the interference, and the SIR goes down. It is a difficult environment for communication. Therefore, it is necessary to improve the SIR for this communication range. Under the same conditions, the proposed method investigates the usage of circular polarization in the next section.

C. Proposed Method

In the system model shown in Fig. 2, we considered the adoption of circular polarization. A circular polarization wave is a polarized wave in which the electric field propagates in a rotation like a circle. There are two advantages of using the circular polarization. The first is that the alignment angle of the transmitting and receiving antennas in the wavefront can be set freely because the electric field component propagates in a rotating pattern. The second is that the direction of rotation of the electric field after reflection can be reversed if the angle of incidence of the electric field is within the Brewster angle, thereby reducing multipath fading [8]. In our system model shown in Fig. 2, Drone 1 and Drone 2 are equipped with antennas that can transmit and receive right-handed circular polarization, and GU1 and GU2 are equipped with antennas that can transmit and receive linearly polarized waves. The right-handed circular polarization transmitted from Drone 1 is converted to left-handed circular polarization after reflection from the ground, and Drone 2, which is equipped with an antenna capable of receiving right-handed circular polarization, cannot receive the left-handed circular polarization. With this principle, we considered how to improve the SIR of Drone 2 by preventing the influence of ground reflection. On the other hand, it should be noted that the desired signal transmitted from GU2 is linearly polarized waves, so the power is only half when it is received by Drone 2. Next, we apply the circular polarization to the system model and explain how to calculate the electric field after reflection. The polarization plane that is vertical to the ground is called a vertical polarization (TM wave), and that that is horizontal is called a horizontal polarization (TE wave). The reflection coefficients for incident vertical and horizontal polarization waves are shown as follows.

$$\rho_V = \frac{(\varepsilon_r - jx)\sin\phi - \sqrt{(\varepsilon_r - jx) - \cos^2\phi}}{(\varepsilon_r - jx)\sin\phi + \sqrt{(\varepsilon_r - jx) - \cos^2\phi}} \tag{13}$$

$$\rho_H = \frac{\sin\phi - \sqrt{(\varepsilon_r - jx) - \cos^2\phi}}{\sin\phi + \sqrt{(\varepsilon_r - jx) - \cos^2\phi}} \tag{14}$$

where ε_r denotes the relative dielectric constant of the earth fields, σ denotes conductivity, ε_0 denotes the dielectric constant of free space, ϕ denotes grazing angle, where x is defined as follows.

$$x = \frac{\sigma}{\omega\varepsilon_0} \tag{15}$$

The reflection coefficient is determined by the shape and material of the ground and is expressed as a complex number. In our research, we adopted the value for an average ground in [9]. Assuming that the wave propagates in the z-axis direction, the right-handed circular polarization can be expressed as follows.

$$\boldsymbol{E}_R = E_0 e^{jwt}\{\boldsymbol{i} + \boldsymbol{j}e^{j\left(-\frac{\pi}{2}\right)}\}e^{-jk_0 z} \tag{16}$$

When the phase is 90° behind, the circular polarization is right-handed, and when the phase is 90° ahead, the circular polarization is left-handed. Since the circular polarization can be decomposed into TM wave and TE wave, the electric field of TM wave and TE wave can be shown as follows.

$$\boldsymbol{E}_{TM} = E_0\boldsymbol{i}(e^{j\omega t})e^{-jk_0 z} \tag{17}$$

$$\boldsymbol{E}_{TE} = E_0\boldsymbol{j}e^{j\left(-\frac{\pi}{2}\right)}(e^{j\omega t})e^{-jk_0 z} \tag{18}$$

$$k_0 = \frac{2\pi f}{c} \tag{19}$$

where E_0 denotes amplitude of electric field, $\boldsymbol{i}$ denotes the unit vector in x-axis direction, $\boldsymbol{j}$ denotes the unit vector in y-axis direction, k_0 denotes a wave number, c denotes the speed of light.

Based on the reflection coefficient and the incident wave, the TM and TE waves after ground reflection are expressed as follows.

$$\begin{bmatrix} E_{TM}^r \\ E_{TE}^r \end{bmatrix} = \begin{bmatrix} \rho_V & 0 \\ 0 & \rho_H \end{bmatrix} \begin{bmatrix} E_{TM}^i \\ E_{TE}^i \end{bmatrix} \tag{20}$$

where E_{TM}^i denotes TM wave before reflection, E_{TE}^i denotes TE wave before reflection, E_{TM}^r denotes TM wave after reflection, E_{TE}^r denotes TE wave after reflection.

By matrix calculation, the right- and left-handed circular polarization after ground reflection are shown as follows.

$$\begin{bmatrix} E_L^r \\ E_R^r \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & j \\ 1 & -j \end{bmatrix} \begin{bmatrix} E_{TM}^r \\ E_{TE}^r \end{bmatrix} \tag{21}$$

where E_L^r denotes left-handed circular polarization, E_R^r denotes right-handed circular polarization.

The desired power to be received from GU2 to Drone 2 is shown as follows.

$$P_{up1} = \frac{1}{2}\left| E_{up} \times \sqrt{P_t \times G_0 \times 1 \times \left(\frac{c}{4\pi f h_2}\right)^2} \right|^2 \tag{22}$$

where E_{up} denotes the amplitude of linear polarization, P_t denotes the transmit power of the terminal, G_0 denotes the gain of receiving antenna (Drone 2).

The reason for the factor of a half in (22) is that a circularly polarized antenna can receive only half the power of a linearly polarized transmission. The power is calculated as the square of the absolute value of the electric field. From the above, Fig. 5 shows the SIR for the system model with h_1 = 50 m and h_2 = 25 m and D varying from 5 m to 125 m.

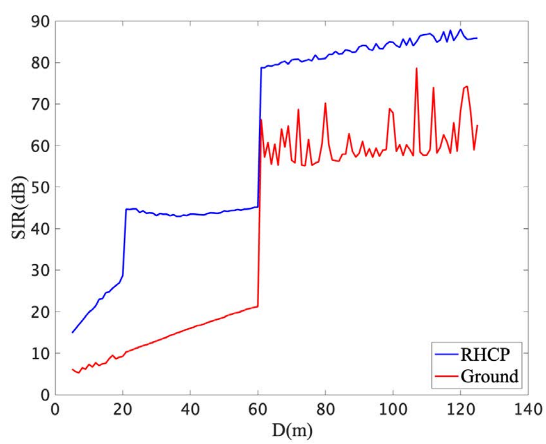

Fig. 5. SIR performance with circular polarization.

The blue curve shows the SIR of the right-handed circular polarization transmitted from Drone 1. The red curve is the same curve as Fig. 4 and is shown for the sake of comparison. The SIR is less than 20 dB when circular polarization is not applied for the range 20 m and 60 m, which is affected by the ground. On the other hand, the SIR of more than 40 dB is achieved in the case of circular polarization. Moreover, when the distance between the users is closer, from 5 m to 20 m, the SIR is less than 30 dB even in the case of circular polarization. This is Drone 2 is placed within the main lobe of Drone 1's antenna. In order to achieve the SIR of more than 30 dB at this distance, it is necessary to narrow the beam width further. After 60 m, we can see a sharp increase in the SIR. This is caused by the fact that the reflected wave is received with side lobes at the receiver. The shape of the graph may change depending on the choice of antenna model.

The parameters used in this paper are listed in the Table I.

TABLE I. NUMERICAL PARAMETERS

PARAMETER	VALUE[UNIT]
CARRIER FREQUENCY	28[GHz]
BANDWIDTH	100[MHz]
TRANSMIT POWER(DRONE)	13[dBm]
TRANSMIT POWER(TERMINAL)	23[dBm]
TRANSMIT ANTENNA HALF-WIDTH	30[°]
RECEIVE ANTENNA GAIN	0[dBi]
CONDUCTIVITY	5×10^{-3}[S]
RELATIVE DIELECTRIC CONSTANT	15

IV. CONCLUSION AND FUTURE WORKS

The application of the circular polarization in this paper is to reduce the effect of ground reflection and to improve the SIR compared with the linearly polarized waves. There are three main issues to be addressed in the future. The first one is the introduction of the AR (Axial Ratio). The AR is an important parameter in the evaluation of circularly polarized antennas and is defined as the ratio of the lengths of the major and minor axes of the ellipse drawn by the trajectory of the electric field. Many papers define AR less than 3 dB as the evaluation value for circularly polarized antennas. However, the AR is closely related to the cross-polarization discrimination, which is the scale of the difference between the main polarization and the cross-polarization. Therefore, the evaluation value of the AR should be determined by considering whether the isolation between the main polarization and the cross-polarization is sufficient or not, and the effect of the polarization loss between the transmitting and receiving antennas. In this research, transmission and reception are assumed to be performed in an ideal circle, but in practice, it is possible that transmission and reception are performed in an ellipse. By introducing the AR, a more realistic study will be possible. The second is the propagation loss. At present, for simplicity, all the paths are considered with free space loss, but in the case of a disaster area, the paths are not free space because of the presence of rubble and buildings. The third is the location of the user. In this research, we assume the case that there is one user directly under one drone. However, it is rare that the user is directly under the drone, and it is assumed that there are multiple users. The above three considerations should be taken into account for a more realistic investigation.

ACKNOWLEDGMENT

Part of the results of this research was supported by a 2019 research study grant from the Telecommunications Advancement Foundation.

REFERENCES

[1] S.Hayat, E.Yanmaz, and R.Muzaffar, “Survey on unmanned aerial vehicle networks for civil applications: A communications viewpoint,” *IEEE Commun. Surveys Tuts.,* vol. 18, no. 4, pp. 2624-2661, 4th Quart., 2016.

[2] A.Ghosh, T.A.Thomas, M.C.Cudak, R.Ratasuk, P.Moorut, F.W.Vook, T.S.Rappaport, G.R.MacCartnry, S.Sun, and S.Nie, “Millimeter-wave enhanced local area systems: A high-data-rate approach for future wireless networks,” *IEEE J. Sel. Areas Commun*., vol. 32, no. 6, pp. 1152-1163, Jun. 2014.

[3] L.Zhang, H.Zhao, S.Hou, Z.Zhao, H.Xu, X.Wu, Q.Wu, and R.Zhang, “A survey on 5G millimeter wave communications for UAV-assisted wireless networks,” *IEEE Access,* vol.7 pp. 117460-117504, Jul. 2019.

[4] Ministry of Internal Affairs and Communications, WHITE PAPER Information and Communications in Japan, 2011

[5] M.Mozaffari, W.Saad, M.Bennis, and M.Debbah, “Drone Small Cells in the Clouds: Design, Deployment and Performance Analysis” in *Proc. of IEEE Global Communications Conference,* San Diego, CA, USA, Feb. 2016.

[6] M.Mozaffari, W.Saad, M.Bennis, and M.Debbah, “Efficient Deployment of Multiple Unmanned Aerial Vehicles for Optimal Wireless Coverage,” *IEEE Commun.Lett*., vol. 20, no. 8, pp. 1647-1650, Aug. 2016.

[7] M.Ozasa, J.Nakazato, K,Hirata, G.K.Tran, K.Sakaguchi, “Design of Millimeter-wave UAV Base Station for Access Link”, 2020 IEEE 92nd Vehicular Technology Conference, Victoria, BC, Canada, Dec. 2020.

[8] T.Fukusako, “Basics of Circularly Polarized Antenna″ , Corona,Inc.

[9] J.D.Parsons(2000)*The Mobile Radio Propagation Channel*. Second Edition, John Wiley&Sons Ltd.