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Research on joint optimization of dynamic user grouping strategies and 3D trajectories in UAV-based NOMA networks

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Abstract: In this paper, a joint optimization of user grouping and unmanned aerial vehicle (UAV) 3D trajectories for dynamic downlink communication in UAV assisted nonorthogonal multiple access (NOMA) systems under a Rician fading channel is proposed, and the Rician fading channel is more suitable for air-to-ground transmission. With the development of wireless communication technology, improving the flexibility of transmission and reducing transmission delay are needed in the emergency communication situations. Considering the full utilization of UAV mobility and communication practicality, the NOMA multiuser sum-rate maximization problem is constructed. To solve this mixed integer nonlinear programming problem, a joint improvement of the cuckoo search algorithm and a simulated annealing algorithm (CSSA) is proposed to compensate for the cuckoo algorithm shortcoming of degradation of the late global search ability. The simulation results show that the CSSA algorithm can better improve the sum-rate of the system, and it has better convergence speed and convergence accuracy. This paper is the first study on joint optimization of the UAV 3D trajectory and dynamic user grouping in angle dependent Rician channel.

Keywords: Unmanned aerial vehicle (UAV), Nonorthogonal multiple access (NOMA), dynamic user grouping, 3D trajectory, cuckoo algorithm improvement, maximum sum-rate.

1. Introduction

In response to the problem of scarce spectrum resources and unavailability of base stations in emergency communication scenarios, it is of great significance to enhance the transmission rate of the UAV communication system. NOMA technology can not only accommodate a larger number of users but also improve the spectral utilization. Among them, NOMA in the power domain multiplexes resources by providing users different channel gains to send signals of different power levels on the same time-frequency resource. Additionally, the respective information of the users is obtained by successive interference cancellation (SIC) techniques [1]. With the continuous development of UAV technology, the application of UAVs has been extended from military to civilian applications [2]. Three channel models are common in UAV communication, including the line-of-sight (Los) channel, the probabilistic Los channel, and the Rician fading channel. UAVs have a high probability of establishing Los links with ground nodes at sufficiently high altitudes, and have been widely used in most existing work on UAV trajectory design [3]. However, this simplified model may be inaccurate in urban and suburban areas, because it ignores random shadows and small-scale fading. This channel model cannot be directly used for UAV trajectory design because the apparent axis probability of a local area along a UAV trajectory is usually not the same as the average apparent axis probability of the whole area, and it is also spatially dependent on the surrounding environment. Therefore, another model more suitable for air-ground links was adopted, namely, the Rician fading model, which consists of a deterministic Los component and a random multipath component [4]. The experimental results in [5] show that with the increase of elevation, the ground reflection, scattering, and obstacles become smaller and smaller, so the Rician factor tends to increase exponentially. This elevation angle dependent Rician fading model has higher practical accuracy than the conventional simplified Los model. In reference [6], the first attempt to design UAV trajectories for this model under an angle-dependent Rician fading channel is presented. Under NOMA access, reference [7] first determines the user grouping scheme based on the access priority, then uses a message passing algorithm for subchannel assignment, and finally jointly optimizes the transmit power of the UAV-NOMA system. Reference [8] proposes a first-tail two-user pairing algorithm, which initially ranks each user in ascending order of equivalent transmission power. Then all users are combined in turn by head and tail. Reference [9] reduces the link outage probability by designing a beam assignment along the two-dimensional flight trajectory of the UAV under a time-varying Rician fading channel. For considering the Rician channel of the UAV-NOMA system, reference [10] considers the uplink interference cancellation constraint and investigates the optimization problem of joint UAV location and the ground base station location to enhance the sum-rate of ground users. Reference [11] investigates the maximum-minimum rate optimization problem, which is solved using a path-tracing algorithm to obtain effective sum-rate enhancement for the UAV-NOMA system.

The optimization of the communication system in the above literature is single, this paper comprehensively considers the problems in the above literature, including Rician channel, three-dimensional trajectory of UAV and dynamic grouping of users. This paper aims to design the UAV flight trajectory with a more realistic time-varying Rician channel, adjust the UAV altitude by optimizing the pitch angle of the communicating users, and optimize the two-dimensional trajectory and altitude of the UAV simultaneously. A more realistic downlink communication model for the UAV-NOMA system is proposed, grouping users at different times of the UAV flight enables three cases: user number increase, user number decrease, and user replacement, so a more flexible user grouping scheme is proposed by us. The system sum-rate problem is solved by the joint improvement of the cuckoo algorithm and simulated annealing algorithm.

2. System Model

Suppose the downlink mobile UAV communication network is as shown in Figure 1, and a UAV is used as an airborne base station to serve *E* ground users. The 3D coordinates of the users can be expressed as follows: $(w_e^T, 0)$, where $w_e = [x[e], y[e]]^T$. We let $\{q[n]^T, z[n]\}$ denote the trajectory of the UAV, where $q[n] = [x[n], y[n]]^T$ and $z[n]$ denote the horizontal and vertical dimensional coordinates of the UAV. The UAV flight trajectory can be approximated by a discrete time series by uniformly dividing the time T into N time intervals, where $\delta = T/N$ is sufficiently small. By using the discrete-time approximation method, the UAV flight trajectory can be approximated by a sufficient series of instantaneous UAV positions, $\{q(n) = [x(n), y(n)], z(n) \ \ \forall n \in \{1, \dots, N+1\}\}$ .The maximum flight speeds of the UAV in the horizontal and vertical directions are assumed to be v_{xy} and v_z. Then, with the maximum horizontal and vertical distances $S_{xy} = \delta V_{xy}$ and $S_z = \delta V_z$, the UAV can fly in a unit time δ. The constraints on the UAV in flight can be expressed as follows:

$$\|q[n+1] - q[n]\| \leq S_{xy}, \tag{1}$$

$$\|z[n+1] - z[n]\| \leq S_z, \ \ \forall n = 1, \dots, N, \tag{2}$$

$$z[n] \geq z_{min}. \tag{3}$$

$\|\cdot\|$- denotes the calculation of the Euclidean distance and z_{min} indicates the lowest safe flight altitude of the UAV is 100 m.

$(q_I, \ z_I)$ and (q_F, z_F) are defined as the initial and end positions of the preset UAV flight trajectory, respectively as follows:

$$(q_1, \ z_1) = (q_I, \ z_I), \tag{4}$$

$$(q_{N+1}, \ z_{N+1}) = (q_F, \ z_F). \tag{5}$$

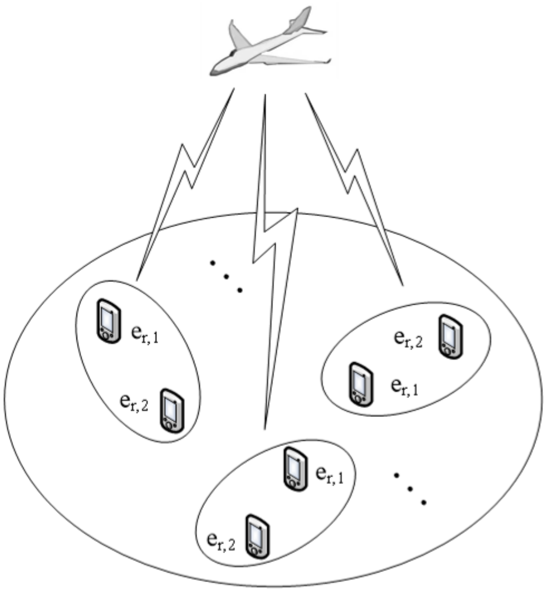

Fig. 1. The model of the UAV-based NOMA system

Considering the communication channel as a Rician fading model, the channel power gain between the UAV and user e in the nth time interval can be expressed as follows:

$$h_e(n) = \sqrt{\beta_e(n)}g_e(n), \tag{6}$$

β_e is the average channel power gain as follows:

$$\beta_e[n] = \gamma_0 d_e^{-\alpha}[n] = \frac{\gamma_0}{\sqrt{z[n]^2 + \|q[n] - w_e\|^2}^{\alpha}}, \quad \forall n, \tag{7}$$

α denotes the path decay index (default $\alpha = 2$ for calculation purposes), and γ_0 denotes the channel power gain per unit distance $d_0 = 1m$(dB). $d_e^{-\alpha}[n]$ denotes the Euclidean spatial distance between the UAV and user e at moment n as follows:

$$\beta_e[n] = \frac{\gamma_0}{z[n]^2 + \|q[n] - w_e\|^2}, \quad \forall n, \tag{8}$$

$g_e(n)$ is the small-scale fading coefficient under the Rician channel as follows:

$$g_e(n) = \sqrt{\frac{K_e(n)}{1 + K_e(n)}}g + \sqrt{\frac{1}{1 + K_e(n)}}\tilde{g}, \quad \forall n, \tag{9}$$

g represents the line-of-sight principal component and satisfies $|g| = 1$, $\tilde{g}$ is the circularly symmetric complex gaussian random scattering component satisfying zero mean and unit variance, and $K_e(n)$ is the instantaneous Rician factor at the nth moment. The formula proves that higher Rician factors can increase the Los principal component by the coefficient $\sqrt{K_e(n)/[1 + K_e(n)]}$, and can reduce the scattering component by the coefficient $\sqrt{1/[1 + K_e(n)]}$. The Los principal component of the air-ground link under the Rician fading channel can be obtained by raising the UAV flight altitude. In addition, the Rician fading channel characteristics depend on the Rician factor that responds to the ratio of the Los principal signal and the random scattering component. The characteristics of Rician fading channel depend on the Rician factor which reflects the ratio of Los main signal to random scattering component.

The Rician factor of the air-ground link is exponentially related to the elevation angle as follows:

$$K_e(n) = a_0 exp\big(b_0 \theta_e(n)\big), \ \forall n, \tag{10}$$

a_0 and b_0 are environment-based constants, where $K_{min} \le K_e(n) \le K_{max}$.

The pitch angle is expressed as follows：

$$\theta_e(n) = arcsin\left(\frac{h(n)}{d_e(n)}\right), \tag{11}$$

When $\theta_e(n) = 0$, $K_{min} = a_0$, when $\theta_e(n) = \frac{\pi}{2}$, $K_{max} = a_0 exp\left(b_0 \frac{\pi}{2}\right)$. The channel power gain between the UAV and user e in the nth time interval can be expressed as follows:

$$h_e(n) = \sqrt{\frac{\gamma_0}{z[n]^2 + \|q[n] - w_e\|^2}} \left[\sqrt{\frac{a_0 exp\left(b_0 arcsin\left(\frac{h(n)}{d_e(n)}\right)\right)}{1 + a_0 exp\left(b_0 arcsin\left(\frac{h(n)}{d_e(n)}\right)\right)}}\, g + \sqrt{\frac{1}{1 + exp\left(b_0 arcsin\left(\frac{h(n)}{d_e(n)}\right)\right)}}\, \tilde{g}\right]. \tag{12}$$

In the power domain NOMA downlink communication system, the channel environment of user 1 in each group is the best, the user can utilize the SIC technique to eliminate the interference of other users. Fixed static power allocation is used in this paper, the rate of user 1 in each group can be expressed as follows:

$$R_1 = log_2\left(1 + \frac{P_1|h_1|^2}{N_0}\right), \tag{13}$$

The rate of user 2 is expressed as follows:

$$R_2 = log_2\left(1 + \frac{P_2|h_2|^2}{P_1|h_2|^2 + N_0}\right). \tag{14}$$

The white noise of the channel observed by the base station is assumed to be N, and its power spectral density is N_0.

To improve the spectral efficiency and transmission rate of the UAV-NOMA system, the problem of joint optimization of the user grouping and UAV 3D trajectory based on system performance sum-rate maximization is considered, which can be expressed as follows:

$$\max_{U_{i,r}^n,\ q^n,\ z^n,\ \theta_{i,r}^n} \sum_{n=1}^{N} \sum_{r=1}^{R} \sum_{i=1}^{E} U_{i,r}^n \, log_2\left(1 + \frac{P_i\left|h_{i,r}^n\right|^2}{\sum_{k=1}^{i-1} U_{k,r}^n P_k \left|h_{i,r}^n\right|^2 + N_0}\right). \tag{15}$$

$$s.t \quad C_1: \sum_{r=1}^{R} U_{i,r}^n = 1,\ U_{i,r}^n \in \{0,1\} \quad \forall i, r. \tag{16}$$

$$C_2: r \ge r_{min}.$$

$$C_3: \frac{\pi}{6} \le \theta_e(n) \le \frac{\pi}{2}.$$

$$C_4: \|q[n+1] - q[n]\| \le S_{xy}.$$

$$C_5: \|z[n+1] - z[n]\| \le S_z,\ \forall n = 1, \dots N.$$

$$C_6: z[n] \ge z_{min}.$$

$$C_7: (q_1,\ z_1) = (q_I,\ z_I).$$

$$C_8: (q_{N+1},\ z_{N+1}) = (q_F,\ z_F).$$

C_1 indicates that a user is assigned to at most one group. $u_{i,r}^n = 1$ indicates that user i belongs to Group r and $u_{i,r}^n = 0$ indicates that user i do not belong to Group r. C_2 indicates the minimum instantaneous rate of each user. C_3 indicates the pitch angle between the UAV and the user.

To solve the above mixed integer nonlinear programming problem, this paper proposes a two-part optimization strategy. First, UAV 3D trajectory optimization is performed, and then, the user dynamic group matching algorithm is executed.

3. Analysis

3.1 Introduction To the CSSA Algorithm

Compared with other algorithms, the Cuckoo Search (CS) algorithm has significantly fewer parameters, better search capability, higher search accuracy and lower algorithm complexity, the time complexity is $O(n)$. The convergence speed and global search capability of the improved CS algorithm are higher than those of other algorithms. In the CS algorithm, if the update produces a better solution, then the original solution is replaced, and if it does not produce a better solution, then the original solution is retained, meaning that this round of evolution fails. To improve the global search ability of the algorithm, the simulated annealing algorithm (SA) is introduced, which still replaces the original solution with a certain probability even if the solution after the Levy flight is inferior to the original solution. The purpose is to improve the global search ability of the algorithm by forcing a variation with a small probability. A penalty function is added to the objective function optimization process to handle the constraint problem, thus solutions that do not satisfy the constraints do not compete with solutions that satisfy the constraints. Since the global historical optimal solution is recorded during the iterative process, the final solution obtained must satisfy the objective function. which, together with the SA algorithm, gives the improved algorithm a stronger global search ability.

3.2 Dynamic User Grouping Strategy

There are E users on the ground, the set of user serial numbers is $e \in \{1,2,E\}$, the set of group numbers is $r \in \{1,2,R\}$, and the set of user serial numbers in a group is $k \in \{1,2\}$. In this paper, we set two users in each group. When the channel gain difference between two users is larger, a greater performance improvement can be obtained by a NOMA system with SIC. Considering the improved user fairness and the system performance, a user matching scheme for dynamic grouping is proposed based on the principle of maximizing the absolute sum of the channel gain differences of all matched users. The channel gains of all the users are first sorted and the users are divided into two parts at the middle position. The greater the difference in the channel gains of the paired users, the better the SIC effect. The objective function is to maximize the sum of the absolute values of the channel gain differences among all communicating users as follows:

$$max \sum_{m+1}^{j} \sum_{j+1}^{E} (|h_j - h_m|). \tag{17}$$

1≤m<j≤E, where *i* represents the first part of users and *j* represents the second part of users.

Users are regrouped every time the UAV moves to the next time interval. To better match the real-world situation, as shown in Table I, 20 users are selected for random communication in this paper, and the number of users requesting communication contains three states: user number increase, user number decrease, and user replacement.

Table 1 Experimental matrix Ethanol and methanol to the main diesel fuel

Time interval	1-5	6-10	11-15	16-20	21-25	26-30
User Number	1,2,3,4	5,6,7,8,9,10	7,8,9, 10,11, 12	9,10, 11,12	11,12, 13,14	9,10,11,12,13, 14,15, 16
Time interval	31-35	36-40	41-45	46-50	51-55	56-60
User Number	13,14,15, 16,17,18, 19,20	15,16, 17,18, 19,20	15,16， 17,18	3,4， 5,6,7,8	1,2,3,4,1 1,12,15, 16	5,6,11, 12,17, 18

3.3 Joint Optimization of the UAV 3D Trajectory and Dynamic User Grouping

The starting position of the UAV is located at the center of the user, and when a user communication request is sent, the UAV takes off for 3D trajectory optimization. The communication channel is considered a Rician channel, where the pitch angle between the UAV and each user is restricted to $\frac{\pi}{6}$ at a minimum. The objective function is to maximize the sum of pitch angles of all communication users as follows:

$$max \sum_{n=1}^{N} \sum_{e}^{E} \theta_i(n) \tag{18}$$

Based on a comparison of the flight trajectory diagrams in Figure 2 and Figure 3, the flight trajectory of the UAV is intricate and complex with long paths and wasted resources in synchronous optimization, while the flight trajectory is simple and well planned in the case of step-by-step optimization, which UAV has more ample time to find a better communication location in the air and more room for maneuvering in the flight range. By optimizing its position, the drone can have a better pitch angle to improve the user's channel conditions, thus enhancing the transmission rate and achieving better fairness in user communication.

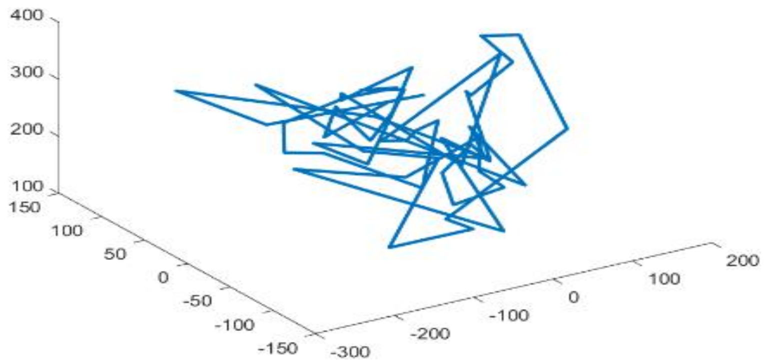

Figure. 2. UAV 3D trajectory and dynamic user grouping synchronization optimization flight trajectory map.

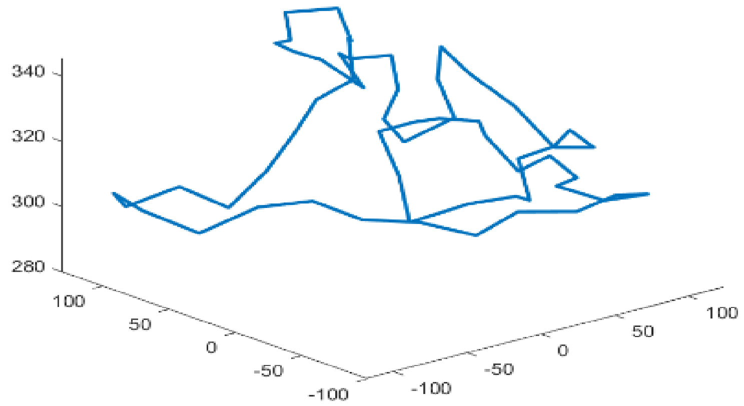

Figure. 3. UAV 3D trajectory and dynamic user grouping step-by-step optimized flight trajectory map.

4. Simulation Resul

The starting coordinates of the UAV are $(0,0,300)$ and the communication service range is $400m * 400m$. Assuming that the channel power gain is -30 db per unit distance $d_0 = 1m$, the noise power spectral density is -170 dbm, the total transmit power of the UAV is 1 W. The fixed power distribution ratio used in this paper is $P_1 : P_2 = 0.2 : 0.8$.

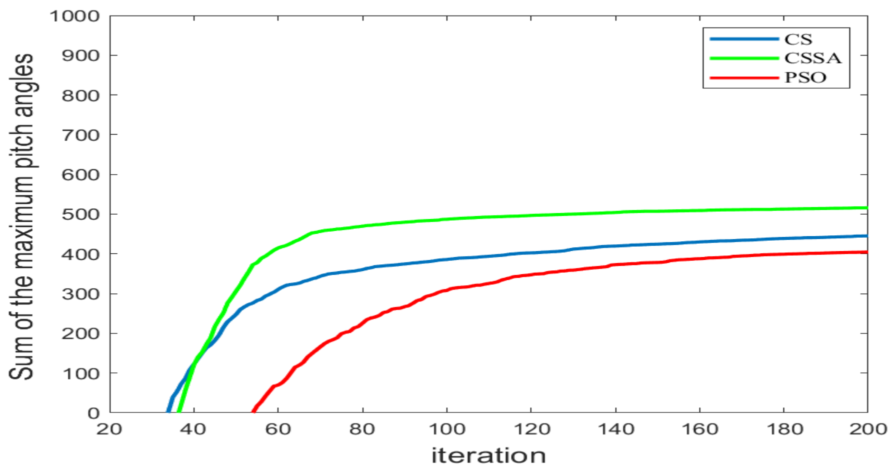

Figure. 4. Sum of the maximum pitch angles with three algorithms.

Figure 4 shows the maximum sum of pitch angles of the communication users under different algorithms, by adjusting the height of the UAV on the vertical path, the distance and angle between the user and the UAV can be balanced, so that the user can obtain better pitch angle and smaller straight-line distance, increase the user's channel power gain, so as to improve the transmission rate of communication. In comparison with the CS algorithm and particle swarm optimization (PSO) algorithm, the CSSA algorithm proposed can obtain a higher sum of pitch angles for communication users with fewer iterations, showing that the CSSA algorithm has better convergence speed and convergence accuracy.

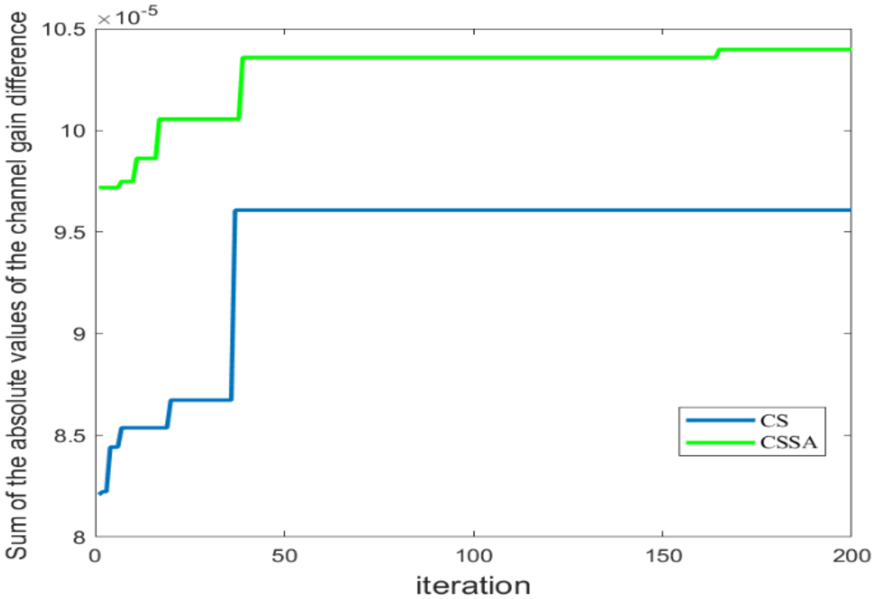

Figure. 5. Sum of the absolute values of the maximum channel gain difference of the communication users with two algorithms.

Figure 5 shows the absolute sum of the maximum channel gain of the communicating users under different algorithms. The dynamic user grouping strategy proposed in this paper is more applicable to the UAV-NOMA system, where the users are regrouped in each time interval with the movement of the UAV. A better grouping policy can help a lot with user rate improvement. Compared with the CS algorithm, the CSSA algorithm can obtain a better sum of absolute values of channel gain differences for the same number of iterations to obtain a better user grouping scheme. The objective function value of the CSSA algorithm is slightly improved with more iterations, while the convergence value of the CS algorithm does not change at the later stage.

Figure 6 shows the average rate of communication transmission at different time intervals, and by limiting the instantaneous rate of the users, the situation in which a particular user has a lower rate is avoided. The Monte Carlo method was used to sample the sample data 100 times and then the arithmetic mean was taken for plotting. The trajectory aspects were all optimized using the CSSA algorithm, and the dynamic user grouping strategy optimization was compared by three different algorithms. According to the figure, applying the dynamic user grouping strategy proposed in this paper, based on a comparison with the KM algorithm and the CS algorithm, the CSSA algorithm has better average rate, which strengthens the spectrum efficiency of the UAV-NOMA system. Compared with the fixed user grouping scheme, the scheme with the CSSA algorithm proposed in this paper is more suitable for the UAV-NOMA system under the Rician channel.

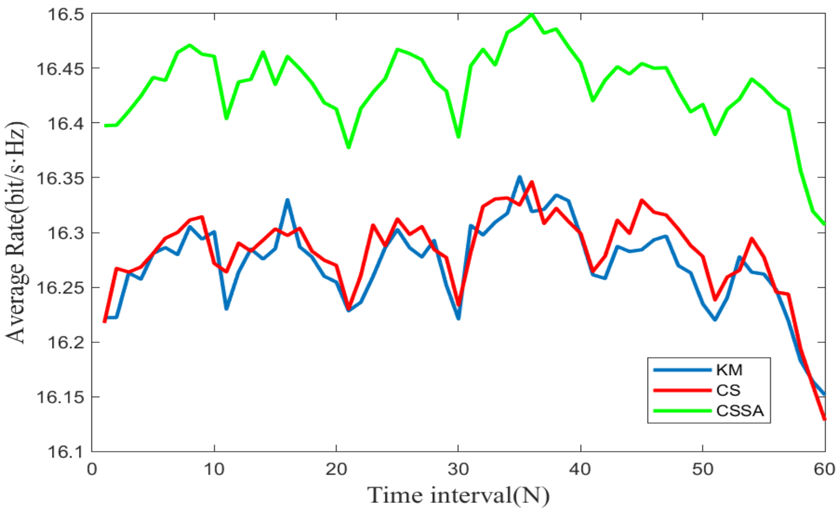

Figure. 6. The average rate at different time intervals with three algorithms. (Monte Carlo method was used to sample the sample data 100 times)

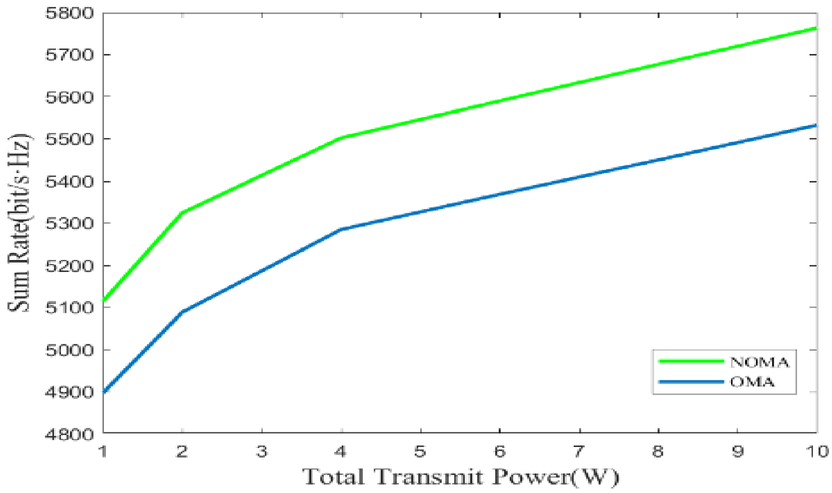

Figure. 7. Sum-rate performance of OMA and NOMA UAV systems at different powers.

Figure 7 shows the orthogonal and nonorthogonal UAV system performance in terms of the sum-rate for communication transmission at different powers. Both orthogonal and non-orthogonal of UAV communication models apply the CSSA algorithm. According to the figure, compared to the OMA scheme, the NOMA scheme has better system sum-rate performance in the UAV communication system. With increasing UAV transmit power, the sum-rate of the UAV-NOMA system also increases and the performance advantage is more obvious. The sum-rate of the NOMA scheme is

220bit/s·Hz higher than that of the OMA scheme, this indicates that the UAV-NOMA system based on the CSSA algorithm still has high spectral efficiency for multiuser communication.

5. Conclusion

In this paper, we study the joint optimization of dynamic user grouping and 3D trajectories for UAV-assisted NOMA system, and an improved CSSA algorithm is proposed to further improve the sum-rate performance of the UAV-NOMA system. Through optimization of the UAV 3D trajectory, better UAV position and user pitch angle under the Rician channel are obtained to improve the channel gain. The dynamic user grouping scheme proposed in this paper can be better for user matching. Because UAV trajectory optimization and user grouping optimization are coupled, which makes the optimization design very complex, the improved CSSA algorithm in this paper maximizes the system performance sum-rate through joint optimization to obtain more flexible downlink communication, and the CSSA algorithm has better performance than other algorithms. In future work, the inclusion of dynamic power allocation will be considered to improve the UAV-NOMA system by joint optimization in many aspects.

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