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Optimal UAV deployment in downlink non-orthogonal multiple access system: a two-user case①

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Abstract

This paper investigates a unmanned aerial vehicle (UAV) deployment problem in a non-orthogonal multiple access (NOMA) system, where the UAV is deployed as an aerial mobile base station to transmit data to two ground users. An optimization problem is formulated by deploying the UAV for maximizing the sum rate of the two users. In order to solve the optimization problem, the feasible solution region is first reduced to a line segment between two users. Then, the optimization problem is simplified to a univariate problem, which can be solved by derivation under a certain situation, and the corresponding analytical solution is also provided. Moreover, a generalized algorithm, which considers 2 situations, is proposed to further determine the optimal UAV's location. Specifically, four cases are discussed in the first situation. Extensive simulations are depicted to demonstrate effectiveness of the proposed algorithm and its superiority over the benchmarks in maximizing the two users' sum rate.

Key words: unmanned aerial vehicle (UAV) deployment, downlink non-orthogonal multiple access (NOMA), two-user case

0 Introduction

Recently, non-orthogonal multiple access (NOMA), which is recognized with high spectrum efficiency, has attracted great attention as a crucial technique for 5G networks[1-3]. Employing the NOMA scheme, users can be multiplexed at different power levels, while users can simultaneously access other resources, such as frequency, time or code resources. At the receiver side, users utilize a successive interference cancellation (SIC) to extract their corresponding signals[4].

Although, NOMA can achieve superior performance, edge users in a network still suffer from service quality degradation. There are still many challenges to advance NOMA in 5G networks. For these reasons, because of the flexibility for deployment, unmanned aerial vehicles (UAVs) or drones with advanced sensors and transceivers have attracted great attentions in communication community. Specifically, UAVs can exploit the benefits of line-of-sight (LoS) air-to-ground communication channels to provide enhanced communication services, such as mobile coverage[5,6], mobile relaying[7,8] and mobile data collection[9-11], etc.

Existing researches on UAVs can be divided into 2 directions, i. e., static-UAV and mobile-UAV directions[12]. The combination researches on the mobile-UAV and NOMA scheme focus on the UAV trajectory design and communication scheduling. In Ref. [13], the authors optimize the trajectory of UAV and the precoding vectors of NOMA base station (BS) in order to maximize the sum rate for UAV-assisted NOMA networks.

In order to enhance the service quality for multiple users, the combination researches on the static-UAV NOMA scenario are also promising. In Ref. [14], the authors derive the outage probability of UAV connected users and device-to-device (D2D) underlaying NOMA static-UAV assisted networks, and provide a sub-optimal power control solution. Besides the outage probability, UAV's placement problem in a static-UAV NOMA scenario is also very important, especially for enhancing the service performance of edge users. In

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Ref. [15], the authors investigate the UAV placement and power allocation problem. The problem is separated into 2 sub-problems. The optimal location of UAV is obtained by minimizing the sum path loss, and the optimal power allocation is then derived.

Different from the existing work, this paper investigates the optimal UAV deployment problem in downlink NOMA system from the perspective of maximizing user's sum rate. The main contributions of this paper are listed as follows.

(1) A UAV-enabled NOMA system, where a UAV is deployed as an aerial base station, which transmits data to two ground users, is considered in this paper.

(2) In order to maximize two users' achievable sum rate, an optimal UAV placement problem is therefore constructed. Since it is intractable to solve this problem, a feasible solution region is first reduced by a theorem. Then, an analytical solution of the proposed problem under a certain situation is discussed.

(3) Finally, an algorithm is proposed to solve the optimization problem in a general manner.

(4) Extensive numerical results are presented to demonstrate effectiveness of the proposed algorithm, and its advantages over the benchmarks from the perspective of maximizing users' sum rate.

This paper is organized as follows. System model and problem formation are presented in Section 1. The proposed algorithm is elaborated in Section 2. Extensive numerical results are depicted in Section 3, and finally conclusions are drawn in Section 4.

1 System model and problem formulation

As shown in Fig. 1, a UAV-enabled NOMA system, where a UAV is deployed as an aerial base station to transmit data to two ground users, is considered in this paper. Without loss of generality, a 3-D Cartesian coordinate system is considered with two ground users, i. e., user 1 and user 2 in Fig. 1, located at $\boldsymbol{w}_1 = [L, 0, 0]^{\mathrm{T}}$ and $\boldsymbol{w}_2 = [-L, 0, 0]^{\mathrm{T}}$, respectively. It is assumed that the UAV is deployed at $\boldsymbol{q} = [x, y, H]^{\mathrm{T}}$, where H is the fixed flight altitude of the UAV. For simplicity, it is assumed that all the nodes in the network are equipped with a single antenna, and the communication links from the UAV to the ground users are line-of-sight (LoS) dominated. It is also assumed that the Doppler effect caused by the UAV motion is perfectly compensated at the ground users. Thus, the channel coefficient h_i from the UAV to user i, $\{i = 1, 2\}$, can be expressed as

$$h_i = \sqrt{\lambda_0 d_i^{-2}} = \sqrt{\frac{\lambda_0}{|\boldsymbol{q} - \boldsymbol{w}_i|^2}} \tag{1}$$

where, λ_0 is the channel gain at the reference distance $d_0 = 1$ m, and $d_i = |\boldsymbol{q} - \boldsymbol{w}_i|$ denotes the distance from the UAV to user i.

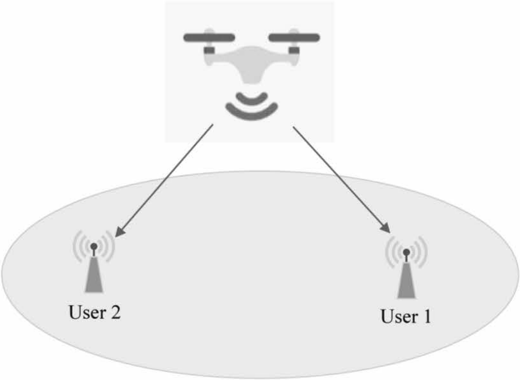

Fig. 1 UAV-enabled NOMA network with two users

The UAV transmits the superposition signal to the two ground users simultaneously, which can be expressed as

$$s = \sqrt{P_1} s_1 + \sqrt{P_2} s_2 \tag{2}$$

where s_1 and s_2 denote the signal intended for user 1 and user 2, respectively. P_1 and P_2 are the corresponding transmission power for user 1 and user 2, respectively. The transmission power must comply with the following 2 conditions.

$$P_1 + P_2 \leqslant P_{\max} \tag{3a}$$

$$P_i \geqslant 0, \quad i = 1,2 \tag{3b}$$

where $P_{\max}$ denotes the maximum transmission power of the UAV. Thus, the received signal at user i is

$$y_i = h_i s + n_i = \sqrt{P_1} h_i s_1 + \sqrt{P_2} h_i s_2 + n_i, \quad i = 1,2 \tag{4}$$

where, n_i denotes the zero-mean additive white Gaussian noise (AWGN) with variance σ_i^2. In order to simply the notations, it is assumed that $\sigma_1^2 = \sigma_2^2 = \sigma^2$.

According to NOMA principle, SIC is utilized at the receivers. Because of symmetry, only the case with $x \geqslant 0$ is considered in the following discussions. Also it is assumed that user 1 is treated as a stronger user, while user 2 is treated as a poorer user. Thus, the signal intended for user 2 is first decoded, and then for user 1. As a result, the achievable rate from the UAV to user 1 and user 2 can be expressed as

$$R_1 = \log_2(1 + P_1 \lambda_1) \tag{5a}$$

and

$$R_2 = \log_2\left(1 + \frac{P_2 \lambda_2}{1 + P_1 \lambda_2}\right) \tag{5b}$$

respectively, where $\lambda_i = \frac{h_i^2}{\sigma^2} = \frac{\gamma_0}{|\boldsymbol{q} - \boldsymbol{w}_i|^2}$ and $\gamma_0 =$

$\frac{\lambda_0}{\sigma^2}$.

In order to maximize users' achievable sum rate, an optimization problem can be formulated as

$$\max_{\boldsymbol{q}, \boldsymbol{P}} (R_1 + R_2) \tag{6a}$$

$$\text{s. t. , Eq. (3a), Eq. (3b)} \tag{6b}$$

$$R_i \geqslant r^*, \quad i = 1,2 \tag{6c}$$

where $\boldsymbol{P} = \{P_1, P_2\}$, and r^* denotes the achievable rate threshold. Constraint Eq. (6c) can be used to guarantee user's quality of service (QoS). It can be seen that problem Eq. (6) is non-convex. Because the objective function Eq. (6a) is non-concave, and the constraint Eq. (6c) is non-convex with respect to $\boldsymbol{q}$ and $\boldsymbol{P}$, respectively. Thus, it is challenging to solve problem Eq. (6) by the conventional optimization methods.

2 Proposed algorithm for problem Eq. (6)

In this section, the solution of problem Eq. (6) will be provided. First, the problem is simplified. Then, an analytical solution of the simplified problem under a certain situation will be presented. At last, a generalized algorithm is proposed to obtain the optimal solution of problem Eq. (6).

2.1 Problem simplification

In order to simplify problem Eq. (6), Theorem 1 is provided as follows.

Theorem 1 To maximize users' summation of the achievable rates, the UAV should be deployed above the line segment between the two users.

Proof Theorem 1 is demonstrated by contradiction. This work first assumes that the optimal UAV deployment location is given by $\boldsymbol{q}^0 = [x^0, y^0, H]^{\mathrm{T}}$, where $y^0 \neq 0$. That is to say, the UAV is not located over the line through the two users. The UAV transmits with the maximum transmission power at the optimal solution[16], i. e. ,

$$P_1 + P_2 = P_{\max} \tag{7}$$

Then, the achievable rates of the two users at the optimal solution can be expressed as

$$R_1^0 = \log_2(1 + P_1\lambda_1^0) \overset{(a)}{\geqslant} r^* \tag{8a}$$

and

$$\begin{aligned} R_2^0 &= \log_2\left(1 + \frac{P_2\lambda_2^0}{1 + (P_{\max} - P_2)\lambda_2^0}\right) \\ &= \log_2(1 + P_{\max}\lambda_2^0) - \log_2(1 + (P_{\max} - P_2)\lambda_2^0) \\ &\overset{(b)}{\geqslant} r^* \end{aligned} \tag{8b}$$

respectively, where $\lambda_i^0 = \frac{\gamma_0}{|\boldsymbol{q}^0 - \boldsymbol{w}_i|^2}$, $i = 1,2$.

Conditions Eqs (8a) and (8b) are satisfied because of the QoS constraints. Given another UAV's location at $\boldsymbol{q}^1 = [x^0, 0, H]^{\mathrm{T}}$, that is to say, the UAV's location is over the line of the two users, i. e. ,

$$\lambda_i^1 = \frac{\gamma_0}{|\boldsymbol{q}^1 - \boldsymbol{w}_i|^2}, \quad i = 1,2 \tag{9}$$

It can be verified that $\lambda_i^1 > \lambda_i^0$, $i = 1, 2$. Thus, there are

$$R_1^1 > R_1^0 \geqslant r^* \tag{10a}$$

$$R_2^1 \overset{(c)}{>} R_2^0 \geqslant r^* \tag{10b}$$

where condition Eq. (6c) in Eq. (10b) holds, since if $\alpha > \beta$, the function $g(x) = \log_2(1 + \alpha x) - \log_2(1 + \beta x)$ is monotonically increasing with respect to the variable x. Therefore, the sum rate at $\boldsymbol{q}^1 = [x^0, 0, H]^{\mathrm{T}}$ is larger than that at $\boldsymbol{q}^0 = [x^0, y^0, H]^{\mathrm{T}}$, $\forall y^0 \neq 0$. This conclusion contradicts the assumption that $\boldsymbol{q}^0$ is the optimal location that can get the maximum sum rate. Therefore, it can be concluded that a higher sum rate can be achieved by deploying the UAV over the line through the two users compared to other locations.

Next, proofs on that the optimal UAV location should over the line segment between the two users are provided. Given a location $\boldsymbol{q}^2 = [x, 0, H]^{\mathrm{T}}$, if $x > L$, i. e. , over the extension line of the two users, the UAV can be always deployed at $\boldsymbol{q}^3 = [L - (x - L), 0, H]^{\mathrm{T}}$ which is a symmetrical location respective to user 1, and obtain a larger sum rate compared to that at $\boldsymbol{q}^2$. As a result, in order to maximize the sum rate of the two users, the UAV should be deployed above the line segment between the two users, i. e. , $0 \leqslant x \leqslant L$. This completes the proof.

Based on Theorem 1, the UAV's location can be simplified as $\boldsymbol{q} = [x, 0, H]^{\mathrm{T}}$. According to the conclusion drawn in Ref. [16], in order to obtain the maximum sum rate, the optimal power allocation strategy can be represented as

$$P_1^* = \frac{P_{\max}}{2^{r^*}} - \frac{2^{r^*} - 1}{2^{r^*}\lambda_2} \tag{11a}$$

and

$$P_2^* = P_{\max} - P_1^* \tag{11b}$$

respectively, where $\lambda_2 = \frac{\gamma_0}{|\boldsymbol{q} - \boldsymbol{w}_2|^2}$. By substituting Eqs (11a) and (11b) into Eqs (5a) and (5b), there are

$$R_1 = r^* + \log_2\left(\frac{P_{\max}\lambda_1 - (2^{r^*} - 1)\frac{\lambda_1}{\lambda_2} + 2^{r^*}}{2^{2r^*}}\right) \tag{12}$$

and

$$R_2 = r^* \tag{13}$$

respectively. Observing Eqs(12) and (13), it can be found that by employing the power allocation strategy, the rate of user 2, i,e, the poorer user, is equal to the rate threshold and irrelevant to the UAV's location. The rate of user 1 can be further enhanced by varying the UAV's location x.

Thus, problem Eq. (6) can be simplified as

$$\max_x f(x) \quad (14a)$$

$$0 \leqslant x \leqslant L \quad (14b)$$

where

$$f(x) = P_{\max}\lambda_1 - (2^{r^*}-1)\frac{\lambda_1}{\lambda_2} = \frac{\gamma_0 P_{\max}}{H^2+(L-x)^2} - (2^{r^*}-1)\frac{H^2+(L+x)^2}{H^2+(L-x)^2} \quad (15)$$

In order to assure rate of the user 1 is larger than the rate threshold r^*, the following remark is provided.

Remark 1 If the maximum value of $f(x)$ is greater than $2^{r^*}(2^{r^*}-1)$, problem Eq. (6) is feasible. Otherwise, problem Eq. (6) is infeasible and a smaller value of r^* should be considered.

When problem Eq. (6) is feasible, the following remark is provided.

Remark 2 The sum rate of the two users, i. e., $R_1 + R_2$, is decreasing as r^* increases.

Proof The first-order derivation of $R_1 + R_2$ is as follows.

$$\frac{\partial(R_1+R_2)}{\partial r^*} = \frac{2^{r^*}\left(1-\frac{\lambda_1}{\lambda_2}\right)}{P_{\max}\lambda_1 - (2^{r^*}-1)\frac{\lambda_1}{\lambda_2} + 2^{r^*}} \quad (16)$$

Since $0 \leqslant x \leqslant L$, thus $\lambda_1 > \lambda_2$ holds. Moreover, based on Remark 1, Eq. (16) <0. Thus, $R_1 + R_2$ is an decreasing function respective to r^*.

Note that problem Eq. (14) is a univariate optimization problem which may be solved by derivation.

2.2 The analytical solution to problem Eq. (14)

The first-order derivation of $f(x)$ is given by

$$f'(x) = \frac{4Lx^2 - 2Ax + 2AL - 4L(H^2+L^2)}{(H^2+(L-x)^2)^2} \quad (17)$$

where, $A = \frac{\gamma_0 P_{\max}}{2^{r^*}-1}$. Let $f(x) = 0$, there is

$$2Lx^2 - Ax + AL - 2L(H^2+L^2) = 0 \quad (18)$$

Eq. (18) is a quadratic function with $\Delta = A^2 - 8AL^2 + 16L^2(H^2+L^2)$. If $\Delta \geqslant 0$, then the stationary points of $f'(x)$ are given by

$$x^1_{\text{Solu}} = \frac{A-\sqrt{\Delta}}{4L} \text{ and } x^2_{\text{Solu}} = \frac{A+\sqrt{\Delta}}{4L}, \text{ if } \Delta \geqslant 0 \quad (19)$$

In the following, it should be determined whether the 2 stationary points are in the interval, and then obtain the optimal x (denoted by x^*). Based on the above derivations, the UAV deployment strategy is concluded in Algorithm 1.

```
Algorithm 1  Proposed UAV deployment strategy
1.  If $\Delta \geqslant 0$ then
2.      Case 1  If $x^1_{Solu} \in (0, L)$, $x^2_{Solu} \in (0, L)$, then
            $x^* = \mathrm{argmax}\{f(0), f(x^1_{Solu}), f(x^2_{Solu}), f(L)\}$
3.      Case 2  If $x^1_{Solu} \in (0, L)$, $x^2_{Solu} \notin (0, L)$, then
            $x^* = \mathrm{argmax}\{f(0), f(x^1_{Solu}), f(L)\}$
4.      Case 3  If $x^1_{Solu} \notin (0, L)$, $x^2_{Solu} \in (0, L)$, then
            $x^* = \mathrm{argmax}\{f(0), f(x^2_{Solu}), f(L)\}$
5.      Case 4  If $x^1_{Solu} \notin (0, L)$, $x^2_{Solu} \notin (0,L)$, then
            $x^* = \mathrm{argmax}\{f(0), f(L)\}$
6.  Else $f(x)$ is a monotonic increasing function
        with respect to $x$. Therefore, $x^* = L$
7.  End if
8.  If
        $f(x^*) \geqslant 2^{r^*}(2^{r^*}-1)$ then $x^*$ is determined.
9.  Else
10.     Reconsider $r^*$.
11. End if
```

The algorithm considers 2 situations. The 1st situation is $\Delta \geqslant 0$, and therefore, x^i_{Solu} $(i = 1, 2)$ is achievable. Since it is hard to determine the concavity/convexity of $f(x)$, four cases will be discussed in the first situation from line 2 to line 5. In the 2nd situation, i. e., $\Delta < 0$, x^i_{Solu} $(i = 1,2)$ cannot be obtained. Since $4L > 0$, i. e., the coefficient of quadratic term in $f'(x)$ in Eq. (17), the conclusion can be got that $f'(x) > 0$, $\forall x$, and therefore, $f(x)$ is a monotonic increasing function with respective to x. Then, $x^* = L$. After obtaining x^*, according to Remark 1, line 9 to line 12 in Algorithm 1 will be applied to verify x^*. After that, the optimal UAV deployment location $q^* = [x^*, 0, H]^{\mathrm{T}}$ can be obtained.

Note that the proposed algorithm is applicable in a two-user scenario. For the multi-user scenario, the optimal UAV deployment problem is complex, and it probably cannot get a closed-form solution. The UAV deployment problem will be investigated in a multi-user scenario in the future work.

3 Numerical results

In this section, numerical results are presented to demonstrate effectiveness of the proposed UAV deployment scheme (denoted as the DP scheme). The simulation parameters are set as $L = 500$ m, $P_{\max} = 1$ W, $H = 100$ m, and $\gamma_0 = 10^6$.

Fig. 2 plots the optimal UAV deployment location using the proposed DP scheme when r^* varies. Linear search curves are also plotted to verify the correctness of the analytical solution. It is clearly presented that the linear search results are well matched with the analytical results. It can also be observed that the optimal UAV deployment location moves away from user 1 as r^* increases. The reason is that as r^* increases, user 2 needs more transmission power to satisfy the QoS constraint, and, therefore, the UAV tries to strike a balance between the transmission power of the two users. This phenomenon can be also verified by Remark 2.

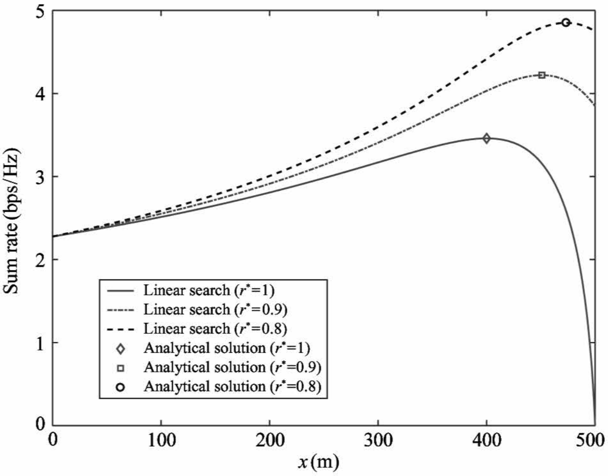

Fig. 2 Optimal deployment location for DP scheme versus r^*.

For comparison, the following 2 schemes are considered as benchmarks.

(1) **FDMA** A UAV-enabled FDMA system, which is different from NOMA system in this paper, also can demonstrate that the optimal UAV deployment location is over the line segment between the two users. Given a UAV's location and the power constraint, in order to maximize the sum rate, the optimal power allocation based on the water-filling scheme is first determined. Then, the location is varied to find the optimal solution that can maximize the sum rate. This scheme can be used to demonstrate advantages of the NOMA system.

(2) **Power optimization without UAV deployment (POWD)** A UAV-enabled NOMA system, where the UAV's location is fixed over user 1 and the optimal transmission power is obtained with the same manner used in our scheme. POWD scheme is used to demonstrate the advantages of the DP scheme.

Fig. 3 plots the variation of sum rate for the FDMA scheme versus different r^*. A curve of NOMA when $r^* = 0.8$ is also plotted for comparison. A portion of the FDMA scheme curves are not drawn, due to the reason that the QoS constraint is not satisfied. Moreover, the NOMA scheme can always achieve a higher sum rate compared to the FDMA scheme. That is because the NOMA scheme is known to have a higher spectrum efficiency compared to the FDMA scheme.

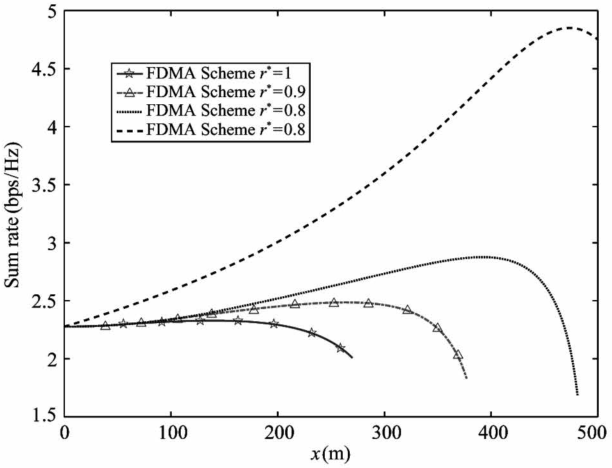

Fig. 3 Optimal deployment location for FDMA scheme versus r^*

Fig. 4 compares the sum rate of the 3 different schemes versus different r^*. It can be noted that the sum rate of the proposed DP scheme decreases as r^* increases. This phenomenon is consistent with Remark 2. Also, it can be observed that the proposed DP scheme outperforms the FDMA scheme and the POWD

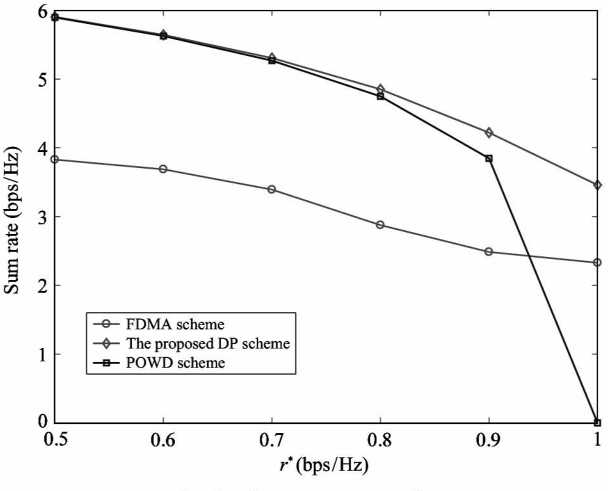

Fig. 4 Sum rate versus r^*

scheme from the perspective of sum rate. The proposed DP scheme can achieve a higher sum rate compared to the FDMA scheme, because of the employed NOMA manner. The proposed DP scheme can obtain a higher sum rate compared to the POWD scheme, because of the optimal UAV location deployment. Moreover, it should be pointed out that when $r^* = 1$ bps/Hz, the POWD scheme cannot satisfy the QoS constraint, and therefore the sum rate drops to zero. Therefore, the conclusion can be drawn that by designing the optimal UAV's deployment location, not only the sum rate can be enhanced, the QoS of each user can also be assured.

4 Conclusion

In this paper, the optimal UAV's deployment problem is studied in a two-user case. In order to maximize users' sum rate, an optimization problem is first constructed, considering the QoS and power constraints. Then, a feasible solution region of the problem is reduced to a line segment between the two users. This conclusion can help us further reduce the original optimization problem to a simplified one. Next, by giving a UAV's location and utilizing the optimal power allocation strategy which is relevant to the UAV's location, the optimization problem is reduced to a univariate problem. The analytical solution to the simplified problem under a certain situation is provided, and moreover, a generalized algorithm is proposed to further determine the optimal UAV's location. Simulation results are presented to demonstrate effectiveness of the proposed DP scheme in maximizing the sum rate and its advantages over the FDMA and POWD schemes.

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