Research on anti-jamming beamforming with multi-UAV relays

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Abstract. As the common means of field emergency communication, the unmanned aerial vehicle (UAV) relay plays an important role in both civil and military fields. With the diversification of requirements and the limitations of single operation, multi-UAV cooperative work has attracted extensive attention. However, due to the UAV signal's universality of broadcast and the limitation of power, information transmission is more likely to be interrupted. Therefore, in the presence of interference, this paper adopts forward amplification protocol under UAV relay transmission model. And two beamforming methods are proposed based on minimizing transmission power and maximizing communication rate of UAV relays. Then, we establish the power-constrained maximum security rate optimization problem with UAV relays, and deduce the corresponding beamforming weight vector and the optimal rate of safety. Finally, the simulation results show the effectiveness and accuracy of the proposed beamforming method.

Keywords: UAV relay, Multi-UAV cooperation, Beamforming.

1 Introduction

With the continuous development of communication technology, unimpeded information transmission is gradually realized in some areas with few people and bad environment. For the armed police force, it is very important to build an emergency communication system to keep it up and running since it is common to perform missions under extreme terrain and climate conditions. As a kind of aerial communication platform, UAV relay communication often plays an important role in field missions. The operation of single UAV is simple and flexible, but its operation capacity is limited, and it is unable to meet the mission requirements of UAV in modern civil and military fields. In order to complete complex and difficult tasks and ensure safety and reliability, cooperative work of multiple UAVs is the trend of future development [1].

In this paper, multiple UAVs are used for cooperative relay communication, and each UAV is equipped with a single antenna. In the cooperative communication system of UAV,

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the communication between UAV formation and ground receiving nodes can not be detected or interfered by eavesdroppers by designing the beamforming vector. Reference [2] studied cooperative relay beamforming in multiple-input and multiple-output (MIMO)communication, established a mathematical model of joint beamforming based on the lower bound of the received SNR, and proposed a scheme of joint beamforming. Reference [3] proposed two different methods to study the joint optimization design of cooperative relay beamforming and base station end linear equilibrium vector under the condition of power limitation of relay transmission nodes. The classical system model and common channel model of hybrid beamforming are presented in reference [4], and the existing hybrid beamforming schemes are summarized from two aspects: ideal channel condition and beam pairing. In addition to the design of hybrid beamforming, reference [5] also put forward the existing problems from the perspective of physical layer security. Reference [6] studied the semi-duplex relay system of multi-antenna UAV and proposed a joint optimization scheme of beamforming and power distribution based on optimal energy efficiency to maximize the data rate. Following the research ideas, reference [7] discussed the scheme of joint optimization of beamforming and power distribution in the UAV full-duplex relay system. To sum up, when designing beamforming in the above references, they usually only consider their own co-frequency interference or reasonably ignore the influence of interference for the convenience of research. Therefore, in the presence of interference, this paper adopts forward amplification protocol under the UAV relay transmission model, which is proposed based on minimizing the maximum transmission power and communication rate of two kinds of beamforming method, establish UAV cooperative communication capacity of limited power optimization problem, deducing different channel factors corresponding to the beamforming weight vector. Finally, the simulation results show the effectiveness and accuracy of the proposed beamforming method.

2 System model

As shown in Figure 1, the system model of multi-UAV relays with interference includes a multi-antenna signal source S, a receiving end D equipped with a single antenna, an eavesdropper E equipped with a single antenna, and n UAV relays equipped with a single antenna.

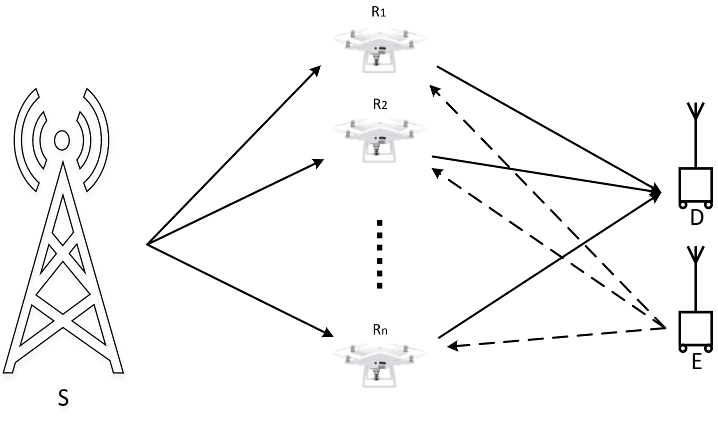

Fig. 1. Multi-UAV relay system model with interference.

The whole communication process consists of two time slots: in the first time slot, the signal source sends a signal to the UAV and satisfies $E\left\{|s|^2\right\}=1$, while the UAV receives interference I from the eavesdropper and satisfies $E\left\{|s|^2\right\}=1$. Therefore, the signal received by the i relay UAV can be expressed as:

$$x_i=\sqrt{P_S}g_{S,i}s+\sqrt{P_E}g_{E,i}I+n_i \tag{1}$$

where, P_S represents the transmitted power of signal source S, P_E represents the power of interference emitted by the jammer E, $g_{S,i}$ represents the channel coefficient from the signal source S to the i relay UAV, $g_{E,i}$ represents the channel coefficient from the jammer to the i st relay UAV, n_i is the additive White Gaussian noise with the mean value of the 1st relay being 0 and the variance being $\delta_{n_i}^2$.

In the second time slot, the first relayed signal is:

$$y_i=w_ix_i \tag{2}$$

Thus, the signal received by receiver D is:

$$Z=\sum_{\mathrm{i}}^{\mathrm{n}}\mathrm{g}_{\mathrm{D,i}}y_i+n=\sqrt{P_S}\sum_{i}^{n}w_ig_{D,i}g_{S,i}s+\sqrt{P_E}\sum_{i}^{n}w_ig_{D,i}g_{E,i}I+\sum_{i}^{n}w_ig_{D,i}n_i+n \tag{3}$$

where $g_{D,i}$ represents the channel coefficient from the receiving end D to the i relay UAV, n represents additive Gaussian white noise of the second time slot , which the mean value is 0, and the variance is δ_n^2 then the total transmission power of UAV can be expressed as:

$$P_T=E\left\{|y_i|^2\right\}=\sum_{i=1}^{n}|w_i|^2E\left\{|x_i|^2\right\}=w^H\Lambda w \tag{4}$$

where

$$w=\begin{bmatrix}w_1 & w_2 & \dots & w_n\end{bmatrix}^T \tag{5}$$

$$\begin{aligned}\Lambda=&P_S diag\left(E\left\{|g_{S,1}|^2\right\},E\left\{|g_{S,2}|^2\right\},\dots,E\left\{|g_{S,n}|^2\right\}\right)\\&+P_E diag\left(E\left\{|g_{E,1}|^2\right\},E\left\{|g_{E,2}|^2\right\},\dots,E\left\{|g_{E,n}|^2\right\}\right)+\delta_n^2I\end{aligned} \tag{6}$$

The total signal transmission power of UAV relays can be expressed as:

$$P_{S_T} = E\left\{\left|S_T\right|^2\right\} = P_S E\left\{\sum_{i,m=1}^{n} w_i w_m^* g_{S,i} g_{S,m}^* g_{D,i} g_{D,m}^*\right\} E\left\{\left|s\right|^2\right\} = w^H M w \tag{7}$$

where, $(\ )^*$ represents complex conjugate, $M = P_S E\left\{\left(g_S \cdot g_D\right)\left(g_S \cdot g_D\right)^H\right\}$. The total interference power can be expressed as:

$$P_r = E\left\{\left|I\right|^2\right\} = P_E \sum_{i=1}^{n} \left|w_i\right|^2 E\left\{\left|g_{D,i}\right|^2\right\} E\left\{\left|g_{E,i}\right|^2\right\} = w^H \Omega w \tag{8}$$

where

$$\Omega = P_E diag\left(E\left\{\left|g_{D,1}\right|^2\right\} E\left\{\left|g_{E,1}\right|^2\right\}, E\left\{\left|g_{D,2}\right|^2\right\} E\left\{\left|g_{E,2}\right|^2\right\}, \dots, E\left\{\left|g_{D,n}\right|^2\right\} E\left\{\left|g_{E,n}\right|^2\right\}\right)$$

The total noise power can be expressed as:

$$P_n = E\left\{\left|n_T\right|^2\right\} = E\left\{\sum_{i,m=1}^{n} w_i w_m^* g_{D,i} g_{D,m}^*\right\} + E\left\{\left|n\right|^2\right\} = w^H G w + \delta_n^2 \tag{9}$$

where $G = \delta_{n_i}^2 E\left\{\left(g_D\right)\left(g_D\right)^H\right\}, g_D = \left[g_{D,1} \quad g_{D,2} \quad \cdots \quad g_{D,3}\right]^T$

The $SINR$ of the receiving end can be expressed as:

$$SINR = \frac{P_{S_T}}{P_r + P_n} = \frac{w^H M w}{w^H \Omega w + w^H G w + \delta_n^2} \tag{10}$$

Then the channel capacity can be expressed as:

$$R = \frac{1}{2}\log\left(1 + SINR\right) = \frac{1}{2}\log\left(1 + \frac{w^H M w}{w^H \Omega w + w^H G w + \delta_n^2}\right) \tag{11}$$

3 Beamforming design under relay power constraints

As the relay node is composed of UAVs, its transmitting power is limited to some extent. This section mainly discusses how to optimize the beamforming vector to minimize the total transmission power of UAV under the condition that the transmission rate is guaranteed, namely the transmission rate is greater than the minimum critical value of communication $R_{\min}$. This optimization problem can be expressed as:

$$\begin{aligned} &Min \quad P_T \\ &s.t. \quad R \geq R_{\min} \end{aligned} \tag{12}$$

From the equation (4) and (9), equation(10) can be transformed to:

$$\begin{aligned} &Min \quad w^H \Lambda w \\ &s.t. \quad \frac{w^H M w}{w^H \Omega w + w^H G w + \delta_n^2} \geq 2^{2R_{\min}} - 1 \end{aligned} \tag{13}$$

Let $\tilde{w} = \Lambda^{1/2} w$, equation(11) can be transformed to:

$$\begin{aligned} &Min \quad \|\tilde{w}\|^2 \\ &s.t. \quad \tilde{w}^H \Lambda^{-1/2}\left[M - \left(2^{2R_{\min}} - 1\right)(\Omega + G)\right]\Lambda^{-1/2}\tilde{w} \geq \delta_n^2\left(2^{2R_{\min}} - 1\right) \end{aligned} \tag{14}$$

By observing the left side of equation (12), the optimal solution of inequality constraints is obtained when taking an equal sign [8],

$$\begin{aligned} &Min \quad \|\tilde{w}\|^2 \\ &s.t. \quad \tilde{w}^H \Lambda^{-1/2}\left[M - \left(2^{2R_{\min}} - 1\right)(\Omega + G)\right]\Lambda^{-1/2}\tilde{w} = \delta_n^2\left(2^{2R_{\min}} - 1\right) \end{aligned} \tag{15}$$

By introducing Lagrange operator λ, the new objective function $L(\tilde{w}, \lambda)$ satisfies:

$$L(\tilde{w}, \lambda) = \|w\|^2 - \lambda\left\{\tilde{w}^H \Lambda^{-1/2}\left[M - \left(2^{2R_{\min}} - 1\right)(\Omega + G)\right]\Lambda^{-1/2}\tilde{w} - \delta_n^2\left(2^{2R_{\min}} - 1\right)\right\} \tag{16}$$

Take the partial derivative with respect to $L(\tilde{w}, \lambda)$, then

$$\frac{\partial L(\tilde{w}, \lambda)}{\partial \tilde{w}^H} = \tilde{w} - \lambda\Lambda^{-1/2}\left[M - \left(2^{2R_{\min}} - 1\right)(\Omega + G)\right]\Lambda^{-1/2}\tilde{w} \tag{17}$$

Let the partial derivative equals to 0, namely $\frac{\partial L(\tilde{w}, \lambda)}{\partial \tilde{w}^H} = 0$, thus

$$\Lambda^{-1/2}\left[M - \left(2^{2R_{\min}} - 1\right)(\Omega + G)\right]\Lambda^{-1/2}\tilde{w} = \frac{1}{\lambda}\tilde{w} \tag{18}$$

By observing equation (16), it can be seen that $\tilde{w}$ is the eigenvector of $\Lambda^{-1/2}\left[M - \left(2^{2R_{\min}} - 1\right)(\Omega + G)\right]\Lambda^{-1/2}$ and $\frac{1}{\lambda}$ is its corresponding eigenvalue. Multiplying $\lambda\tilde{w}^H$ to both sides of equation (18), then

$$\lambda\tilde{w}^H \Lambda^{-1/2}\left[M - \left(2^{2R_{\min}} - 1\right)(\Omega + G)\right]\Lambda^{-1/2}\tilde{w} = \tilde{w}\tilde{w}^H = \|\tilde{w}, \lambda\|^2 \tag{19}$$

We can attain

$$\|\tilde{w}\|^2 = \lambda\delta_n^2\left(2^{2R_{\min}} - 1\right) \tag{20}$$

Then the objective function of the optimization problem can be transformed into the minimum value λ. Combining equation (16), it can be obtained that the optimal solution of Equation (13) is the corresponding feature vector of maximization $\frac{1}{\lambda}$, which is also consistent with the objective function mentioned above. Let the solution of equation (13) be $\tilde{w}_0$, then

$$\tilde{w}_0 = \alpha u = \alpha p\left\{\Lambda^{-1/2}\left[M-\left(2^{2R_{\min}}-1\right)\left(\Omega+G\right)\right]\Lambda^{-1/2}\right\} \tag{21}$$

where, $p\{\ \}$represents the normalized principal eigenvector of the matrix, and α is the coefficient that makes it meet the conditions.

$$\alpha = \left(\frac{\delta_n^2\left(2^{2R_{\min}}-1\right)}{u^H\Lambda^{-1/2}\left[M-\left(2^{2R_{\min}}-1\right)\left(\Omega+G\right)\right]\Lambda^{-1/2}u}\right)^{1/2} \tag{22}$$

Therefore, the optimal beamforming vector can be obtained

$$w_0 = \left(\frac{\delta_n^2\left(2^{2R_{\min}}-1\right)}{u^H\Lambda^{-1/2}\left[M-\left(2^{2R_{\min}}-1\right)\left(\Omega+G\right)\right]\Lambda^{-1/2}u}\right)^{1/2}\Lambda^{-1/2}p\left\{\Lambda^{-1/2}\left[M-\left(2^{2R_{\min}}-1\right)\left(\Omega+G\right)\right]\Lambda^{-1/2}\right\} \tag{23}$$

At the moment, the total relay power of UAV reaches the minimum value of

$$P_{T\min}\left(R_{\min}\right) = \frac{\delta_n^2\left(2^{2R_{\min}}-1\right)}{\lambda_{\max}\left\{\Lambda^{-1/2}\left[M-\left(2^{2R_{\min}}-1\right)\left(\Omega+G\right)\right]\Lambda^{-1/2}\right\}} \tag{24}$$

where, $\lambda_{\max}\{\ \}$ is the maximum eigenvalue of the corresponding matrix.

4 Simulation results

From the simulation results, the number of relay UAVs was set, and the channel noise at the relay UAVs and the legitimate receiver was respectively set as $\sigma_v^2 = \sigma_n^2 = 1$, and the transmit power is $P_{S_T} = 9dBmW$, interference power is $P_I = 3dBmW$ and channel noise at the receiver is assumed to be $P_n = 0dBmW$. Rician channel model is used for S-R and R-D channels, and Rayleigh channel model is used for R-E channels.

In the process of experimental simulation, Fig.2 shows the change of the minimum transmission power of relay UAVs with the minimum communication rate when rice factor is adopted in S-R and R-D channels, the number of relay UAVs is set as $N = 16$, and the interference power is $P_I = 3dBmW$. As can be seen from the figure, when the minimum communication rate $R_{\min}$ is fixed, the minimum transmission power P_T of relay UAVs also increases with the increase of rice factor, and the growth trend is from fast to gentle. It can be concluded that the improvement of the diameter component of the received signal in the Rice channel is not conducive to the concentration of signal transmission energy, which leads to the degradation of system performance. Fig. 3 shows that when the number of relay UAVs is set as $N = 16$, and the Rice factor is set as $K = 0dB$, the minimum transmission power P_T of relay UAVs changes with the minimum communication rate $R_{\min}$ when the jammers send different interference power $P_I = 1,2,3,4,5dBmW$. As can be seen from the figure, when the interference signal sent by the jammer is larger, the minimum transmission power required by the relay UAVs is larger. Therefore, in further research, the minimum transmission power of the relay can be reduced by suppressing the interference signal sent by the jammer. Fig.4 shows the change of the minimum transmission power P_T of relay UAVs with the minimum communication rate $R_{\min}$ when the Rice factor is set as $K = 0dB$, the interference power is set as $P_I = 3dBmW$, and the number of relay UAVs is set as $N = 14,16,18,20,22$. Further, it can be seen that for the same secure communication rate, when the number of secondary UAVs increases, the minimum transmission rate of relay UAVs decreases. In other words, the diversity gain of the system can be improved by increasing the number of UAVs, thus effectively improving the signal sent by relay UAVs to the receiving end.

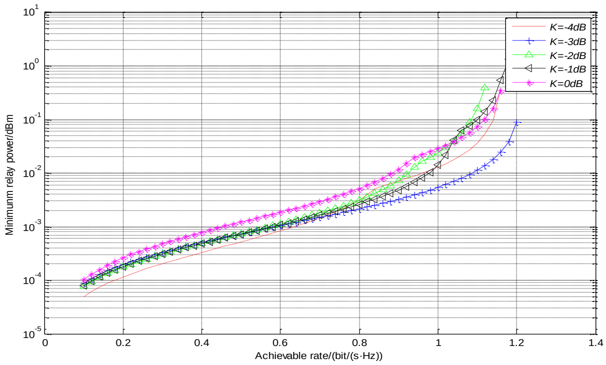

Fig. 2. The minimum communication rate versus minimum transmission power under different Rice factor K.

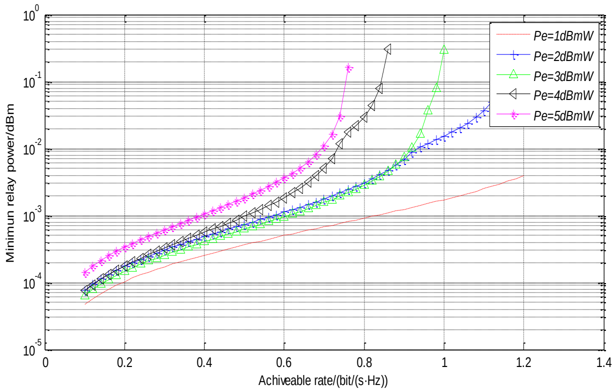

Fig. 3. The minimum communication rate versus minimum transmission power under different different interference power Pe.

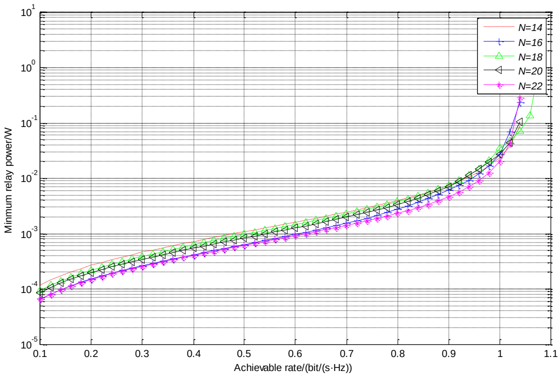

Fig. 4. The minimum communication rate versus minimum transmission power under different different number of relay UAVs N.

5 Conclusion

This paper deduces the SINR of the receiving end and the expression of the minimum safety rate expression, in the presence of interference on the basis of Rice channel and Rayleigh channel model. At the same time, we propose a beamforming strategy under relay UAVs transmit power minimization and reachable security rate maximization. And the corresponding optimal beamforming weight vector is obtained through theoretical derivation. Finally, using the matlab simulation software to verify the accuracy and efficiency under the condition of the two constraints in the optimization of beamforming, which provides the new thinking to the optimization of the relay UAV system with interference.

References

1. Luo Wencui, Research on cooperative multi-input and multi-output technology of UAV[D]. Shaanxi: University of Electronic Science and Technology of Shaanxi, 2017.
2. Li Chunguo, Zhong Chongxian, Yang Luxi. Joint beamforming for cooperative relay enhanced MIMO communication system [J]. Signal Processing, 2009(12):1853-1860.
3. LIU Ju, WANG Chao, XU Hongji, et al. Data Acquisition and Processing, 2014(3):360-365.
4. Xu Huazheng, Zhu Shibing, Xi Youyou. A Review of hybrid beamforming technology for millimeter-wave Large-scale MIMO Systems [J]. Telecommunications Technology, 2019(2): 241-248.
5. WANG Shilian, ZHU Li, LUO Junshan, et al. Research on secure communication technology of millimeter wave line-of-sight MIMO [J]. Journal of Radio Science,2020(4):457-468.
6. Song Qingheng, Zheng Fuchun. Energy efficient multi-antenna UAV-enabled mobile relay[J]. China Communications, 2018, 15(5): 41-50.
7. Song Qingheng, Zheng Fuchun, Zeng Yong, et al. Joint beamforming and power allocation for UAV-enabled full-duplex relay [J]. IEEE Transactions on Vehicular Technology, 2019, 68(2): 1657-1671.
8. Havary-Nassab V, Shahbazpanahi S, Grami A, et al. Distributed beamforming for relay networks based on second-orderstatistics of the channel state information[J]. IEEE Transactions on Signal Processing, 2008, 56(9): 4306-4316.