

Multiple Unmanned Aerial Vehicles Deployment and User Pairing for Non-Orthogonal Multiple Access Schemes

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Abstract—Non-orthogonal multiple access (NOMA) significantly improves the connectivity opportunities and enhances the spectrum efficiency (SE) in the fifth generation and beyond (B5G) wireless communications. Meanwhile, emerging B5G services demand of higher SE in the NOMA based wireless communications. However, traditional ground-to-ground (G2G) communications are hard to satisfy these demands, especially for the cellular uplinks. To solve these challenges, this paper proposes a multiple unmanned aerial vehicles (UAVs) aided uplink NOMA method. In detail, multiple hovering UAVs relay data for a part of ground users (GUs) and share the sub-channels with the left GUs that communicate with the base station (BS) directly. Furthermore, this paper proposes a K-means clustering based UAV deployment and location based user pairing scheme to optimize the transceiver association for the multiple UAVs aided NOMA uplinks. Finally, a sum power minimization based resource allocation problem is formulated with the lowest quality of service (QoS) constraints. We solve it with the message-passing algorithm and evaluate the superior performances of the proposed scheduling and pairing schemes on SE and energy efficiency (EE). Extensive experiments are conducted to compare the performances of the proposed schemes with those of the single UAV aided NOMA uplinks, G2G based NOMA uplinks, and the proposed multiple UAVs aided uplinks with a random UAV deployment. Simulation results demonstrate that the proposed multiple UAVs deployment and user pairing based NOMA scheme significantly improves the EE and the SE of the cellular uplinks at the cost of only a little relaying power consumption of the UAVs.

Index Terms—Unmanned aerial vehicle (UAV), non-orthogonal multiple access, UAV deployment, user pairing, energy efficiency, spectrum efficiency.

I. INTRODUCTION

Ubiquitous connectivity with ultra-high spectrum efficiency and system throughput is one of the crucial requirements for

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the fifth generation and beyond (B5G) wireless communication systems [1]–[3] and internet of things (IoT) [4]–[7]. Through significantly improving the connectivity and spectrum efficiency [8]–[12], non-orthogonal multiple access (NOMA) has become a promising solution for the B5G communications. Generally, in the NOMA aided systems, multiple users with different channel conditions are multiplexed in power domain and served on the same sub-channels simultaneously. Then the receivers utilize successive interference cancellation (SIC) technique to remove intra-channel interference with the decoding order based on channel conditions [11]–[13]. Especially in recent years, many other promising techniques have been widely researched through combining NOMA. For examples, multiple input multiple-output based NOMA techniques were investigated in [14], [15]. Dynamic resource allocation schemes for improving performances of the NOMA based networks were explored in [16]–[18]. Dynamic user grouping was explored in [19]. A new definition of fairness for NOMA was proposed in [20]. And also applying NOMA to heterogeneous networks were discussed in [21]–[23].

Although plenty of previous works have proved the excellent performances of NOMA on massive connectivity and high SE, there still exist many challenges for applying NOMA to support B5G communications, especially for designing effective uplink NOMA schemes [24]–[27]. Firstly, the spectrum efficiency (SE) of the cellular systems needs to be further improved by NOMA. Secondly, the energy efficiency (EE) of the cellular systems needs to be raised by NOMA. Because of the high mobility, flexible deployment and line-of-sight (LoS) channels of unmanned aerial vehicle (UAV), UAV aided B5G technologies have attracted increasing attentions from both academia, and industry [28]–[32]. Specifically, there are many existing works about integrating NOMA into UAV aided communication systems to improve the throughput of the systems, mainly focusing on optimal UAV deployment, optimal user pairing strategy, optimal sub-channel allocation scheme and fair control for different users [33]–[35]. In [33], a mobile UAV based downlink NOMA model was considered, and then UAV trajectory design and resource allocation in NOMA are jointly optimized to maximize the capacity of the system. M. T. Nguyen *et al.* [34] also considered a single UAV based downlink NOMA system, and optimized the user pairing, power allocation, and UAV placement to maximize the minimum sum rate for individual

user pair. The communication reliability and fairness among users for a single-UAV aided downlink NOMA cell system was investigated in [35] by optimizing the UAV's altitude and the users' power allocation coefficients. The maximum stable throughput of a single-UAV based uplink NOMA cell system was investigated by [26], in terms of the altitude and bandwidth of the UAV. R. Duan *et al.* [27] considered a multi-UAV aided IoT NOMA uplink transmission system and evaluated that combining NOMA and UAV communication can achieve higher capacity than orthogonal multiple access (OMA) based UAV communication systems.

To the best of our knowledge, utilizing multiple UAVs to improve the SE and the EE of the uplink NOMA cell systems have not been investigated. Motivated by this background, in this paper a multiple UAVs aided NOMA technology is proposed to enhance the SE and the EE of the cellular uplinks. Particularly, we propose a K-means clustering based UAV deployment scheme and a location based user pairing scheme. In addition, considering the energy limited GUs' devices, a sum power minimization based resource allocation scheme is adopted to evaluate the outperformance of the proposed schemes. The contributions of this paper can be summarized as follows:

- We propose a multiple UAVs aided NOMA technology to enhance the SE and the EE of the uplink cellular systems.
- A K-means clustering based UAV deployment scheme is proposed to optimize the serving areas of the proposed multiple UAVs aided uplink NOMA.
- A location based user pairing scheme is proposed to determine the decoding orders of the users for the proposed multiple UAVs aided uplink NOMA.
- To save transmitted power for the GUs' devices, we consider a sum power minimization based resource allocation scheme with the lowest quality of service (QoS) constraints to evaluate the performance of the proposed schemes for the multiple UAVs aided uplink NOMA.

II. MULTIPLE UAVS AIDED UPLINK NOMA CELLULAR SYSTEM MODEL

A multiple UAVs aided uplink NOMA cellular system consists of a BS, N GUs and M UAVs. The BS is located at the center of a ground cell of which the radius is R . And N GUs are randomly and uniformly distributed in the coverage of the cell. For applying UAVs to improve the SE and EE of the uplink transmissions in this system, the proposed multiple UAVs aided uplink NOMA technology is designed as follows. Firstly, all the M UAVs are considered as relays to help half of the GUs in hovering pattern. At the same time, the left GUs communicate with the BS directly. Especially, the relayed and the directly transmitting users can be paired together and their messages are accommodated on the same spectrums. In detail, the UAVs relay data by using decode-and-forward (DF) protocol and full duplex (FD) technology. Specially, each UAV is equipped with two antennas. One antenna receives signals and another antenna transmits signals simultaneously. For convenience, the receiving antenna and the transmitting

antenna of each UAV are denoted as a and b respectively. To be general, the residual self-interference (RSI) after SIC in UAVs is considered, see Fig. 1.

As is shown in Fig. 1, the relay links and direct links in same color are located on the same sub-channels. $\theta_1, \dots, \theta_m, \dots, \theta_M$ denote the elevation angle between the BS and the UAVs. $\varphi_{i,m}$ represents the elevation angle between the i -th GU and the m -th UAV. We assume that the total available frequency bands of the system are equally divided into Z^T orthogonal sub-channels and the bandwidth of each sub-channel is B_0 .

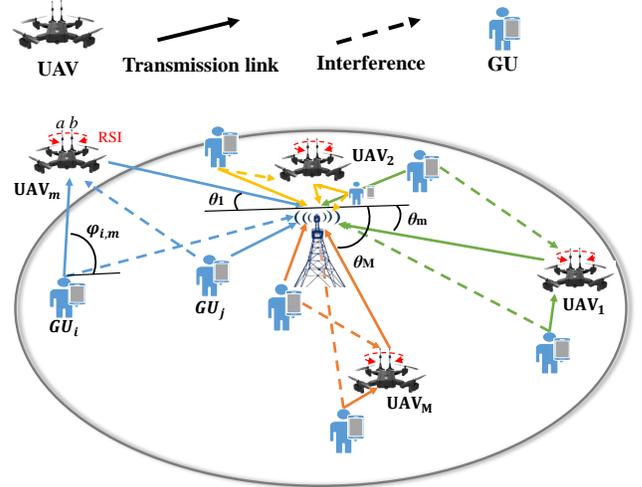


Fig. 1: The multiple UAVs aided uplink NOMA cellular system model.

In this model, let GU_n denote the n -th GU, $n \in \{1, 2, \dots, N\}$ and UAV_m denote the m -th UAV, $m \in \{1, 2, \dots, M\}$. The typical channel models in [36] for the ground to ground links and the ground to air links are adopted in this system model. In detail, the GU-BS channels are modeled as Rayleigh fading channels and the GU-UAV channels are LoS channels or NLoS channels depending on the environments. Specially, the UAV-BS channels in this system model are always LoS channels based on our UAV deployment scheme, which will be detailed in Section III. The channels between receiving antenna a and transmitting antenna b are also modeled as LoS channels. Let $g_{n,m,z}^{UA}$ denote the channel gain between GU_n and UAV_m on sub-channel z , $z \in \{1, 2, \dots, Z^T\}$, $g_{n,m,z}^{AB}$ denote the channel gain between the UAV_m and the BS on sub-channel z for GU_n , $g_{n,B,z}^{UB}$ denote the channel gain between the GU_n and the BS on sub-channel z and $g_{a,b,z}$ denotes the channel gain between the antenna a and the antenna b on sub-channel z , P denotes the LoS probability of GU-UAV channels. Based on [36], they are defined as

$$g_{n,m,z}^{UA} = \begin{cases} \eta_{LoS}(d_{n,m}^{UA})^{-\alpha_R}, & \text{with } P \\ \eta_{NLoS}(d_{n,m}^{UA})^{-\alpha_R}, & \text{with } 1 - P \end{cases} \quad (1)$$

$$g_{n,m,z}^{AB} = \eta_{LoS}(d_{m,B}^{AB})^{-\alpha_R} \quad (2)$$

$$g_{a,b,z} = \eta_{LoS}(d_{a,b})^{-\alpha_R} \quad (3)$$

$$g_{n,B,z}^{UB} = (d_{n,B}^{UB})^{-\alpha_B} |h_z|^2 \quad (4)$$

where $P = 1/[1 + \psi \exp(-\beta(\varphi_{n,m} - \psi))]$, in which $\varphi_{n,m} = (180^\circ/\pi) \arcsin(H_m/d_{n,m}^{UA})$ is elevation angle between the GU_n and the UAV_m , β and ψ are environment dependent constant values. H_m is the height of the UAV_m . $d_{n,m}^{UA}$, $d_{m,B}^{AB}$, $d_{a,b}$, $d_{n,B}^{UB}$ denote the distance between GU_n and UAV_m , the distance between UAV_m and BS, the distance between receiving antenna a and transmitting antenna b . The distance between GU_n and BS, respectively. η_{LoS} and η_{NLoS} denote additional attenuation factors of LoS and NLoS channels, respectively. α_R and α_B denote the path loss factor of the ground to air channel and the Rayleigh fading channel, respectively. h_z denotes the complex Gaussian channel coefficient which follows the distribution of $CN(0,1)$.

III. THE PROPOSED UAV DEPLOYMENT SCHEME

The performance of the multiple UAVs aided uplink NOMA cellular system is determined by the UAV deployment. Aim to maximize the SE as well as the EE of the considered cellular uplinks, we propose a K-means clustering based UAV deployment scheme (Multi-UAV-K-cluster scheme).

We assume that all the GUs' locations are known to the UAVs and the BS. Thus, the GUs can be equally divided into two groups based on their Euclidean distance between GUs and BS. The central group and the edge group, respectively, are shown by the orange area and white area in Fig. 2. The GUs in orange area are closer to the BS, thus they are assigned to communicate with the BS directly and we denote them as direct GUs. Similarly, the GUs in the white area are far to the BS, thus they are relayed by the UAVs and we denote them as relay GUs. After determining the direct GUs and relay GUs, all the relay GUs can be clustered into M clusters based on their locations by the BS with K-means clustering algorithm. In detail, to obtain a uniformly distributed clustering results, we choose the coordinates of the M GUs that are closest to the M points of Φ_C as the initial centroids. The M points of Φ_C are uniformly distributed at the edge of the cell, see (5). Specially, the GU that is assigned as one centroid will be excluded in the following computing to avoid repeatedly assigning one GU as different centroids.

$$\Phi_C = \{(R \cos(2\pi/M), R \sin(2\pi/M)), (R \cos(4\pi/M), R \sin(4\pi/M)), \dots, (R \cos(2\pi), R \sin(2\pi))\} \quad (5)$$

Then, the M UAVs are scheduled to hovering on the centroids of M clusters with random heights. To resist the interference from direct GUs, the heights of all the UAVs should be adjusted until all the UAV-BS links have LoS channels. The detailed Multi-UAV-K-cluster scheme are summarized in **Algorithm 1**. After the UAV deployment, each relay GU will communicate with the UAV that is deployed above the cluster it belongs to.

IV. SUM POWER MINIMIZATION PROBLEM FORMULATION

To save transmitted power for the GUs' devices, we consider a sum power minimization based resource allocation

Algorithm 1 The proposed multi-UAV-K-cluster scheme.

- 1: **Input:** The number of clusters M ; Φ_C ; The coordinates of all relay GUs $L = \{(x_1, y_1), (x_2, y_2), \dots, (x_{N/2}, y_{N/2})\}$.
- 2: **Initialization:** Set $\text{cluster}^0 = [0, 0, \dots, 0]_{1 \times N/2}$, denotes the initial cluster every relay GU belongs to; Compute the initial M centroids Centr^0 based on Φ_C ;
- 3: **While:** $\text{cluster}^{(t+1)} \neq \text{cluster}^t$, **do:**
- 4: Compute distance between each relay GU and each centroid;
- 5: Find the index of closest centroid for each relay GU and update $\text{cluster}^{(t+1)}$;
- 6: Recalculate centroids $\text{Centr}^{(t+1)}$ using current cluster memberships;
- 7: **End while**
- 8: **Output:** The final cluster's result $\text{cluster}^{(t+1)}$ and the final centroids $\text{Centr}^{(t+1)}$.
- 9: **UAV deployment:** The M UAVs will be located on the M centroids of $\text{Centr}^{(t+1)}$ with initial heights. And the heights of all UAVs will be adjusted until the UAV-BS channels are LoS channels.

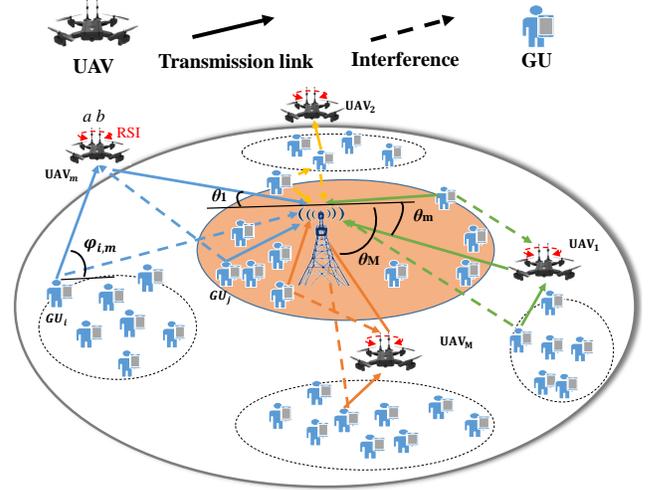


Fig. 2: The demonstration of the Multi-UAV-K-cluster scheme.

scheme with the lowest QoS constraints to evaluate the performance of the proposed schemes for the multiple UAVs aided uplink NOMA. For convenience to formulate the sum power minimization problem, we make an assumption as following.

Assumption 1: GU_i and GU_j are paired to assign different receivers and share the same sub-channel z , and GU_i is assigned to UAV_m while GU_j is assigned to BS directly.

Since UAV-BS channels are LoS channel, they are obviously much better than the GU-BS channels. Therefore, the SINR of the UAVs relayed signals on the BS is higher than the directly transmitted signals. Accordingly, the BS is able to successfully decode the relayed data in the first order. As a result, under **Assumption 1**, the interference introduced to GU_j only consists of Additive White Gaussian Noise (AWGN). Meanwhile, the interference introduced to GU_i includes the co-channel interference (CI) from GU_j , the RSI of the UAV_m and AWGN. Let $\gamma_{i,m,z}^{UA}$ denote the SINR from the GU_i to UAV_m on sub-channel z , $\gamma_{i,m,z}^{AB}$ denote the SINR from UAV_m to the BS on sub-channel z for relaying GU_i 's data, and $\gamma_{j,B,z}^{UB}$ denote the SINR from GU_j to the BS. Then,

they are respectively computed as

$$\gamma_{i,m,z}^{UA} = \frac{g_{i,m,z}^{UA} p_{i,m,z}^{UA}}{\underbrace{N_0 B_0}_{AWGN} + \underbrace{g_{j,m,z}^{UA} p_{j,B,z}^{UB}}_{CI} + \underbrace{\tau g_{a,b,z} p_{i,m,z}^{AB}}_{RSI}} \quad (6)$$

$$\gamma_{i,m,z}^{AB} = \frac{g_{i,m,z}^{AB} p_{i,m,z}^{AB} + g_{i,B,z}^{UB} p_{i,m,z}^{UA}}{\underbrace{N_0 B_0}_{AWGN} + \underbrace{g_{j,B,z}^{UB} p_{j,B,z}^{UB}}_{CI}} \quad (7)$$

$$\gamma_{j,B,z}^{UB} = \frac{g_{j,B,z}^{UB} p_{j,B,z}^{UB}}{\underbrace{N_0 B_0}_{AWGN}} \quad (8)$$

where $p_{i,m,z}^{UA}$, $p_{i,m,z}^{AB}$, $p_{j,B,z}^{UB}$ are the transmitted power on sub-channel z , consumed by GU_i , UAV_m , and GU_j respectively. In addition, N_0 denotes the power spectral density of the AWGN, and τ denotes the RSI coefficient. Especially, $\gamma_{i,m,z}^{AB}$ also benefits from the signals of GU_i received by the BS, which can be computed as $g_{i,B,z}^{UB} p_{i,m,z}^{UA}$. By denoting $R_{i,m,z}^{UA}$, $R_{i,m,z}^{AB}$ and $R_{j,B,z}^{UB}$ as the data rates of the GU_i , UAV_m and GU_j on sub-channel z , their upper bound can be further computed based on the Shannon's capacity.

We define a matrix \mathbb{U} with a size of $N \times M$, in which the binary variable $u_{n,m} \in \{0, 1\}$ represents whether the GU_n is assigned to UAV_m . If GU_n is assigned to UAV_m for transmission, then $u_{n,m} = 1$, otherwise $u_{n,m} = 0$. Likewise, a matrix \mathbb{S} with a size of $1 \times N$ is defined to denote which GUs are assigned to the BS. If GU_n is scheduled to communicate with BS directly, then its binary assignment variable $s_{n,B} = 1$, otherwise $s_{n,B} = 0$. Besides, a matrix \mathbb{Z} with a size of $N \times Z^T$ is defined to denote the sub-channel allocation results. Its binary element $v_{n,z} \in \{0, 1\}$ denotes whether the sub-channel z is allocated to GU_n . If sub-channel z is allocated to GU_n , then $v_{n,z} = 1$, otherwise $v_{n,z} = 0$. Moreover, if p_n^U , p_m^A denote the total transmitted power of GU_n and UAV_m , then they can be computed as (9) and (10). Similarly, let R_n^U denotes the sum rate of GU_n , then it can be computed as (11),

$$p_n^U = \sum_{z=1}^{Z^T} v_{n,z} \left(\left(\sum_{m=1}^M u_{n,m} p_{n,m,z}^{UA} \right) + s_{n,B} p_{n,B,z}^{UB} \right) \quad (9)$$

$$p_m^A = \sum_{n=1}^N \sum_{z=1}^{Z^T} u_{n,m} p_{n,m,z}^{AB} \quad (10)$$

$$R_n^U = \sum_{z=1}^{Z^T} v_{n,z} \times \left(\left(\sum_{m=1}^M u_{n,m} \min\{R_{n,m,z}^{UA}, R_{n,m,z}^{AB}\} \right) + s_{n,B} R_{n,B,z}^{UB} \right) \quad (11)$$

where $\sum_{m=1}^M u_{n,m} \leq 1$ denotes that each GU can be assigned to one UAV which is determined by using our proposed UAV

deployment scheme.

$$\min_{\mathbb{U}, \mathbb{S}, \mathbb{Z}} \sum_{i=1}^N p_n^U$$

s. t.

$$(C1) \quad p_n^U \leq p_n^{U*}$$

$$(C2) \quad p_m^A \leq p_m^{A*}$$

$$(C3) \quad R_n^U \geq R_n^{U*}$$

$$(C4) \quad \sum_{z=1}^{Z^T} \sum_{m=1}^M u_{n,m} R_{n,m,z}^{UA} \leq \sum_{z=1}^{Z^T} \sum_{m=1}^M u_{n,m} R_{n,m,z}^{AB} \quad (12)$$

$$(C5) \quad \sum_{m=1}^M u_{n,m} \gamma_{n,m,z}^{UA} + s_{n,B} \gamma_{n,B,z}^{UB} \geq \gamma_n^{U*}$$

$$(C6) \quad p_{n,m,z}^{UA}, p_{n,B,z}^{UB}, p_{n,m,z}^A \geq 0$$

$$(C7) \quad \sum_{n \in \Omega_S} v_{n,z} \leq 1$$

$$(C8) \quad \sum_{z=1}^{Z^T} v_{n,z} = Z_n$$

In order to prolong the working life of the GUs' devices, in this paper we aim to minimize the total transmitted power of the GUs by optimizing \mathbb{U} , \mathbb{S} and \mathbb{Z} . The optimization problem with the lowest QoS constraints can be formulated as (12). In (12), p_n^{U*} and p_m^{A*} are the maximum power budget of GU_n and UAV_m respectively. R_n^{U*} and γ_n^{U*} are minimum sum rate demand and SINR demand of the GU_n . (C4) guarantees the feasibility of the relay links. Constraint (C7) denotes that one sub-channel can be assigned to at most one direct GU, and Ω_S is the set of direct GUs. Constraint (C8) denotes the number of the sub-channels one GU should be occupied. Moreover, Z_n is the minimum number of sub-channels demanded by GU_n , and it can be computed as $Z_n = \lfloor R_n^{U*} / B_0 \log(1 + \gamma_n^{U*}) \rfloor$.

V. THE SOLUTION OF THE SUM POWER MINIMIZATION PROBLEM

In the power minimization problem (12), $p_{n,m,z}^{UA}$, $p_{n,B,z}^{UB}$, and $p_{n,m,z}^A$ are nonnegative and continuous variables. In addition, $u_{n,m}$, $s_{n,B}$ and $v_{n,z}$ are binary variables. Therefore, the transmitted power minimization problem is nonconvex and NP-hard. In order to solve it, a stepwise algorithm in our previous work [37] is adopted. In detail, the original problem is decoupled into three steps including user pairing (UP), power allocation (PA), sub-channel allocation (SA). Specifically, a location based UP scheme is proposed in this paper. The three steps are detailed as follows.

A. Step 1: The location based UP scheme

The performance of the multiple UAVs aided uplink NOMA cellular system is determined by the user pairing results. Aim to maximize the SE as well as the EE of the considered cellular uplinks, we propose a location based UP scheme. The UP scheme is to pair the direct GUs and the relay GUs. In general, a relay GU should be paired to a direct GU. Aiming to reduce the transmitted power of the relay GUs, according to

(6), the interference introduced by their pairs should be as low as possible. Obviously, the interference introduced by direct GUs are related to their GU-UAV channels and transmitted power. Accordingly, a variable A^d is defined to evaluate the interference level of the direct GUs and a variable A^r is defined to evaluate the channel condition of relay GUs. Under **Assumption 1**, they can be calculated as

$$A_{j,m,z}^d = (\eta_{j,m,z})^{C_A} \frac{(d_{j,B}^{UB})^{\alpha_B}}{(d_{j,m}^{UA})^{\alpha_R}} \quad (13)$$

$$A_{i,m,z}^r = \frac{(\eta_{i,m,z})^{C_A}}{(d_{i,m}^{UA})^{\alpha_R} (d_{i,B}^{UB})^{\alpha_B}} \quad (14)$$

where C_A is a configurable hyper parameter, $\eta_{j,m,z}$ is the additional attenuation factors of the sub-channel z from GU_j to UAV_m and $\eta_{i,m,z}$ is the additional attenuation factors of the sub-channel z from GU_i to UAV_m . In detail, $A_{j,m,z}^d$ is proportional to the channel gains $g_{j,m,z}^{UA}$ and the distance $d_{j,B}^{UB}$, so the larger $A_{j,m,z}^d$ is, GU_j will introduce more interference to UAV_m . Likewise, $A_{i,m,z}^r$ is proportional to the channel gains $g_{i,m,z}^{UA}$ and is inversely proportional to the distance $d_{i,B}^{UB}$, so the smaller $A_{i,m,z}^r$ is, the worse GU_i 's channel condition is.

We define a matrix \mathbb{A}^r with a size of $1 \times N/2$ to store the values of A^r between the relay GUs and their assigned UAVs. In addition, a matrix \mathbb{A}^d with a size of $M \times N/2$ is defined to store the values of A^d between the direct GUs and all the UAVs. Therefore, the proposed location based UP scheme is achieved by using two sorting steps as follows. Firstly, \mathbb{A}^r is sorted in ascending order. If the relay GUs with large A^r and direct GUs with small A^d are paired, while the relay GUs with small A^r and direct GUs with large A^d are paired, the performance of the relay GUs with high channel gains and their pairs will be selfishly optimized. To be fair, the relay GUs will select their feasible partners in the above \mathbb{A}^r order, i.e. the relay GUs with small A^r will be paired with the direct GUs with small A^d first. Secondly, when one relay GU connected to UAV_m selects its partner, the m -th row of \mathbb{A}^d can be sorted in ascending order and the first direct GU will be paired with the relay GU. Especially, the direct GUs that have been paired should be removed from \mathbb{A}^d during the following user pairing for avoiding assignment conflicts. When all the GUs have been paired together, the location based UP scheme is completed.

B. Step 2: Minimum SINR demands based PA

In order to minimize the sum transmitted power of the GUs, the transmitted power of the GUs and the UAVs on each sub-channel can be initialized based on their minimum SINR demands. Under **Assumption 1**, the initial PA of every GU pair can be computed based on (6)-(8) as follows.

$$p_{j,B,z}^{UB} = \frac{\gamma_{j,B,z}^{UB} N_o B_o}{g_{j,B,z}^{UB}} \quad (15)$$

$$p_{i,m,z}^{UA} = \frac{\gamma_{i,m,z}^{UA} N_o B_o g_{i,m,z}^{AB} (g_{j,B,z}^{UB} + g_{j,m,z}^{UA} \gamma_{j,B,z}^{UB})}{\tau \gamma_{i,m,z}^{UA} g_{a,b,z} g_{i,B,z}^{UB} g_{j,B,z}^{UB} + g_{i,m,z}^{UA} g_{i,m,z}^{AB} g_{j,B,z}^{UB}} + \frac{\tau \gamma_{i,m,z}^{UA} \gamma_{i,m,z}^{AB} N_o B_o g_{a,b,z} g_{j,B,z}^{UB} (1 + \gamma_{j,B,z}^{UB})}{\tau \gamma_{i,m,z}^{UA} g_{a,b,z} g_{i,B,z}^{UB} g_{j,B,z}^{UB} + g_{i,m,z}^{UA} g_{i,m,z}^{AB} g_{j,B,z}^{UB}} \quad (16)$$

$$p_{i,m,z}^{AB} = \frac{\gamma_{i,m,z}^{AB} N_o B_o g_{i,m,z}^{UA} g_{j,B,z}^{UB} (1 + \gamma_{j,B,z}^{UB})}{\tau \gamma_{i,m,z}^{UA} g_{a,b,z} g_{i,B,z}^{UB} g_{j,B,z}^{UB} + g_{i,m,z}^{UA} g_{i,m,z}^{AB} g_{j,B,z}^{UB}} - \frac{\gamma_{i,m,z}^{UA} N_o B_o g_{i,m,z}^{UB} (g_{j,B,z}^{UB} + \gamma_{j,B,z}^{UB} \gamma_{j,m,z}^{UA})}{\tau \gamma_{i,m,z}^{UA} g_{a,b,z} g_{i,B,z}^{UB} g_{j,B,z}^{UB} + g_{i,m,z}^{UA} g_{i,m,z}^{AB} g_{j,B,z}^{UB}} \quad (17)$$

Based on our proposed UP scheme, the channel gains between UAV and relay GUs is higher than channel gains between UAV and direct GUs, while the channel gains between BS and relay GUs is lower than channel gains between BS and direct GUs, i.e. $g_{i,m,z}^{UA} \geq g_{j,m,z}^{UA}$, $g_{i,B,z}^{UB} \leq g_{j,B,z}^{UB}$. Therefore (17) is always larger than 0 which satisfies the constraint (C6).

C. Step 3: MP algorithm based SA

According to the channel model of the relay channels in (2) and (3), it can be found that the channel gains of the relay channels have no relations to the frequency bands of the sub-channels. Therefore, according to (6) and (7), the sum rates of the relayed GUs are only determined by the interference from the direct GUs on the same sub-channels and the RSI of the UAVs. As a result, it is reasonable to just focus on the SA for the direct GUs. Accordingly, the original resource allocation problem can be simplified as a SA problem for the direct GUs. To solve this problem, a stepwise scheme is adopted.

1) *Sub-step 1*: We temporarily ignore the power constraints, (12) can be reformulated as (18) based on the initial PA results.

$$\min_{\mathbb{Z}} \sum_{n \in \Omega_S} \sum_{z=1}^{Z^T} v_{n,z} p'_{n,z}$$

s. t.

$$(C1') \quad v_{n,z} \in \{0, 1\} \quad (18)$$

$$(C2') \quad \sum_{n \in \Omega_S} v_{n,z} \leq 1$$

$$(C3') \quad \sum_{z=1}^{Z^T} v_{n,z} = Z_n$$

where Ω_S is the set of direct GUs and $p'_{n,z}$ is the total transmitted power of the n -th GU pair on sub-channel z . According to **Assumption 1**, it is easy to achieve that $p'_{j,z} = p_{j,B,z}^{UB} + p_{i,m,z}^{UA}$. Here problem (18) is solved by the message passing (MP) algorithm [37]–[39] with iterative computations, the details can be found in *Appendix A*. Under **Assumption 1**, the SA results of the relayed GUs are determined by direct GUs as follows

$$v_{i,z} = v_{j,z}. \quad (19)$$

2) *Sub-step 2*: After the step of SA, the total power consumption of the GUs and the UAVs can be computed according to (9) and (10). Since the power constraints are

removed in sub-step 1, the SA results for the GUs should be rechecked according to (C1) and (C2). Based on SIC, the interference to the direct GUs can be totally canceled at the BS, their power constraints can be independently checked without considering the access status of the relay GUs. However, the transmitted power of the relay GUs is related to the access status of the direct GUs. Besides, the transmitted power of the UAVs is dependent on the access status of both the relay GUs and the direct GUs. Therefore, it is necessary to conduct access control (AC) for the direct GUs, the relay GUs and the UAVs in sequences. Under **Assumption 1**, a soft AC scheme [37] can be considered as follows.

Firstly, if the total power of GU_j is larger than its power budget, the highest power $p_{j,B,z}^{UB}$ will be reduced and the GU_j is refused to access the corresponding sub-channel z . Then, its total power can be recomputed and rechecked again. If $p_j^U \leq p_j^{U*}$, the soft access control scheme for GU_j is finished and the present PA and SA results are regarded as the optimal results for GU_j . Otherwise, the soft access control scheme will be carried out continuously, until the power budget constraint can be satisfied.

Secondly, according to the AC results for the direct GUs, the initialized power of the relayed GUs should be rechecked. In detail, if the power of GU_j on sub-channel z is reduced, GU_i won't be interfered by GU_j and the minimum required power for GU_i on sub-channel z can be recomputed as

$$p_{i,m,z}^{UA} = \frac{\gamma_{i,m,z}^{UA} (N_o B_o + \tau g_{a,b,z} p_{i,m,z}^{AB})}{g_{i,m,z}^{UA}} \quad (20)$$

According to the updated power, the total power of GU_i can be achieved according to (9). Then the total power should be rechecked by the soft AC scheme similar to that for the direct GUs.

Thirdly, According to the AC results for the direct GUs and the relay GUs, the power of the UAVs on each sub-channel should also be updated based on (21) where $I_e = \tau \gamma_{i,m,z}^{UA} g_{a,b,z} g_{i,B,z}^{UB}$, $I_g = \gamma_{i,m,z}^{UA} g_{i,B,z}^{UB} (g_{j,B,z}^{UB} + \gamma_{j,B,z}^{UB} g_{j,m,z}^{UA})$. Based on the updated power results of the UAVs, the total transmitted power of the UAVs can be computed as in (10). Then the power budget constraint (C2) can also be rechecked for the UAVs by the soft AC scheme,

$$p_{i,m,z}^{AB} = \begin{cases} 0, & \text{if } v_{i,z} = 0; \\ \frac{\gamma_{i,m,z}^{AB} N_o B_o (g_{i,m,z}^{UA} - g_{i,B,z}^{UB})}{g_{i,m,z}^{AB} g_{i,m,z}^{UA} + I_e}, & \text{if } v_{i,z} = 1, v_{j,z} = 0; \\ \frac{N_o B_o [\gamma_{i,m,z}^{AB} g_{i,m,z}^{UA} g_{j,B,z}^{UB} (1 + \gamma_{j,B,z}^{UB}) - I_g]}{I_e g_{j,B,z}^{UB} + g_{i,m,z}^{UA} g_{i,m,z}^{AB} g_{j,B,z}^{UB}}, & \text{otherwise} \end{cases} \quad (21)$$

Additionally, since the UAVs are utilized as the relays for the relay GUs, their AC results influence the access status of the relay GUs. In detail, if $p_{i,m,z}^{AB}$ is reduced, then $u_{i,m} = 0$, $v_{i,z} = 0$ and $p_{i,m,z}^{UA} = 0$, which means GU_i is refused to use sub-channel z . After the UP, PA, SA steps, the EE and SE of the uplinks can be further optimized with the optimal PA and SA results based on multiple UAVs aided NOMA.

VI. SIMULATION RESULTS AND ANALYSIS

This section evaluates the SE and EE performances of the proposed multiple UAVs aided uplink NOMA through extensive simulations. In detail, we simulate four uplink NOMA schemes, including ground to ground (G2G) uplink NOMA without UAVs, single UAV aided uplink NOMA (single UAV), multiple UAVs aided uplink NOMA with random UAV deployment (Multi-UAV-r) and the proposed Multi-UAV-K-cluster scheme for comparisons.

In single UAV based cellular NOMA scheme, the UAV is placed above the BS with an initial height. All the GUs will compute their own A^d based on (13) and all A^d will be sorted in descending order. The first half GUs have higher A^d , thus they will be assigned to communicate with UAVs. In addition, the left GUs will be assigned to communicate with BS directly. For fairness, the first half of GUs will be paired with the last half of GUs with the sorted order for the A^d .

In multi-UAV-r scheme, M UAVs are randomly and uniformly deployed in the cell with initial heights. Same to the multi-UAV-K-cluster scheme, the heights of the UAVs will be adjusted until the UAV-BS channels are LoS. The receiver determination and user pairing are detailed as follows. We define a matrix \mathbb{A}_r^d with size of $M \times N$ to store the A^d values between M UAVs and N GUs. Firstly, every column of \mathbb{A}_r^d is sort in descending order and the UAV with largest A^d value is the best UAV for the GU to select. The number of every GU's best UAV is recorded in vector $\mathbb{I}_{1 \times N}$. Secondly, the largest A^d of every GU are sorted in descending order and the results are recorded in vector $\mathbb{K}_{1 \times N}$. Then the first half of GUs in $\mathbb{K}_{1 \times N}$ are assigned to communicate with UAVs and the other GUs communicate with the BS directly. After receiver determination, the user pairing steps are same to multi-UAV-K-cluster scheme.

For simulations, a ground cellular network is considered with a radius of 500 meters. In this cellular network, 32 GUs require uplink transmissions at the same time. In detail, these GUs are randomly and uniformly distributed within the coverage of the cellular network. Moreover, for the Multi-UAV-r scheme and the Multi-UAV-K-cluster scheme, the numbers of the UAVs are both set as $M = 4$. The initial height of the UAVs is assumed as 200 meters. The distance between antenna a and antenna b is set as $d_{ab} = 1$ m. The residual self-interference coefficient is set as $\tau = -100$ dB. The parameter values for the simulated scenario are concluded in Table. III.

Followed by the scenario considerations, the channel parameters are set as follows. At first, the total number of the available sub-channels is 32. Then the unit bandwidth of each sub-channel is 0.3125 MHz and the power spectral density of the noise is 5×10^{-20} watt/Hz. Moreover, for the large-scale fading, the path losses of the GU-UAV and the GU-BS channels are $\alpha_R = 2$ and $\alpha_B = 4$ respectively. Meanwhile, the additional attenuation factors for the LoS and NLoS channels are $\eta_{LoS} = -1$ dB and $\eta_{NLoS} = -20$ dB. Especially, we just consider an urban environment for simulating the schemes. Thus, according to [40], the LoS probability related parameters are set as $\psi = 9.6$ and $\beta = 0.16$ for the simulated urban

TABLE I: Parameter setting of the simulation scenario.

Parameters	Values
The radius of the cellular network	$R = 500$ meter
Number of GU	$N = 32$
Number of UAV	$M = 4$
Number of sub-channel	$Z^T = 32$
Unit bandwidth of each sub-channel	$B_0 = 0.3125$ MHz
The power spectral density of the noise	$N_0 = 5 \times 10^{-20}$ Watt/Hz
The path loss of GU-UAV channels	$\alpha_R = 2$
The path loss of GU-BS channels	$\alpha_B = 4$
The additional attenuation factor for the LoS channel	$\eta_{LoS} = -1$ dB
The additional attenuation factor for the NLoS channel	$\eta_{NLoS} = -20$ dB
The power budget of each UAV	$P_{UAV} = 3$ Watt
The power budget of each GU	$P_{GU} = 0.5$ Watt
The distance between two antennas of UAV	$d_{ab} = 1$ meter
The residual self-interference coefficient	$\tau = -100$ dB

TABLE II: The definition of performance criteria.

Performance Criterion	Definition
Energy Efficiency (EE) of GUs	$\sum R^U / \sum P^U$
Normalized access ratios of sub-channels	The number of sub-channels used by UAVs and GUs)/ Z^T

environment. Furthermore, the power budgets of each UAV and each GU are set as 3 watt and 0.5 watt. For simplicity, the simulated QoS demands of all the GUs are equally considered as $\gamma_n^{U*} = \gamma^*$, $R_n^{U*} = R^*$ and $Z_n = 2$, $\forall n \in \{1, \dots, N\}$. The simulation performances have been averaged by 3,000 Monte Carlo experiments and the definitions of the critical performances are given in Table. II.

Firstly, Fig. 3 shows the EE performance of the four schemes in term of the varying SINR target of the GUs. Also it shows that both the Multi-UAV-r scheme and the Multi-UAV-K-cluster scheme significantly outperform the single UAV scheme and G2G scheme, especially with a low GUs' SINR target. It can be explained according two reasons. One reason is that most of the GU-UAV channels are LoS channels which demand dramatically low power for the GUs to transmit information under the same SINR targets. Another reason is that benefitting from the high channel gains of the GU-UAV channels, the BS is able to remove the interference from the direct GUs perfectly with SIC, which increases the normalized access ratio for the sub-channels.

Apart from the conclusions above, from Fig. 3 it can also be observed that the Multi-UAV-K-cluster scheme always outperforms Multi-UAV-r scheme. It can be explained that, for the Multi-UAV-K-cluster based UAV deployment scheme, the UAVs are placed on more accurate locations for relay GUs than under the random UAV deployment. Accordingly, the relay GUs will have much higher channel gains to the UAVs based on K-means clustering.

Moreover, with the increasing of the GUs' SINR target, the EE performances of all the schemes degrade significantly. It is reasonable since the sum power of GUs increases to satisfy

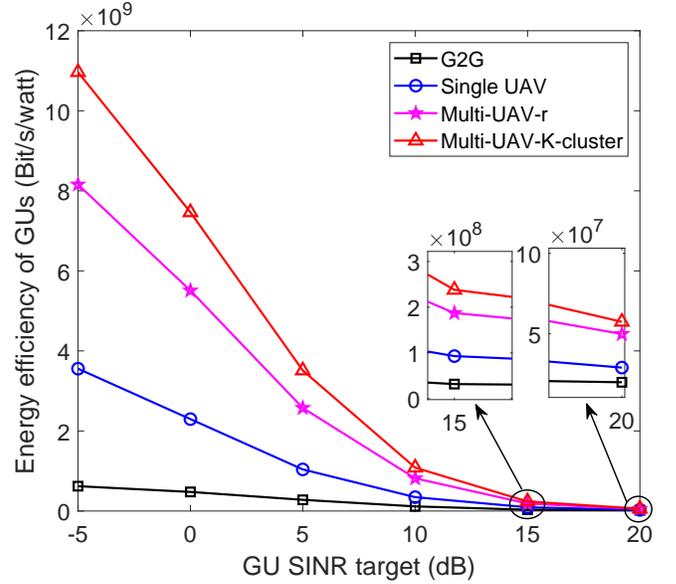


Fig. 3: The EE performance of GUs in term of GUs' SINR target.

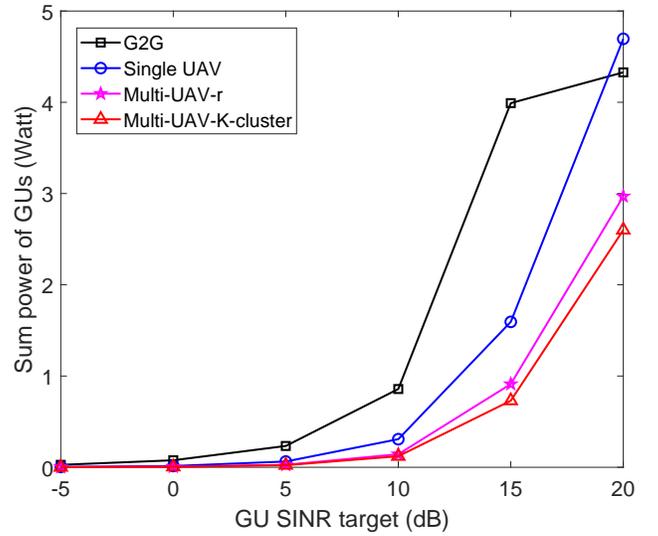


Fig. 4: The sum power of the GUs in term of GUs' SINR target.

the QoS of the GUs. Then, it definitely introduces higher interference to the relay GUs and causes decrease drop of the normalized access ratios for the sub-channels. Fig. 4 shows the sum transmitted power of GUs in term of GUs' SINR target. From Fig. 4 we can see that the transmitted power of GUs increases with the GUs' SINR target increases. And under Multi-UAV-K-cluster scheme, GUs demand lowest transmitted power. Especially, the sum power of the GUs decreases in the G2G scheme when the GUs' SINR target exceeds 15dB. It is due to the reason that the co-channel interference is too high to enable the paired GUs to share the sub-channels with the G2G scheme. Fig. 5 shows the normalized access ratios of sub-channels in term of GUs' SINR target. It shows that

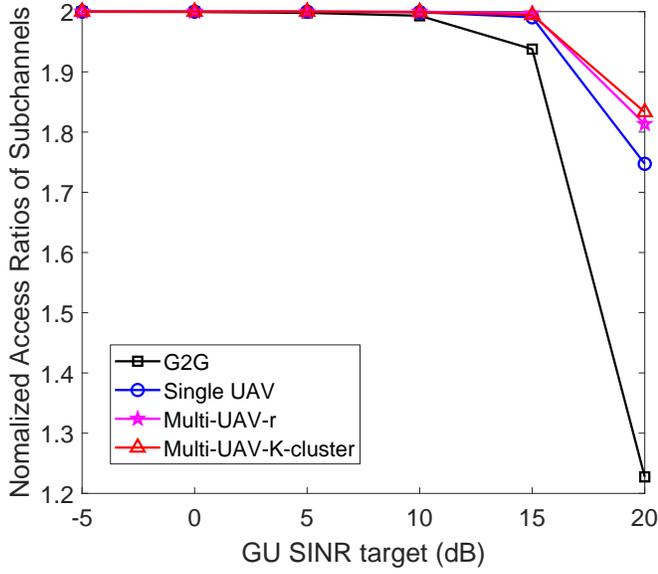


Fig. 5: Normalized access ratios of subchannels in term of GUs' SINR target.

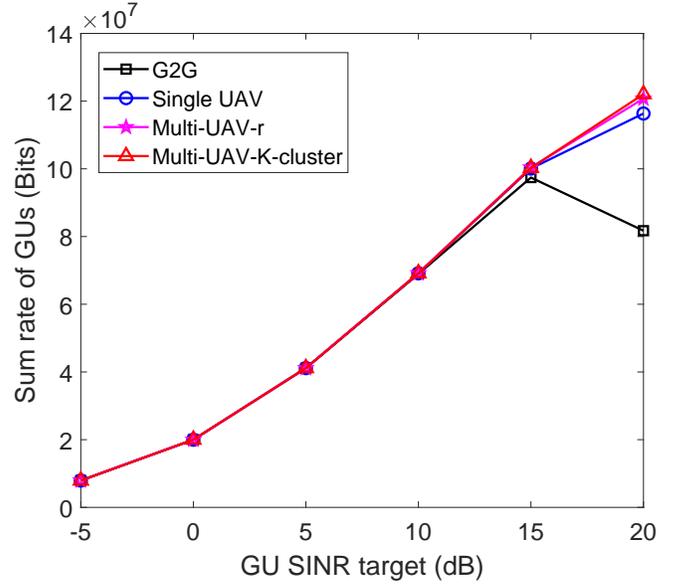


Fig. 7: The sum rate of the GUs in term of GUs' SINR target.

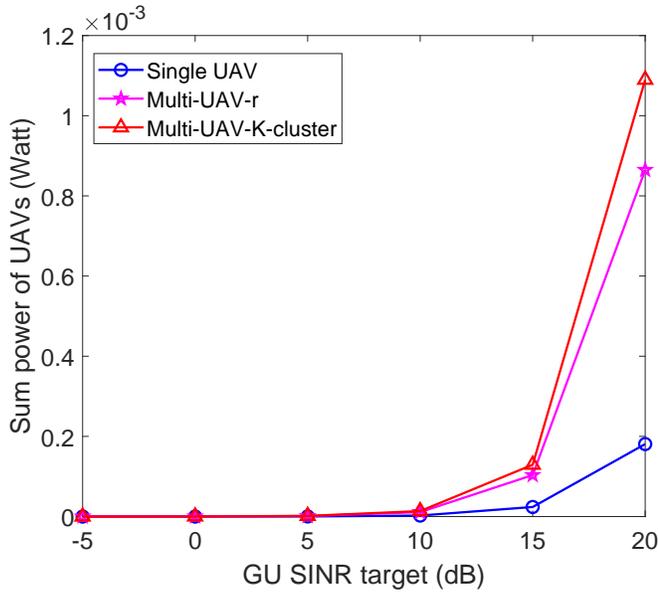


Fig. 6: The sum power of UAVs in term of GUs' SINR target.

when the GUs' SINR target exceeds 15 dB, the normalized access ratios of sub-channels under G2G scheme decrease dramatically, while that under Multi-UAV-K-cluster scheme still keep high level.

Furthermore, in order to evaluate the feasibility of the proposed multiple UAVs aided uplink NOMA, the sum power of the UAVs has been simulated and the corresponding result is depicted in Fig. 6. Compared with the results in Fig. 4, it can be found that the sum power of the UAVs is much less than that of the GUs. As a result, the proposed schemes can achieve higher EE and SE for the uplinks with a limited power cost of the UAVs.

TABLE III: The number of UAVs used in multi-UAV-K-cluster scheme under $M = 4$.

The number of UAVs actually used	Count	Percent(%)
3	245	8.2
4	2755	91.8

In Fig. 7, the sum rates of the GUs are simulated in term of the GUs' SINR target. Since we consider a sum power minimization based resource allocation strategy with the lowest QoS constraints, the sum rates of the GUs in the four schemes are same under low GUs' SINR targets (i.e. -5 dB and -10 dB). When the GUs' SINR targets are larger than 15dB, the sum rate of the proposed multi-UAV-K-cluster scheme still increases with the increase of the GUs' SINR targets. However, the sum rate of the GUs in the single UAV scheme decrease slightly and that of G2G scheme decrease significantly. This is due to the fact that under high GUs' SINR target, high channel gains for the GU-UAV channels and UAV-BS channels can still resist the interference introduced by direct GUs successfully without exceeding the power budgets of GUs.

Besides the outstanding performance in EE and SE, another advantage of the proposed multi-UAV-K-cluster scheme is that when the GUs' locations are relatively concentrated, the actual number of the clusters might be less than the number of the UAVs. In this case, less UAVs can be occupied to serve the GUs with no loss of the system SE and EE. When the number of UAVs is set as $M = 4$, among 3,000 Monte Carlo experiments, there are 245 times of the simulations accomplished the transmission by using 3 UAVs, see Table. III.

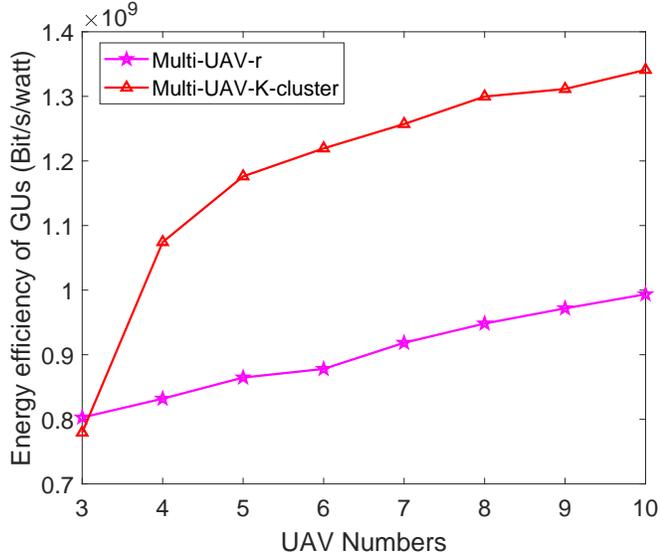


Fig. 8: The EE performance of GUs in term of the number of UAVs when the GUs' SINR target is 10dB.

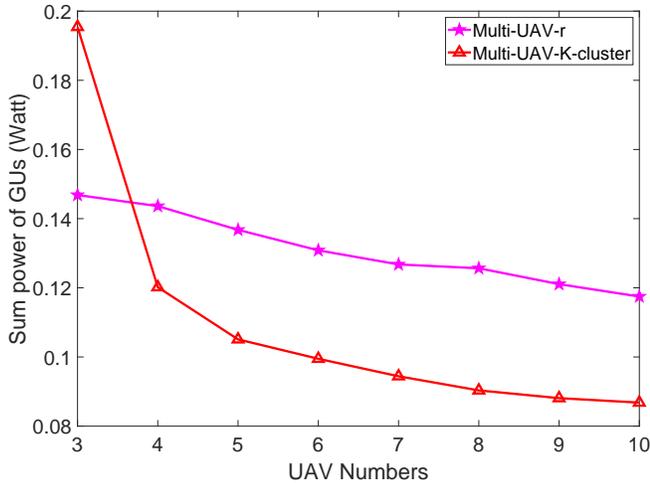


Fig. 9: The sum power of GUs in term of the number of the UAVs when the GUs' SINR target is 10dB.

After comparing the EE and the SE performances of the uplinks with the four schemes, we investigate multiple performances of the proposed multiple UAVs aided uplink NOMA technology in term of the UAVs' number. For saving space, we just investigate them when the GUs' SINR target is 10 dB. On the EE performance, Fig. 8 shows its changing tendency with the growth of the UAVs' number. Fig. 8 demonstrates that the uplink EEs for both the Multi-UAV-r scheme and the multi-UAV-K-cluster scheme continuously get higher when the UAVs' number increases. It is reasonable that the more the UAVs are, the better the GU-UAV channels can be. With the GU-UAV channels become better, the transmitted power of relay GUs will be lower under the same GUs' SINR targets. As a result, the interference introduced to direct GUs by relay GUs will be smaller under above case, which will make direct GUs consume less transmitted power and will

enhance the EE of the system. Therefore, the sum power of the GUs is also decreasing with the number of the UAVs increases. Fig. 9 shows the sum transmitted power of GUs in term of the number of UAVs. From Fig. 9 we can obtain that the sum transmitted power of GUs decreases with the number of UAVs increases.

Fig. 8 and Fig. 9 demonstrate that the Multi-UAV-K-cluster scheme significantly outperforms the Multi-UAV-r scheme because of its accurate UAV deployment by using the GUs' location information. Besides, the Multi-UAV-K-cluster scheme achieves the outperformance with the optimized UAV number. Table. III shows the number of actually used UAVs when $M = 4$. To be more concise, the average number of the actually used UAVs from the 3,000 Monte Carlo experiments for two multiple UAVs schemes in term of the number of UAVs are depicted in Fig. 10. From this figure, we can obtain that the Multi-UAV-K-cluster scheme can achieve better performances with less UAVs. When the number of the available UAVs is more than 6, the multi-UAV-K-cluster scheme uses one less UAVs than multi-UAV-r scheme statistically.

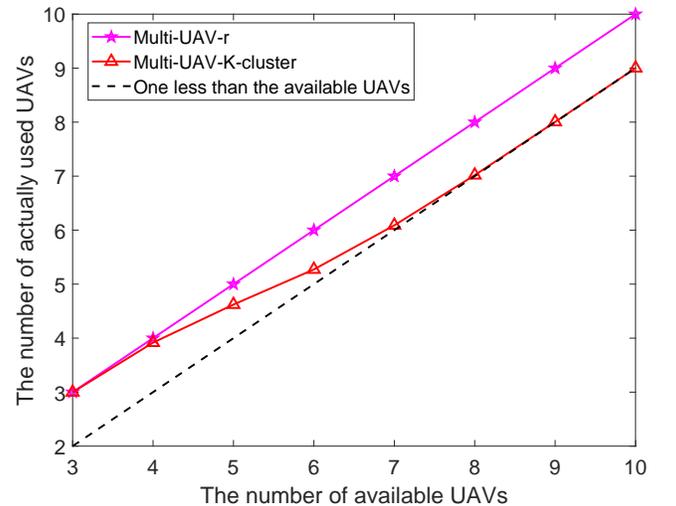


Fig. 10: The average number of the actually used UAVs in term of the number of available UAVs.

VII. CONCLUSION

This paper proposed a multiple UAVs aided uplink NOMA technology to improve the energy efficiency and spectral efficiency of the GUs' uplink transmission in cellular networks. Moreover, a multi-UAV-K-cluster based UAV deployment scheme and a location based user pairing scheme have been developed to optimize the performances of the multiple UAVs aided uplink NOMA. Furthermore, a sum power minimization based resource allocation scheme was formulated to evaluate the performance of the optimized uplink transmissions based on the proposed schemes. At last, exhaustive experiments were conducted for comparing the proposed multiple UAVs aided NOMA scheme with the single UAV aided NOMA scheme and traditional NOMA with no helps from the UAVs. Simulation results confirmed that the

proposed multiple UAVs aided NOMA significantly improves the energy efficiency and spectral efficiency of the GUs' uplinks with the optimized deployment, pairing and resource allocation schemes.

APPENDIX A

In our problem, the iterative message passing process is as follows

$$\mu_{n,z}^{(t+1)} = p'_{n,z} - \rho_n \{ \mu_{f,n}^{(t)} + p'_{n,z} \} Z_n^{\text{th}} - (1 - \rho_n) (p'_{n,z} + \mu_{z,n}^{(t)}), f \neq z \quad (22)$$

$$\mu_{z,n}^{(t+1)} = -\rho_n \min_{l \neq n} \mu_{l,z}^{(t+1)} - (1 - \rho_n) \mu_{n,z}^{(t+1)} \quad (23)$$

$$\tau_{n,z}^{(t)} = \mu_{z,n}^{(t)} + \mu_{n,z}^{(t)} \quad (24)$$

$$v_{n,z} = \begin{cases} 1 & \text{if } \tau_{n,z}^{(t)} < 0 \\ 0 & \text{otherwise} \end{cases} \quad (25)$$

$$v_{n,z}^T = v_{n,z}^{T-1}, \forall n, z \quad (26)$$

The process from (22) to (25) will iterate continuously until (26) is satisfied at the T time, when the optimal SA result is obtained for the GU_n . In detail, ρ_n is a weight for formulating the messages and $\{ \mu_{f,n}^{(t)} + p'_{n,f} \} Z_n^{\text{th}}$ denotes the Z_n -th value of $\mu_{f,n}^{(t)} + p'_{n,f}$ when it is sorted in ascending order with the constraint condition of $f \neq z$. In general, the message $\mu_{n,z}$ from GU_n to sub-channel z and the message $\mu_{z,n}$ from sub-channel z to GU_n are initialized by $\mu_{n,z}^0 = 0$ and $\mu_{z,n}^0 = 0$, respectively.

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