Analysis of Unmanned Aerial Vehicle MIMO Channel Capacity Based on Aircraft Attitude

Xijun Gao, Zili Chen, Yongjiang Hu
Unmanned Aerial Vehicle Engineering Department
Mechanical Engineering College
050003, Shijiazhuang
China
Email: richardlawson94@sohu.com

Abstract: - In the paper, the demand of Unmanned Aerial Vehicle Multi-Input Multi-Output (UAV-MIMO) communication are taken into consideration, four-element circular antenna array are adopted on the UAV. In order to analyze UAV-MIMO communication system, the uniform coordinate is proposed, and the three-dimensional geometrically based single bounce cylinder model (3D-GBSBCM) channel model of UAV-MIMO system based on four transmitting antennas and two receiving antennas is put forward. The methods of channel matrix factorization and channel coefficient normalization are adopted to deduce the average channel correlation matrix of UAV-MIMO. The influences of UAV attitude parameters on UAV-MIMO channel capacity are simulated and analyzed. The simulation and analysis results have good reference and application values in improving UAV-MIMO system capacity through changing attitude parameters of UAV.

Key-Words: - UAV-MIMO, Circular Antenna Array, Attitude Change, Channel Capacity

1 Introduction

With the wide applications of UAV, its high performance complex tasks are emerging. So the demands of communication rate of UAV data-link need to be improved accordingly. As known that MIMO technology can improve communication capacity without expensing extra spectrum resources and adding transmit power [1]. So the MIMO technology can be adopted in UAV communication system which will provide solutions for the high-speed data-link of UAV. The analysis of UAV-MIMO channel capacity will play an important role in the application of UAV MIMO data-link.

The MIMO technology applied in airplane communication system is proposed in recent years. In paper [2], the problem that the antenna is sheltered by fuselage of UAV is studied. The proposal of adopting multi-antennas and space-time code technology to realize reliable communication between the UAV and ground station are put forward. In paper [3], the combined technology of beamforming and differential space-time modulation are proposed in aeronautical communication, and the parameter performances of aeronautical channel model are simulated based on paper [4]. In paper [5], the problems of spatial correlation and shelter effects of fuselage are taken into consideration and the statistical channel model for multi-antennas communication of unmanned helicopter are put forward. In paper [6], the 3D UAV-MIMO channel model of dual-element antenna array is given out based on GBSBCM in paper [7], and the factors of non-omnidirectional antennas on the correlation of UAV-MIMO channel are analyzed. In paper [2], the performance analysis is based on Gaussian White Noise channel, ignoring the aircraft communication channel modeling; in paper [3] the effects of airplane attitude and spatial correlation on channel are not put into consideration in the multi-antenna channel model; in paper [5], the reliability of multi-antenna communication is researched, the analysis of effective communications is ignored; in the paper [6], the analysis of UAV-MIMO channel capacity isn't given out.

In the paper, according to the characteristics of communication conditions between the ground station and the UAV, we adopt four-element circular antenna array to analyze effects of UAV attitude change on

UAV-MIMO channel capacity. The 3D-GBSBCM channel model of UAV-MIMO based on four transmitting antennas and two receiving antennas are proposed. And the average channel correlation matrix of the model is deduced. The structure of paper is as follows, In Section II, the UAV-MIMO communication coordinate is proposed. In Section III, the UAV-MIMO channel model contains the straight, reflection and scattering components is presented. In Section IV, the deducing of average channel correlation matrix based on four transmitters and two receivers is given out. In Section V, the effects of UAV attitude change on MIMO channel capacity are simulated and analyzed. Conclusions are drawn in Section VI.

2 Coordinate System of UAV-MIMO Communication

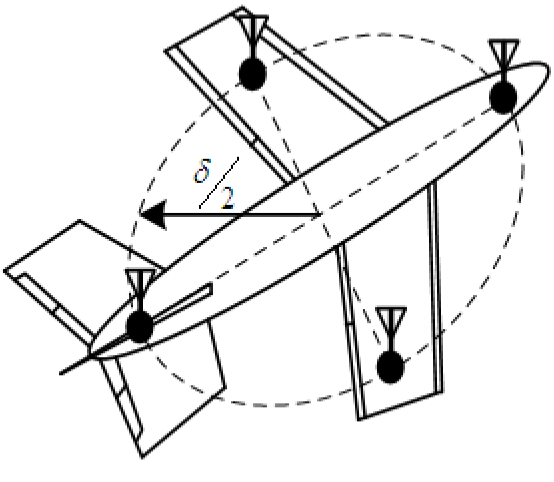


Fig. 1 Structure of four-element antenna on UAV

Its attitude is often changes when UAV is flying in the air. The change will influence the angles of electromagnetic waves which are sent from multi-antennas on the UAV. So the effectiveness of UAV-MIMO communication will be influenced [8]. According to the configuration of UAV, we adopt the four-element antenna configured effectively on the UAV. Now, the linear antenna array structure which is widely researched, its channel capacity will be declined sharply when the arrival wave angle is large enough. But the antennas structures of which are evenly distributed as the circular will present better diversity performances in different scattering circumstance [9-11]. So we adopt the four antennas as circular symmetrical layout on the font, tail and wings of UAV, and the diameter of circle is δ . The four-element antenna structure is shown as Fig. 1.

As known that in the UAV-MIMO communication system, the UAV and the ground station are both in the movement, the premise of parameters analysis of moving system is to establish a proper coordinate system. In the UAV-MIMO communication system, we can select different coordinate systems according to different moving objects, thus the parameters need to analyze are very complex. In order to reduce the difficulty of analysis, it is very necessary to establish a uniform and rational coordinate system, which is shown as Fig.2. If we make the assumption that the UAV is arranged with four-element antennas, the two-element antenna is adopted in the ground control station, which also is the omni-directional antenna. The ground station is in the 3D-cylinder scattering environment that the radius is R and H_c is the height, just shown as Fig.2. The coordinate system is defined as follows.

We define that the $x-y$ plane contains the section circle, the line midpoint O_g (height is H_g) of the two-element antenna of ground station is taken as the center; O denotes the projection of the circular antenna array center O_u in the $x-y$ plane, which is as the base point in the coordinate system; the connection of $O-O_g$ is looked as the x -axis, the connection of $O-O_u$ is looked as z -axis; the z_u axis of UAV coordinate system and the Z axis is the same; x_u-y_u plane is parallel to $x-y$ plane; in the reception coordinates of ground station, x_g axis and x axis are superposition; y_g-z_g plane is parallel to the plane of $y-z$. So that the coordinate system $O_u-x_uy_uz_u$ of transmitter, the coordinate system of receivers $O_g-x_gy_gz_g$, and the coordinate system $O-xyz$ will have the same attributes in parallel.

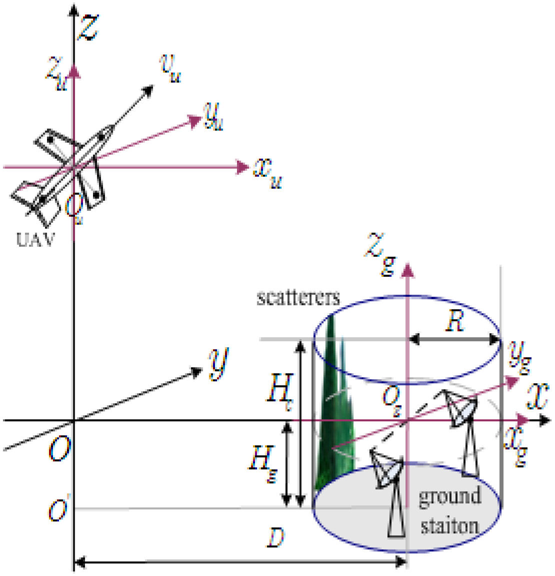


Fig.2 Coordinate system of UAV-MIMO communication

In the coordinate system of UAV-MIMO communication, the coordinate system of UAV $O_b-x_by_bz_b$ can be defined as , the center O_u of circular antenna array is looked as the base point O_b ; x_b axis is coincidence with the axial speed of UAV v_u ; y_b axis is vertical to the symmetry plane (which is over x_b axis and vertical to $x-y$ plane) of UAV fuselage, which points to the right side of the fuselage; z_b axis is vertical to the $x_bO_by_b$ and points to the fuselage below. Then the attitude angle of flying can be described as:

(1)Pitch angle γ_u is the angle between the x_b axis and the horizontal plane x_u-y_u , the rising direction is positive direction.

(2)Roll angle β_u is the angle between z_b axis and the vertical plane which is over x_b axis, the right direction UAV tilted to is positive direction.

(3)Yaw angle α_u is the angle between the projection of x_b axis in the $x-y$ plane and the x axis, the right direction front of UAV yawed is the positive direction.

3 UAV-MIMO Channel Model

The traditional aeronautical MIMO channel model mainly involves Line-of-Sight (LOS) components and Specular (SPE) ones [3, 12].

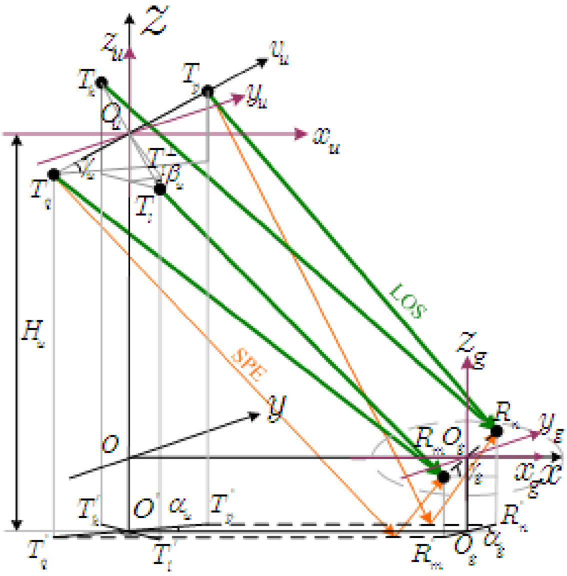


Fig.3. Propagation model with the line of sight and specular components

But there are direct or reflection components and some diffuse components in the UAV communication system. So the aeronautical MIMO channel model cannot reflect the characteristics of UAV-MIMO channel precisely. According to the paper [7,8,14-17], if there exists the obvious height difference between transmitter and the receiver, the receiver is the center of the scatterers which are distributed around, when there is the extension of the pitch angle, the "cylinder" scattering model can be described as statistical characteristics of the MIMO channel. The related measurement results have prove the reasonableness of scattering cylinder distribution [15,16-19]. Therefore, we propose UAV-MIMO channel model with direct, reflection and diffuses components based on GBSBCM, which is as shown in Fig. 3 and Fig. 4.

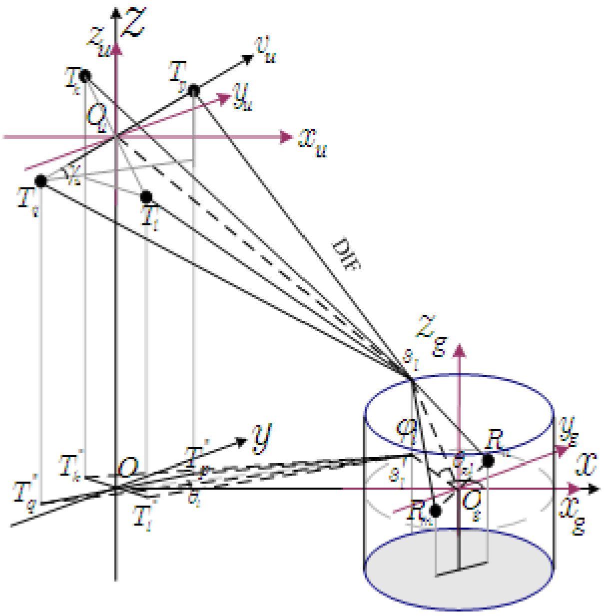


Fig.4.Propagation model with the diffuse components

In the figures, the pitch angle and the roll angle of the connection of UAV antennas T_p T_q are γ_u and α_u respectively; the projection from the wing antenna T_l to the vertical plane r T_p is $T_l^{\perp}$, the angle of $T_kT_lT_l^{\perp}$ is β_u; γ_g and α_g are the pitch and site angles of the connection of receiving antennas R_m, R_n in the ground station; D is the horizontal distance of the UAV, the height is H_u , the distance between receiving antennas R_m, R_n is δ_{nm} , these parameters are satisfied with: $D >> H_u >> R >> H_c >> H_g >> \max(\delta, \delta_{nm})$; s_l denotes the scatterer of number l, s_l' represents the projection of s_l in the $x-y$ plane.

The model parameters involves the parameters of flight altitude, horizontal distance, attitude angle and others, e.g., the height of the ground receiving station, the angle of receiving antenna and the scattering environment parameters of scattering radius, height and others, but also involves the many components of the channel. So it is consistent with the real environment, and the model is coincidence with the requirements of application, it also can reflect the statistical characteristics of the UAV-MIMO channel.

4 Correlation Matrix of UAV-MIMO Channel

Under the condition of WSSUS (wide-sense stationary uncorrelated scattering), we can assume that the probability density function of pitch and site angle presents the Von-Mises distribution and belongs to complex parameter model [14, 15]. If we take the channel between the transmitters T_p , T_q and the receivers R_n , R_m as the example, the space-time-frequency correlation functions of line-of-sight and specular can be simplified as follows.

$$\begin{aligned}&R_{np,mq}^{LOS}\left(\Delta t, \Delta f\right)\\&= E\left(h_{np,LOS}\left(t, f\right)h_{mq,LOS}^{*}\left(t+\Delta t, f+\Delta f\right)\right)\\&= e^{jk_0\left(d_{np}^{LOS}-d_{mq}^{LOS}\right)} \times R_{LOS}e^{jf_{LOS}\left(\Delta t, \Delta f\right)}\end{aligned} \tag{1}$$

$$\begin{aligned}&R_{np,mq}^{SPE}\left(\Delta t, \Delta f\right)\\&= E\left(h_{np,SPE}\left(t, f\right)h_{mq,SPE}^{*}\left(t+\Delta t, f+\Delta f\right)\right)\\&= e^{jk_0\left\{d_{np}^{SPE}-d_{mq}^{SPE}\right\}} \times R_{SPE}e^{jf_{SPE}\left(\Delta t, \Delta f\right)}\end{aligned} \tag{2}$$

Where, λ represents wavelength; $k_0 = 2\pi / \lambda$ represents wave number in free-space; R_{LOS} and R_{SPE} represent the correlation functions amplitude of line-of-sight and specular paths, respectively; d^{LOS} and d^{SPE} represent the distance of line-of-sight and specular paths respectively. $f_{LOS}(\Delta t, \Delta f)$ and $f_{SPE}(\Delta t, \Delta f)$ are the functions with variables of Δt and Δf , and which are also satisfied: $f_{LOS}(0,0) = f_{SPE}(0,0) = 0$. According to paper [7], the space-time-frequency correlation functions of diffuse can be simplified as follows.

$$\begin{aligned}&R_{np,mq}^{DIF}\left(\Delta t, \Delta f\right)\\&= R_{DIF}e^{jf_{DIF}\left(\Delta t, \Delta f\right)} \times e^{j2\pi k_0\left(\cos\vartheta_u \cos\alpha_u - \Delta_1 \sin\vartheta_u\right) \big/ \sqrt{1+\Delta_1^2}}\\&\times I_0\left(\sqrt{x^2+y^2}\right) \times R\left(m,n\right) \big/ I_0\left(k\right)\end{aligned} \tag{3}$$

Where, $I_o(\cdot)$ represents Zero-order Bessel modified function; k represents the angle spread factor in the Von-Mises distribution; θ_{go} is the average of the azimuth angle in the circumstance of scatterring; $f(\varphi_g)$ is belong to the complex parameter model; R_{DIF} represent the amplitude of correlation functions of diffuse paths. $f_{DIF}(\Delta t, \Delta f)$ is also the functions which variables are Δt and Δf, and it is satisfied with the $f_{DIF}(0,0)=0$.

According to the paper [1], if the channel parameters in the transmitting part are unknown and the channel coefficients are the constant, in the MIMO communication system which has n_T transmitting antennas and n_R receiving antennas, and then its channel capacity can be expressed as follow (4).

$$C = \log_2\left[\det(\boldsymbol{I}_{n_R} + \frac{SNR}{n_T}\boldsymbol{H}\boldsymbol{H}^*)\right](bit/s/Hz) \quad (4)$$

Where, SNR is the receiving signal-to-noise ratio, $\boldsymbol{H}$ is the channel correlation matrix of $n_T \times n_R$, $\boldsymbol{H}^*$ is the conjugate transpose of $\boldsymbol{H}$. When the channel coefficients are stochastic, equation (4) represents instantaneous channel capacity. Then, the channel capacity can be taken as an ergodic process and the channel coefficients can be obtained through appling the average method.

$$\overline{C} = E_H(C) \quad (5)$$

It is obvious that the channel correlation matrix $\boldsymbol{H}$ is the key to analyze MIMO channel capacity. As the UAV channel coefficient $h_{n_T,n_R}(t,\tau)$ is a random variable, so the average of channel correlation matrix is necessary to analyze the average channel capacity. If we take the UAV communication system as a whole into consideration, and apply the methods of channel matrix analysis and channel coefficient normalization, then the correlation matrix of UAV-MIMO channel can be deduced.

The UAV-MIMO channel correlation matrix H can be decomposed as below (6).

$$\boldsymbol{H} = \eta_{LOS}\boldsymbol{H}_{LOS} + \eta_{SPE}\boldsymbol{H}_{SPE} + \eta_{DIF}\boldsymbol{H}_{DIF} \quad (6)$$

Where H_{LOS}, H_{SPE} and H_{DIF} represent the correlation matrix of direct, reflection and scattering components. If in the channel model $n_R=2$, $n_T=4$, H_{LOS} can be expressed as follows (the expression of H_{SPE} and H_{DIF} is similar as H_{LOS}).

$$\boldsymbol{H}_{LOS} = E\left\{\begin{bmatrix} h_{np}^{LOS}(t,f)\, h_{nq}^{LOS}(t,f)\, h_{nk}^{LOS}(t,f)\, h_{nl}^{LOS}(t,f) \\ h_{mp}^{LOS}(t,f)\, h_{mq}^{LOS}(t,f)\, h_{mk}^{LOS}(t,f)\, h_{ml}^{LOS}(t,f) \end{bmatrix}\right\}$$

(7)

η_{LOS}, η_{SPE} and η_{DIF} represent the proportion factor of direct, reflection and scattering components of the receiving power, respectively, they can be written as (8).

$$\begin{cases} \eta_{LOS} = \sqrt{\dfrac{K_{Rice}}{1+K_{Rice}+K_{Rice}\Gamma^2}} \\ \eta_{SPE} = \Gamma\sqrt{\dfrac{K_{Rice}}{1+K_{Rice}+K_{Rice}\Gamma^2}} \\ \eta_{DIF} = \sqrt{\dfrac{1}{1+K_{Rice}+K_{Rice}\Gamma^2}} \end{cases} \quad (8)$$

In the previous expressions, $\Gamma \in [-1,1]$ represents the specular reflection coefficient which is the ratio between the incident wave and the reflected wave, $K_{Rice} \in [0,+\infty)$ represents the Rice factor which is the ratio between the direct and the scattering component.

Through applying the normalization method of the channel coefficient, the corresponding channel correlation matrix can be obtained. Firstly, we take $h_{np}^{LOS}(t,f)$ as standard and $h_{np}^{LOS}(t,f)=1$. The matrix $\boldsymbol{H}_{LOS}$ can be divided by $h_{np}^{LOS}(t,f)$, which can keep the relativity between each channel. Finally, the channel correlation matrix can be obtained as below.

$$\boldsymbol{H}_{LOS} = E\left\{\begin{bmatrix} 1 & \dfrac{h_{nq}^{LOS}(t,f)}{h_{np}^{LOS}(t,f)}\cdots \\ \dfrac{h_{mp}^{LOS}(t,f)}{h_{np}^{LOS}(t,f)} & \dfrac{h_{mq}^{LOS}(t,f)}{h_{np}^{LOS}(t,f)}\cdots \end{bmatrix}\right\} \quad (9)$$

Taking the $h_{nq}^{LOS}(t,f) \Big/ h_{np}^{LOS}(t,f)$ For example, it can be represented as $R_{np,nq}^{LOS}(0,0) \Big/ \mathrm{Re}\{R_{np,nq}^{LOS}(0,0)\}$. The rest of the ranks can be solved through the similar principle, then we will obtain $\boldsymbol{H}_{LOS}$. In the process of solving $\boldsymbol{H}_{DIF}$, we can separate the distance between the transmitters and the receivers into two parts, they are the distance from the transmitting antennas to the scatterers and the distance from scatterers to receiving antennas. When the transmitting antennas are the same, the normalization average channel correlation function of different receiving antennas (e.g.,$T_p - R_m, T_p - R_n$) can be expressed as (10).

$$\frac{R_{np,mp}^{DIF}(0,0)}{Re\left\{R_{np,mp}^{DIF}(0,0)\right\}} \approx \frac{I_0\left(\sqrt{x_1^{\,2}+y_1^{\,2}}\right)}{I_0(k)} \times R(m,n) \qquad (10)$$

$$\begin{cases} x_1 = jk_0\delta_{nm}\cos\vartheta_g cos\alpha_g + k\cos\theta_{g0} \\ y_1 = jk_0\delta_{nm}\cos\vartheta_g sin\alpha_g + k\sin\theta_{g0} \end{cases} \qquad (11)$$

When the receivers are the same, the normalization average channel correlation function of different transmitters (e.g., $T_p - R_n, T_q - R_n$) can be expressed as (12).

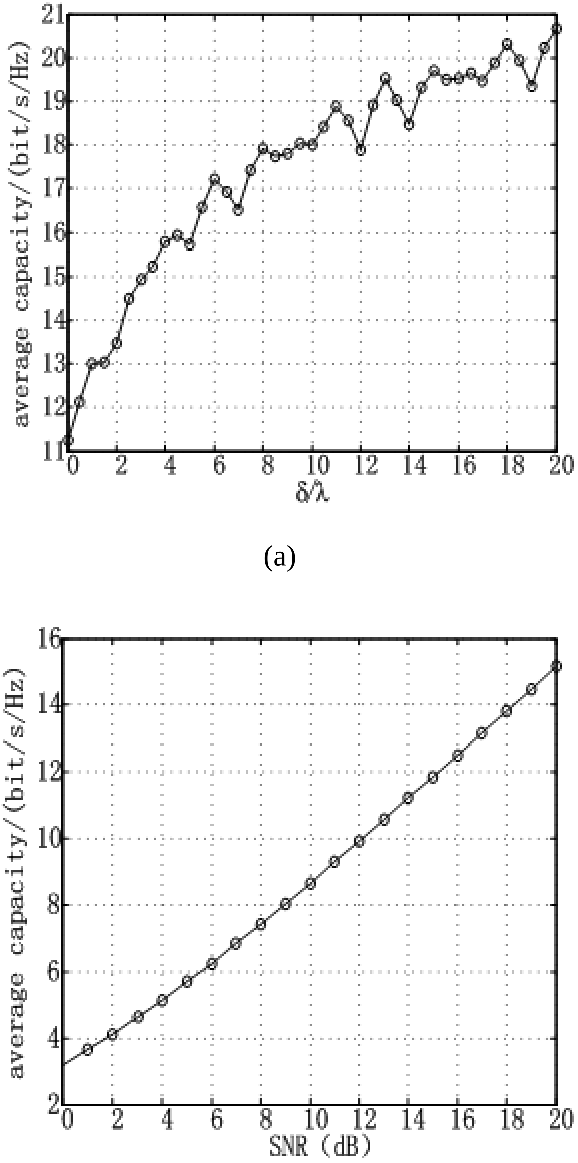
$$\frac{R_{np,nq}^{DIF}(0,0)}{Re\left\{R_{np,nq}^{DIF}(0,0)\right\}} = e^{jk_0\Delta d_{np,nq}} \qquad (12)$$

Where, $\Delta d_{np,nq}$ is the path difference from the transmitting antennas T_p, T_q to the scatter s_l.When the receivers and the transmitters are both different antennas.The normalization average channel correlation function can be expressed as (13).

$$\frac{R_{np,mq}^{DIF}(0,0)}{Re\left\{R_{np,mq}^{DIF}(0,0)\right\}} = \frac{I_0\left(\sqrt{x_1^{\,2}+y_1^{\,2}}\right)}{I_0(k)} \times R(m,n) \times e^{jk_0\Delta d_{np,nq}} \qquad (13)$$

5 Simulation of UAV-MIMO Channel Capacity

In equation (6), there are many parameters in the average channel correlation. So there are many influence factors about UAV-MIMO channel capacity. According to the characteristics of UAV communication environment, we adopt a quantificational method to analyze UAV-MIMO average channel capacity. In the method, some of the parameters are assumed to be a fixed value in the application environment of UAV, and then we analyze the effects of some interested parameter on the UAV-MIMO average channel capacity.



(a)

(b)

Fig.5 (a) Effect of circular array diameter on the average capacity when $SNR = 20dB$

(b) Effect of receiving Signal-to-noise ratio on the average capacity when $\delta = 6\lambda$

Firstly, we analyze the effect of diameter of circular antenna array δ and the receiving SNR on the UAV-MIMO channel capacity are shown as Fig. 5 and Fig. 6. In the simulations, we assume that $D=60Km$, $H_u=2Km$, $H_g=5m$, $H_c=300m$, $R=3Km$, $K_{Rice}=4dB$, $\Gamma=-1$, $\theta_{g0}=\pi/8$, $\gamma_u=\beta_u=\alpha_u=\gamma_g=\alpha_g=\pi/4, k=0, \delta_{nm}=10\lambda$. In the Fig. 5, it is shown that the larger diameter of circular antenna array, the lager the average channel capacity is. It is due to the larger diameter of the circular antenna array will lead to the greater distance between antennas, so the relativity of communication channel in space is reduced. Then the capacity of the channel will be improved. Fig. 5(b) indicates that the receiving signal-to-noise ratio is proportional to the average channel capacity. In the three-dimensional simulation shown as Fig. 6, when the receiving signal-to-noise ratio is large, the improving of UAV channel capacity can be realized by a smaller antenna distance and it can reduce the dependence of antenna distance on the spatial structure of the UAV.

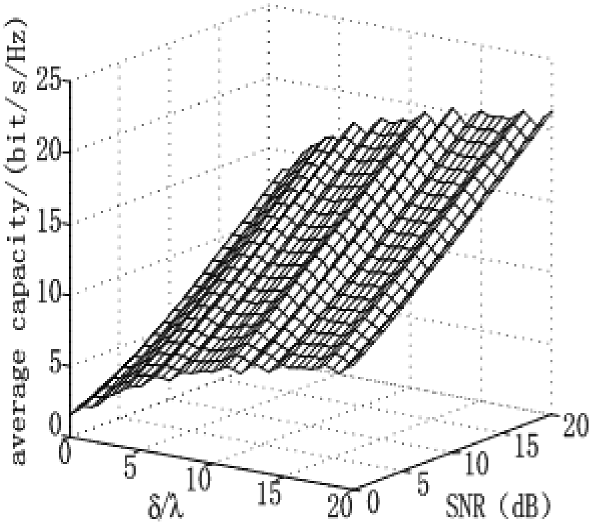
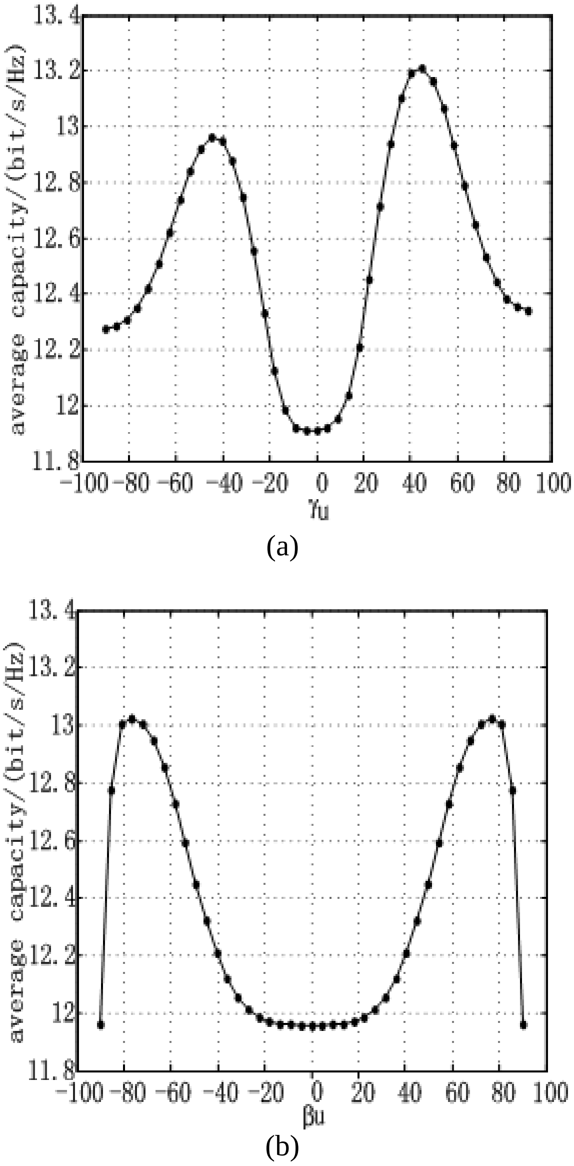


Fig.6.Effect of circular array diameter and receiving SNR on the average capacity

Secondly, under the simulation conditions above-mentioned, the further assumption are that $\delta=10\lambda$ and $SNR=20dB$. But the attitude angles of UAV γ_u and β_u are in the dynamic range. Then we analyze the effect of UAV flight pitch and roll on the MIMO channel capacity, the results are shown as Fig. 7 and Fig. 8. In the Fig. 7, it is shown that the change values of average channel capacity is small when the pitch and roll angles vary between [-90°, 90°], (a) of Fig. 7 indicates that the influence of pitch angle on the channel capacity has a symmetrical variation characteristic at 0°, -45°and 45°. The average channel capacity near 0°, -90°,90° is smaller, which is due to the strong correlation of the channel space near these angles, so the average channel capacity will be reduced. Fig. 7(a) shows that effect of roll angle on the channel capacity is also symmetrical at angle of 0 °, and the average channel capacity is low when β_u is near 0°, -90°, 90°. The reason is the same as the above analyzed. When the absolute value of β_u changes between [0°,80°], the spatial correlation of the channel is gradually decreased, which leads to the improving of the average channel capacity. Fig. 8 presents the changes of average channel capacity on the combined effects of the flight attitude γ_u and β_u. So if one angle is certain in the flight process of UAV, we can change another angle to enhance the average channel capacity.



(a)

(b)

Fig.7 (a) Effect of the pitch angle of UAV on the average channel capacity when $\beta_u = \pi/4$

(b) Effect of the roll angle of UAV on the average channel capacity when $\gamma_u = \pi/8$

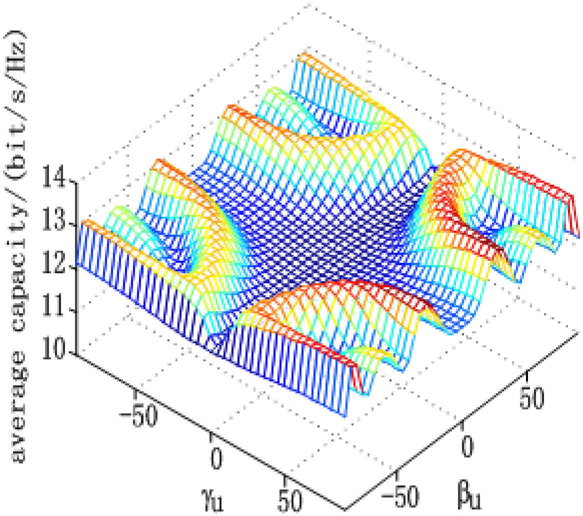
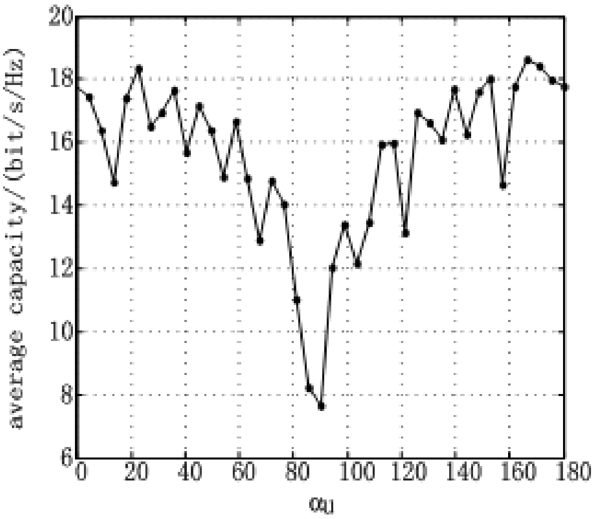
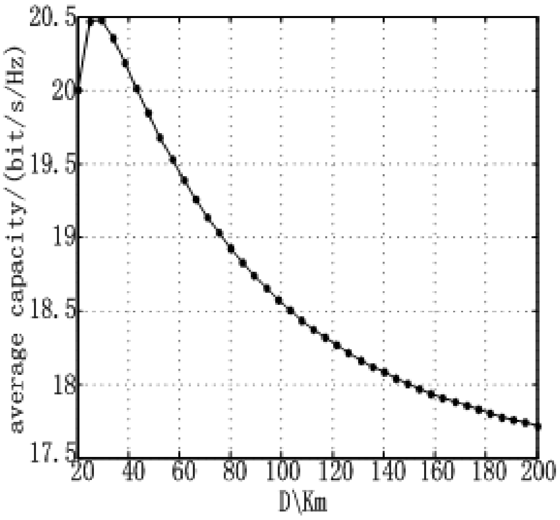


Fig.8 Effect of the attitude of UAV on the average channel capacity

Finally, we simulate and analyze the effect of UAV flight yaw angle and flight distance on the MIMO average channel capacity in the condition of $\beta_u = 0$ and $\gamma_u = 0$, they are shown in Fig. 9 and Fig.10. In (a) of Fig. 9, we can find that the effect of flight yaw angle on average channel capacity presents symmetrical distribution at the angle of 90° which is due to the symmetrical distribution of circular antenna array.



(a)



(b)

Fig. 9 (a) Effect of the yaw angle of UAV on the average capacity when $D = 200Km$

(b) Effect of the flying distance of UAV on the average capacity when $\alpha_u = 0$

The angles of the receiving and transmitting antennas make the receiving part relativity stronger, while the average channel capacity is smaller; (b) of Fig. 9 indicates that the farther the flight distance of UAV is, the weaker the distinguish ability of space multipath will be. Then the spatial correlation is stronger, so the average channel capacity is lower. Fig.10 gives out that the overall trends of combined effects of the yaw angle and the flight distance on the average channel capacity.

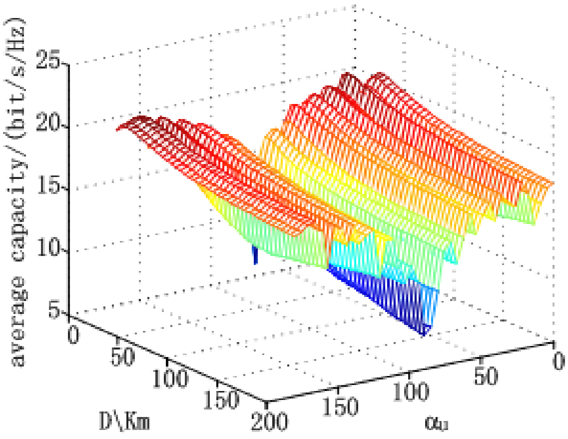


Fig.10 Effect of the yaw angle and flying distance of UAV on the average capacity

4 Conclusion

In the paper, according to the configuration characteristics of UAV, we propose the circular layout of four antennas on the UAV. We put forward the uniform coordinate system between the UAV and ground station in order to analyze the UAV-MIMO communication system thoroughly. According to the characteristics of UAV-MIMO communication system; we propose the channel model of UAV-MIMO based on four transmitting antennas and two receiving antennas. The correlation matrixes of UAV-MIMO channel of line-of-sight, specular and diffuse components are deduced. Moreover, we simulate and analyze effects of diameter of circular antenna array and flying attitude of UAV on the MIMO channel capacity. It can be found that the rational allocation of antenna and changing of flying attitude play an important role in improving the UAV-MIMO channel capacity.

Acknowledgement

This project is supported by the National Defence Research Fund of China (Grant No. 9140A25030210A). This is partially supported by the Science Fund of China (No.60902876).

References:

[1] Foschini G. J. Layered Space-time Architecture for Wireless Communication in a Fading Environment When Using Multiple Antennas ， Bell Labs Tech. Journal ， 1996 ， L(2), pp.41~59.

[2] Jensen, M. A., Rice, M.D. , Anderson, A.L.. Anderson. Aeronautical Telemetry using Multiple Antenna Transmitters. IEEE Transactionson Aerospace and Electronic Systems, 2007, 43 (1), pp.262~272.

[3] Lu Y., An J. P., Wu Y.B.. A differential MIMO-Beamforming scheme for transmission over aeronautical channels. Proceedings of WiCOM 08 Dalian,USA: IEEE,2008, pp.1~4.

[4] Haas, E. Aeronautical channel modeling. IEEE Transactions onVehicular Technology, 2002,51 (2) , pp.254~264.

[5] Tan Z., Zhang X. L. Modeling and performance analysis of multiple antennae communication channel for pilotless helicopter. Journal of Beijing University of Aeronautics and Astronautics, 2010, 36(10), pp.1171~1175 (in Chinese).

[6] Hu Y. J., Li X. M. Investigation on MIMO Wideband Channel Model for Unmanned Aerial Vehicle with Non-omnidirectional Antennas Acta Aeronautica et Astronautica Sinica, 2011, 32 (6), pp.1192~1101 (in Chinese).

[7] Leong, S.Y., Zheng, Y.R., Xiao, C. Space-Time Fading Correlation Functions of a 3-D MIMO Channel Model. In Proceedings of IEEE Wireless Communications and Networking Conference, 2004,2,pp. 1127~1132.

[8] BelloPA. Aeronautical channel characterization. IEEE Trans Commun, 1973,21(5) ,pp. 548-563.

[9] Tsai J. A., Woerner B. D.. The Fading Correlation Function of a Circular Antenna Array in Mobile Radio Environment. IEEE Global Telecommun., Conf., San Antonio, Texas, USA. 2001, pp. 3232-3236.

[10] Zhou J., Xiao D. R., Sasaki S., Kikuchi H., Luo H.. Analysis of circular antenna arrays with MRC in Nakagami fading channels by approximate approaches.IEEE Inter., Symp., on MicrowaveAntenna, Propag., and EMC Tech., for Wireless Commun., 2005, pp. 99-103.

[11] LI Y. H., Zhao J.. Effect of mutual coupling on the capacity of 4-element squared antenna array MIMO system, 2011,26(1), pp.546-551(in Chinese).

[12] Ghanem, F., Denidni, T., Delisle, G., Ghanem, K.. On the channel capacity in MIMO systems for aeronautical channels. In 2005 IEEE/ACES International Conference on Wireless Communications and Applied Computational Electromagnetics,2005, pp. 466~469.

[13] JIN, S., ZHANG X. l., ZHOU Q.. A Statistical Model for the UAV Communication Channel. Acta Aeronautica et Astronautica Sinica, 2004,25(1), pp.62~65 (in Chinese).

[14] ParsonsJ.D.,TurkmaniA.M.D.. Characterization of mobile radio signals: model description. IEE Proc.-I, vol. 138, No. 6, Dec. 1991, pp.549-556.

[15] TurkmaniA.M.D.,ParsonsJ.D.. Characterization of mobile radio signals: base station crosscorrelation. IEE Proc.-I, vol.138, No. 6, Dec. 1991, pp.557-565.

[16] Zajic, Alenka G, Stuber, Gordon L. A Three-Dimensional MIMO Mobile-to-Mobile Channel Model. 2007. WCNC 2007. IEEE 1883-1887,March 2007,pp.11-15.

[17] Zajic, Alenka G., Stuber, Gordon L. Influence of 3-D spatial correlation on the capacity of MIMO mobile-to-mobile channels. Vehicular Technology Conference, 2007. VTC2007-Spring. IEEE 65th, April 2007, pp.461-465.

[18] Abdi, A, Barger, J.A. , Kaveh, M. A parametric model for the distribution of the angle of arrival and the associated correlation function and power spectrum at the mobile station. IEEE Trans.Vehicular Tech., 51(3),2002, pp.425~434.

[19] Qu, S., Yeap, T. A three-dimensional scattering model for fading channels in land mobile environment. IEEE Trans. Vehicular. Tech., 1999, 48 (5), pp.765-781.