Placement and Power Allocation for NOMA-UAV Networks

Xiaonan Liu, Jingjing Wang, Nan Zhao, *Senior Member, IEEE,* Yunfei Chen, *Senior Member, IEEE,* Shun Zhang, Zhiguo Ding, *Senior Member, IEEE,* and F. Richard Yu, *Fellow, IEEE*

***Abstract*—Unmanned aerial vehicles (UAVs) can be used as flying base stations to provide ubiquitous connections for mobile devices in over-crowded areas. On the other hand, non-orthogonal multiple access (NOMA) is a promising technique to support massive connectivity. In this letter, the placement and power allocation (PA) are jointly optimized to improve the performance of the NOMA-UAV network. Since the formulated joint optimization problem is non-convex, the location of the UAV is first optimized, with the total path loss from the UAV to users minimized. Then, the PA for NOMA is optimized using the optimal location of the UAV to maximize the sum rate of the network. Simulation results are presented to show the effectiveness and efficiency of the proposed scheme for NOMA-UAV networks.**

***Index Terms*—Placement optimization, non-orthogonal multiple access, power allocation, unmanned aerial vehicle.**

I. Introduction

To satisfy the increasing demand for data services, the 5G networks are being standardized to provide wider coverage, support more devices, and achieve higher throughput. Meanwhile, unmanned aerial vehicle (UAV) communication is an emerging technique which can help 5G achieve better performances, due to its mobility, flexibility and good channel condition [1], [2]. Recently, much research has already been conducted on UAV communications [3]–[7]. In [3], to minimize the number of UAVs, a 2-D placement optimization algorithm was proposed for multiple UAVs. In [4], the UAV trajectory was studied to offload traffic for base stations (BSs).

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X. Liu and N. Zhao are with the School of Inform. and Commun. Eng., Dalian University of Technology, Dalian, Liaoning, 116024, P. R. China, and also with the State Key Laboratory of Integrated Services Networks, Xidian University, Xi'an, 710071, P. R. China (email: liuxiaonan@mail.dlut.edu.cn, zhaonan@dlut.edu.cn).

J. Wang is with the School of Information Science and Technology, Qingdao University of Science and Technology, Qingdao, Shandong, 266000, P. R. China (e-mail: Kathy1003@163.com).

Y. Chen is with the School of Engineering, University of Warwick, Coventry CV4 7AL, U.K. (e-mail: Yunfei.Chen@warwick.ac.uk).

S. Zhang is with the State Key Laboratory of Integrated Services Networks, Xidian University, Xi'an, 710071, P. R. China. (Email: zhangshunsdu@xidian.edu.cn).

Z. Ding is with the School of Electrical and Electronic Engineering, the University of Manchester, Manchester, U.K. (e-mail: zhiguo.ding@manchester.ac.uk).

F. R. Yu is with the Department of Systems and Computer Engineering, Carleton University, Ottawa, ON, K1S 5B6, Canada (email: richard.yu@carleton.ca).

Through trajectory optimization, the energy trade-off problem of ground-to-UAV communications was studied in [5]. In [6], a fundamental tradeoff was made between the throughput and delay in UAV networks with cyclical multiple access. In [7], a blind beam tracking approach for a Ka-band UAV-satellite communication system was proposed.

On the other hand, non-orthogonal multiple access (NOMA) can provide massive connectivity, high reliability and efficient spectrum utilization [8]–[16]. In [8], the performance of downlink NOMA was studied with randomly deployed users. A power allocation (PA) scheme was proposed in [9], under the outage constraints in NOMA systems. The impact of user pairing in two NOMA systems, i.e., fixed-NOMA and cognitive-radio-NOMA, was characterized in [10]. In [11], the PA and scheduling problems were studied for NOMA relay-assisted networks. A NOMA multicast scheme was proposed in [12], to improve the spectrum efficiency of content caching networks. In [13], the non-orthogonal angle division multiple access was studied from the array signal processing perspective. In [14], a unified framework was proposed to study UAV networks assisted by NOMA. The beamforming and PA were jointly optimized for satellite-terrestrial networks with NOMA in [15]. NOMA was utilized to reduce the transmission latency for short-packet communications in [16].

In the aforementioned works, NOMA has not been well researched in UAV-aided networks, motivated by which, UAV and NOMA are combined to provide wireless data service for ground users in this letter. Specifically, the placement and PA for the UAV are jointly optimized. Nevertheless, due to the non-convexity of the proposed optimization problem, it is extremely difficult to solve directly. Thus, we first select a proper location for the UAV so that the total path loss from the UAV to ground users can be minimized. Then, PA for NOMA at the UAV is further performed to maximize the sum rate.

II. System Model and Problem Formulation

A. System Model

We consider a wireless network with a single UAV providing data services as a BS for multiple ground users. The UAV is deployed at a height H, which can serve at most K mobile devices simultaneously. We assume that the UAV and each device are equipped with a single antenna. Thus, the received signal at the kth user from the UAV can be expressed as

$$\bar{y}_k = h_k \bar{x}_k + h_k \sum\nolimits_{j=1, j\neq k}^{K} \bar{x}_j + n_k, \tag{1}$$

where h_k is the channel coefficient between the UAV and the kth user. $\bar{x}_k$ is the transmitted message for the kth user, and n_k represents the additive white Gaussian noise (AWGN) following $\mathcal{CN}(0, \sigma^2)$. Without loss of generality, the channel gains follow $0 < |h_1|^2 \leq \cdots \leq |h_k|^2 \leq \cdots \leq |h_K|^2$. Also, $|\bar{x}_k|^2 = P_{UAV} a_k$, where P_{UAV} is the maximum transmit power of the UAV, a_k is the PA coefficient, which follows

$$\sum\nolimits_{k=1}^{K} a_k = 1, \ a_1 \geq \cdots \geq a_k \geq \cdots \geq a_K. \tag{2}$$

According to NOMA, successive interference cancellation (SIC) is utilized at users according to their channel conditions [8]. For example, the kth user needs to decode information from the 1st to the $(k-1)$th user before decoding its own. Then, the received signal-to-interference-plus-noise-ratio (SINR) at the kth user $(1 \leq k \leq K-1)$ can be presented as

$$\text{SINR}^{[k]} = \frac{P_{UAV}|h_k|^2 a_k}{P_{UAV}|h_k|^2 \sum\nolimits_{i=k+1}^{K} a_i + \sigma^2}. \tag{3}$$

For the Kth user, the received SINR can be denoted by

$$\text{SINR}^{[K]} = P_{UAV}|h_K|^2 a_K / \sigma^2. \tag{4}$$

The transmission rate for the kth user can be presented as

$$R^{[k]} = \log_2\left(1 + \text{SINR}^{[k]}\right), \ k = 1, 2, \ldots, K. \tag{5}$$

B. Problem Formulation

To maximize the sum rate of the UAV-assisted NOMA network, the location and transmit power of the UAV BS should be jointly optimized, which can be expressed as

$$\text{(P1)} \max_{a_k, X_U, Y_U} \sum\nolimits_{k=1}^{K} \log_2\left(1 + \text{SINR}^{[k]}\right) \tag{6a}$$

$$s.t. \ R^{[k]} \geq \bar{r}^{[k]}, \tag{6b}$$

$$\sum\nolimits_{k=1}^{K} a_k = 1, \tag{6c}$$

$$\min\{x_i\} \leq X_U \leq \max\{x_i\}, 1 \leq i \leq K, \tag{6d}$$

$$\min\{y_j\} \leq Y_U \leq \max\{y_j\}, 1 \leq j \leq K, \tag{6e}$$

where $\bar{r}^{[k]}$ is the rate threshold for the kth user, and (x_k, y_k) denotes the coordinate of the kth user. Due to the fact that the UAV is assumed to stay at a fixed height to guarantee the coverage of all the users, we use (X_U, Y_U) to present the location of the UAV in the horizontal dimension.

III. Low-Complexity Solutions to (P1)

We should notice that (P1) is non-convex, which is difficult to solve. Therefore, we propose to solve it through the following two steps: (1) Placement optimization for the UAV; (2) PA for NOMA.

A. Placement Optimization for the UAV

We assume that the path loss from the UAV to users is mainly line-of-sight (LoS) [3]–[6]. The path-loss model for the LoS link of the kth user in dB can be denoted as

$$L_{LoS}^{[k]} = 20\log_{10}(4\pi f_c d_k / c) + \eta_{LoS}, \ k = 1, 2, ..., K, \tag{7}$$

where f_c is the carrier frequency, and d_k is the distance between the UAV and the kth user, i.e.,

$$d_k = \sqrt{H^2 + (X_U - x_k)^2 + (Y_U - y_k)^2}. \tag{8}$$

η_{LoS} is the mean additional loss for LoS transmission.

Furthermore, for a given transmit power $P_t^{[k]}$ of the kth user from the UAV, its received power $P_r^{[k]}$ in dB can be determined using the path loss as

$$P_r^{[k]} = 10\log_{10} P_t^{[k]} - L_{LoS}^{[k]}, \tag{9}$$

$$P_t^{[k]} = P_{UAV} a_k. \tag{10}$$

Thus, the optimal location for UAV can be achieved by minimizing the total path loss of the UAV as

$$\text{(P2)} \min_{L_{LoS}^{[k]}} \sum\nolimits_{k=1}^{K} L_{LoS}^{[k]} \tag{11a}$$

$$s.t. \ \min\{x_i\} \leq X_U \leq \max\{x_i\}, 1 \leq i \leq K, \tag{11b}$$

$$\min\{y_j\} \leq Y_U \leq \max\{y_j\}, 1 \leq j \leq K, \tag{11c}$$

which can effectively improve the network performance.

According to (7), (P2) can be recast as

$$\begin{aligned} \min_{d_k} \ & 20\log_{10}\left(\prod_{k=1}^{K}\left(\frac{4\pi f_c d_k}{c}\right)\right) + K\eta_{LoS} \\ s.t. \ & \min\{x_i\} \leq X_U \leq \max\{x_i\}, 1 \leq i \leq K, \\ & \min\{y_j\} \leq Y_U \leq \max\{y_j\}, 1 \leq j \leq K. \end{aligned} \tag{12}$$

In addition, based on

$$d_1 d_2 \ldots d_K \leq \left((d_1 + d_2 + \cdots + d_K)/K\right)^K, \tag{13}$$

we can know that obtaining the optimal location of the UAV is equivalent to minimizing the sum distance between the UAV and users. Hence, (12) can be further rewritten as

$$\begin{aligned} \min_{X_U, Y_U} \ & \sum\nolimits_{k=1}^{K} (X_U - x_k)^2 + (Y_U - y_k)^2 \\ s.t. \ & \min\{x_i\} \leq X_U \leq \max\{x_i\}, 1 \leq i \leq K, \\ & \min\{y_j\} \leq Y_U \leq \max\{y_j\}, 1 \leq j \leq K. \end{aligned} \tag{14}$$

To obtain the optimal solution of (14), Lemma 1 and Lemma 2 are provided.

Lemma 1: (14) is a convex optimization problem.

Proof: According to (14), the second derivative of X_U or Y_U is $2K > 0$, which means (14) is convex in X_U or Y_U. In addition, the constraints are affine functions, and hence, we can conclude that (14) is a convex problem. ■

Lemma 2: The optimal solutions of X_U and Y_U in (14) can be denoted as

$$X_U = \sum\nolimits_{k=1}^{K} x_k / K, \ \ Y_U = \sum\nolimits_{k=1}^{K} y_k / K. \tag{15}$$

Proof: Because (14) is convex, its first-order derivative of X_U and Y_U are $2KX_U - 2\sum_{k=1}^{K} x_k$ and $2KY_U - 2\sum_{k=1}^{K} y_k$, respectively. When they equal to 0, (15) can be obtained. ■

B. Power Allocation for NOMA

With the optimal location of UAV in (15), the sum rate can be further maximized by PA at the UAV among users. According to (6b), a minimum transmission rate should be satisfied by each user. (6b) can be further changed into

$$a_k \geq \left(2^{\bar{r}^{[k]}} - 1\right)\left(\sum\nolimits_{i=k+1}^{K} a_i + \frac{\sigma^2}{P_{UAV}|h_k|^2}\right). \tag{16}$$

Due to (16), the PA problem cannot be solved when P_{UAV} is not high enough. Thus, there exists a minimum transmit power $P_{UAV-min}$ that can satisfy all users' minimum rate requirements, which can be obtained as

$$\text{(P3)} \min_{P_t^{[k]}} \sum_{k=1}^{K} P_t^{[k]} \tag{17a}$$

$$s.t.\ P_t^{[k]} \geq \left(2^{\bar{r}^{[k]}}-1\right)\left(\sum_{i=k+1}^{K} P_t^{[i]}+\sigma^2/|h_k|^2\right). \tag{17b}$$

Lemma 3: The optimal solution of (P3) can be presented as

$$P_{t-min}^{[k]} = \left(2^{\bar{r}^{[k]}}-1\right)\left(\sum_{i=k+1}^{K} P_{t-min}^{[i]}+\sigma^2/|h_k|^2\right). \tag{18}$$

Proof: (P3) is convex, and Karush-Kuhn-Tucker (KKT) condition can be used to obtain its closed-form solution as

$$1+\sum_{i=1}^{k-1} \lambda_i \left(2^{\bar{r}^{[i]}}-1\right) = \lambda_k, \tag{19}$$

$$\lambda_k \left[\left(2^{\bar{r}^{[k]}}-1\right)\left(\sum_{i=k+1}^{K} P_t^{[i]}+\frac{\sigma^2}{|h_k|^2}\right)-P_t^{[k]}\right]=0, \tag{20}$$

$$\lambda_k \geq 0, k=1,2,...,K. \tag{21}$$

According to (19), we have $\lambda_k > 0$, due to the fact that $(2^{\bar{r}^{[k]}}-1)$ is a nonnegative number. Then, $P_t^{[k]}$ can be calculated according to (20). ■

Based on Lemma 3, we have

$$P_{UAV} \geq P_{UAV-min} = \sum_{k=1}^{K} P_{t-min}^{[k]}, \tag{22}$$

which can be utilized to check whether P_{UAV} is high enough to satisfy the minimum transmit power of all users.

To separate the PA from (P1), the sum rate of the network can be changed into

$$\begin{aligned}\sum_{k=1}^{K} R^{[k]} &= \log_2\left(\frac{P_{UAV}|h_1|^2}{\sigma^2}+1\right)\\ &+\sum_{k=1}^{K-1}\log_2\left(\frac{P_{UAV}|h_{k+1}|^2\sum_{i=k+1}^{K}a_i+\sigma^2}{P_{UAV}|h_k|^2\sum_{i=k+1}^{K}a_i+\sigma^2}\right).\end{aligned} \tag{23}$$

In addition, we assume that

$$z_k = \sum_{i=k+1}^{K} a_i, 1 \leq k \leq K-1, \tag{24}$$

$$\begin{aligned}U(z_k) &= \log_2(P_{UAV}|h_{k+1}|^2 z_k+\sigma^2)\\ &-\log_2(P_{UAV}|h_k|^2 z_k+\sigma^2), 1 \leq k \leq K-1.\end{aligned} \tag{25}$$

Thus, based on the optimal location of the UAV, (P1) can be reformed as

$$\max_{a_k} \sum_{k=1}^{K-1} U(z_k) \tag{26a}$$

$$s.t.\ \sum_{k=1}^{K} a_k = 1 \text{ and } (16). \tag{26b}$$

According to (25), we can know that the problem is the sum of $K-1$ nonconvex subfunctions. To solve (26), the first-order derivation of $U(z_k)$ can be derived as

$$\frac{\partial U(z_k)}{\partial z_k}=\frac{P_{UAV}(|h_{k+1}|^2-|h_k|^2)\sigma^2}{\ln 2(P_{UAV}|h_{k+1}|^2 z_k+\sigma^2)(P_{UAV}|h_k|^2 z_k+\sigma^2)}. \tag{27}$$

Since $|h_{k+1}|^2 \geq |h_k|^2$, $U(z_k)$ is a monotonically increasing function of z_k. Thus, maximizing $U(z_k)$ is equal to maximizing z_k. Then, (26) can be further reformulated as

$$\begin{aligned}&\max_{a_k} z_s\\ &s.t.\ \sum_{k=1}^{K} a_k = 1 \text{ and } (16),\\ &1 \leq k \leq K, 1 \leq s \leq K-1,\end{aligned} \tag{28}$$

which can be solved by Lemma 4.

Lemma 4: The closed-form solution of a_k $(1 \leq k \leq s)$ and z_s can be given as

$$a_k = \frac{(2^{\bar{r}^{[k]}}-1)}{2^{\bar{r}^{[k]}}}\left(1-\sum_{i=1}^{k-1}a_i+\frac{\sigma^2}{P_{UAV}|h_k|^2}\right), \tag{29}$$

$$z_s = 1-\sum_{k=1}^{s} a_k. \tag{30}$$

Proof: Due to the fact that (28) is convex, KKT conditions can be utilized to get

$$v=\begin{cases} u_k-\sum_{i=1}^{k-1}u_i(2^{\bar{r}^{[i]}}-1), & 1 \leq k \leq s,\\ u_k-\sum_{i=1}^{k-1}u_i(2^{\bar{r}^{[i]}}-1)+1, & s+1 \leq k \leq K,\end{cases} \tag{31}$$

$$u_k\left[\left(2^{\bar{r}^{[k]}}-1\right)\left(\sum_{i=k+1}^{K}a_i+\frac{\sigma^2}{P_{UAV}|h_k|^2}\right)-a_k\right]=0, \tag{32}$$

$$u_k \geq 0, k=1,2,...,K, \tag{33}$$

where v and u_k are the Lagrange multipliers for constraints in (28). We first justify $u_k > 0$ by contradiction. Assuming that $u_1 = 0$, then $v = u_1 = 0$ can be obtained via setting $k = 1$ in (31). Thus, as for $1 \leq k \leq s$, $u_k = \sum_{i=1}^{k-1} u_i(2^{\bar{r}^{[i]}}-1)$ can be further calculated. Due to the fact that $(2^{\bar{r}^{[i]}}-1) > 0$, u_k are all equal to zeros if $u_1 = 0$. Nevertheless, through setting $k = s+1$ in (31), we are able to derive that

$$u_1=v=u_{s+1}-\sum_{i=1}^{s}u_i(2^{\bar{r}^{[i]}}-1)+1 = u_{s+1}+1>0, \tag{34}$$

which does not meet the assumption that $u_1 = 0$. Accordingly, $v = u_1 > 0$. After that, as for $2 \leq k \leq s$, we can obtain that $u_k = \sum_{i=1}^{k-1} u_i(2^{\bar{r}^{[i]}}-1)+v$, which means that $u_k > 0$. Then, when $\sum_{i=k+1}^{K} a_i$ in (32) is replaced by $(1-\sum_{i=1}^{k} a_i)$, the closed-form solution of a_k $(1 \leq k \leq s)$ and z_s can be deduced as (29) and (30), respectively. ■

Therefore, according to Lemma 4, when $s = K-1$, the optimal solution a_k $(1 \leq k \leq K-1)$ can be calculated through (29). Moreover, because $\sum_{k=1}^{K} a_k = 1$, a_K can be further

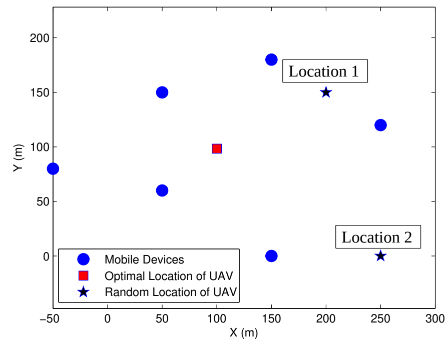

Fig. 1. Locations of the UAV and mobile users in the horizontal dimension.

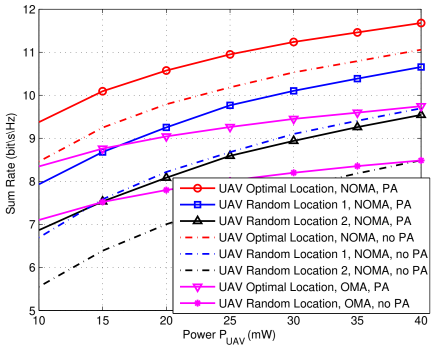

Fig. 2. Sum rate comparison of the NOMA-UAV network with different transmit power of the UAV P_{UAV} according to Fig. 1, when the locations of the UAV and the PA are optimized or not.

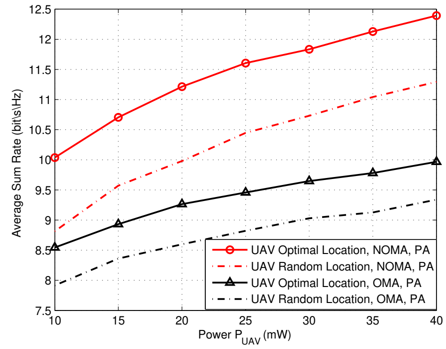

Fig. 3. Average sum rate comparison of the NOMA-UAV network, with different locations of ground users.

deduced as $a_K = 1 - \sum_{k=1}^{K-1} a_k$.

IV. Simulation Results and Discussion

Consider a NOMA UAV wireless network, in which all the mobile users are randomly deployed. We set $K = 6$, $H = 50$ m, σ^2 is -110 dBm, and $\bar{r} = 1$ bit/s/Hz.

First, the locations of the UAV and mobile users are shown in Fig. 1, where 6 users are randomly deployed in the horizontal dimension, which are marked by blue circles. Meanwhile, three locations are selected for the UAV. The red square is the optimal location calculated according to Lemma 2. The other two black stars are the randomly chosen locations for the UAV. The sum rate of the network is compared in Fig. 2 for different values of P_{UAV} at the UAV with the NOMA or orthogonal multiple access (OMA) schemes, based on the locations of the UAV in Fig. 1. When no PA is considered, the values of PA coefficients from a_1 to a_6 are fixed, which equal to 0.519, 0.25, 0.13, 0.065, 0.035 and 0.001, respectively. From the results, we can see that when the total transmit power of the UAV is higher, the sum rate increases. Furthermore, we can see that, when the location of the UAV is optimized according to Lemma 2, the performance is better than that when the location of the UAV is randomly generated. We can also observe that NOMA and PA can increase the sum rate.

Then, the average sum rate of the network is compared in Fig. 3 with different locations of ground users using the Monte-Carlo method. The 95% confidence interval of the point $P_{UAV} = 20$ mW on the curve of the optimal UAV location with both NOMA and PA is [9.18, 12.46]. From the result, we can also see that the performance of the proposed scheme is better than that when the UAV is randomly deployed or the OMA is adopted, with different locations of ground users.

V. Conclusions

The placement and PA of UAV have been optimized in NOMA-UAV networks in this letter to maximize the sum rate of users. To solve this non-convex optimization problem, it has been separated into two sub-problems. First, the location of UAV has been optimized to minimize the sum path loss from UAV to users. Then, the PA for UAV has been optimized according to its optimal location to further maximize the sum rate. Simulation results have been presented to show the effectiveness of the proposed scheme.

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