Optimization of Transmission Power for NOMA in Networks with Flying Base Stations

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***Abstract*—Deployment of unmanned aerial vehicles (UAVs) as flying base stations (FlyBSs) is considered as an efficient tool to enhance capacity of mobile networks and to facilitate communication in emergency cases. The improvement provided by such network requires a dynamic positioning of the FlyBSs with respect to the mobile users. In this paper, we focus on an optimization of transmission power of the FlyBS in networks with non-orthogonal multiple access (NOMA). We propose a solution jointly positioning the FlyBS and selecting the optimal grouping of users for NOMA in order to minimize the FlyBS's transmission power under the constraint on guaranteeing a minimum required capacity for the mobile users. Moreover, we derive the grouping of users corresponding to the optimal transmission power in a low-degree polynomial time, which makes it suitable for real-time applications. According to the simulations, the proposed method brings up to 31% of FlyBS's transmission power saving compared to existing solutions.**

***Index Terms*—Flying base station, Non-orthogonal multiple access, user grouping, transmission power, mobile users, mobile networks, 6G.**

I. Introduction

Unmanned aerial vehicles (UAVs) acting as flying base stations (FlyBSs) provide a promising way to address various concerns in mobile networks. Due to their high mobility, the FlyBSs present exclusive features, such as adaptability to the network topology and to the actual users' requirements, in comparison to conventional static base stations. These advantages make the FlyBSs an efficient solution for multiple practical applications including surveillance and monitoring [1], data traffic management [2], emergency missions [3], network coverage enhancement [4], data gathering of IoT devices [5], or improvement in users' quality of service [6].

In our previous works ([7], [8]), we study the problem of power optimization for the FlyBS serving moving users and we provide a joint power control and FlyBS's positioning for orthogonal multiple access (OMA) in the mobile networks. In this paper, we focus on the FlyBS's positioning and transmission power consumption for non-orthogonal multiple access (NOMA).

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Non-orthogonal multiple access (NOMA) is considered as a promising and suitable technique for future mobile networks. NOMA provides a high spectral efficiency by including superposition coding at the transmitter and successive interference cancellation (SIC) decoding at the receivers [9]. Thus, unlike OMA, NOMA enables to group multiple users into clusters and serve the users in the same cluster at the same time-frequency resources with a separation in a power domain ([10], [11], [12]). Consequently, NOMA increases throughput and spectral efficiency with respect to OMA [6].

Key challenges related to NOMA include fairness control [13], throughput improvement [14], resource allocation [11], network coverage [15], and user pairing or grouping [11], [12]. These key challenges are even emphasized and extended when NOMA is integrated to the networks with FlyBSs. For example, the grouping schemes provided for the networks with static base stations consider instantaneous gains of the users' channels as a criteria to find the user grouping [11], [12]. However, these methods are not suitable for the networks with FlyBS, as the next position of FlyBS is determined based on the current pairing/grouping, while the selected grouping is based on the current position of the FlyBS.

A full exploitation of NOMA together with the FlyBSs' characteristics requires a precise positioning of the FlyBSs, advanced resource allocation, interference control, and grouping of the users for NOMA and SIC in order to efficiently deal with the challenges mentioned above.

In [16], the authors study the coverage in the network with two static ground users served by the FlyBS. Adopting a fading channel model, the authors provide a combination of NOMA and OMA transmission modes to reduce an outage probability of the ground users. However, the positioning of the FlyBS (trajectory) is not optimized. Then, in [15], the authors determine an altitude of the FlyBS serving also only two static ground users in the network with NOMA to maximize Jain's fairness index. The paper [15] is extended in [14] by a power allocation and a determination of the FlyBS's altitude to maximize the sum capacity of two static ground users. Nevertheless, the x and y coordinates of the FlyBS are fixed. Thus, the flexibility in a spatial deployment offered by the FlyBSs is not fully exploited. Furthermore, in [17], the authors provide a resource allocation algorithm for NOMA with one FlyBS acting as a relay to maximize the throughput in a scenario with, again, only two static ground users. We note that, since there is only one pair of users in the system model, the problem of user pairing/grouping is not inclusively studied by any of the works in [14]-[17], and none of these works provide a concrete paring/grouping for multiple users.

In [10], a heuristic solution for a joint user grouping and positioning of the FlyBS is proposed to improve the sum capacity. The grouping of users for NOMA is limited to only two users (i.e., pairing of users) and its generalization to the grouping of more than two users is not straightforward. Moreover, the provided solution is sub-optimal and loses performance as the number of users increases.

To the best of our knowledge, a study of the transmission power consumption and an analysis of the user grouping for NOMA in networks with FlyBSs is not investigated in the literature. However, the transmission power consumption affects the coverage and, hence, should not be ignored. This is supported by many works focused on the transmission power consumption of the FlyBSs for a variety of OMA scenarios ([6]-[8]). Moreover, due to limitations on a maximum transmission power of the FlyBSs, the FlyBS might fail to satisfy the minimum required capacity for the users. Thus, a solution reducing the transmission power is necessary to enhance the users' coverage reliability. In NOMA, the transmission power becomes even more critical aspect, as adopting an inefficient grouping scheme can lead to a very high transmission powers beyond the limit of the FlyBS.

In this paper, we focus on the problem of the FlyBS's transmission power optimization in NOMA networks. We formulate the problem of the transmission power minimization with a constraint on a minimum guaranteed capacity for all mobile users. We analytically provide an optimum strategy for the grouping of users for NOMA and we determine related optimum position of the FlyBS to minimize the transmission power. The proposed solution is of a very low complexity (low degree polynomial) and, thus, can be applied in real networks. We show that our proposed solution reduces the transmission power consumption by up to 31% compared to existing solutions

The rest of the paper is organized as follow. In Section II, we present the system model and formulate the problem of transmission power optimization via the grouping of users for NOMA and FlyBS's positioning. The proposed solution for the transmission power optimization is introduced and thoroughly described in Section III. The performance of the proposed solution and comparison with the performance of existing solutions is discussed in Section IV. Last section concludes the paper and outlines future research directions.

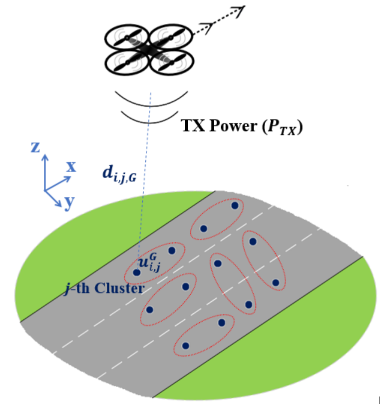

Fig. 1: System model with multiple mobile users (blue dots) deployed within coverage area of the FlyBS and grouped into clusters (red circles) for NOMA purposes.

II. System model and problem formulation

In this section we first define the system model by explaining users grouping in non-orthogonal transmission model, and SIC decoding in the network with FlyBS, and we also provide details about the transmission power modeling. Then, we formulate the transmission power optimization problem.

A. System Model

We consider one FlyBS serving N_u mobile users $U = \{u_1, u_2, \ldots, u_{N_u}\}$ in an area as shown in Fig. 1. The users are moving along the same direction similar to, e.g., vehicles on a road or a highway. Without a loss of generality, we assume the movements are aligned with the x-axis to simplify notations and explanation of the idea. All N_u users in the area communicate directly with the FlyBS.

Let $\{X(t), Y(t), H(t)\}$ denote the location of the FlyBS at the time t. We assume that the altitude of the FlyBS is fixed at $H(t) = H$ as in many previous related works (e.g., [8], [10], [17], [18]). Furthermore, let $\{x_{i,j}^G(t), y_{i,j}^G(t)\}$ denote the coordinates of the i-th user at the time t. Note that we consider mobile users, and so the coordinates of the users as well as of the FlyBS change over time. As commonly expected in related works, we also assume that the current positions of the users are known to the FlyBS (see, e.g., [14], [18]). Also, the FlyBS can determine its own position as the knowledge of the FlyBS's position is needed for a common flying and navigation of the FlyBSs ([17]).

In non-orthogonal transmission, the users are grouped into clusters such that all users in each cluster share the same bandwidth at the same time. Thus, the data transmission to the users in the same cluster imposes an interference (referred to as intra-cluster interference). However, there is no interference among different clusters.

Let $\mathbb{G}$ denote the space of all possible functions that group the users into N_{cl} clusters with N_{cu} users in each cluster, (hence, $N_u = N_{cl} \times N_{cu}$). Each function $G \in \mathbb{G}$ is defined as a bijective mapping G: $\langle 1, N\rangle \rightarrow \langle 1, N_{cl}\rangle \times \langle 1, N_{cu}\rangle$. More specifically, the function G assigns the user u_n as the n_{cu}-th user in the n_{cl}-th cluster if $G(n) = (n_{cl}, n_{cu})$ for the given n. We refer to n_{cu} and n_{cl} as the index of the user in the cluster and the index of the cluster, respectively. Let $u^G_{1,j}, u^G_{2,j}, \ldots, u^G_{N_{cu},j}$ denote the clustered users in the j-th cluster $(1 \leq j \leq N_{cl})$ that is determined by the grouping function G.

For SIC in non-orthogonal transmission, canceling the strong interferences in each cluster is a more efficient approach than canceling the weak interferences, in the sense that the total transmission power to satisfy the minimum required capacity of all users is lower in the first approach [12]. In the following we define model for the SIC regardless of the different signals' strengths, and only based on the users' indices within each cluster. This assumption helps to solve the problem in a simpler way and without loss of generality, as we find the minimum transmission power among all possible grouping options.

Suppose that, by applying SIC, the user $u^G_{i,j}$ in the j-th cluster $(1 \leq i \leq N_{cu} - 1)$ cancels the interfering signals from the user i' in the same cluster (i.e., $u^G_{i',j}$) for $i+1 \leq i' \leq N_{cu}$ to extract its own signal. As a result of this, the achievable SINR $\gamma^G_{i,j}, (1 \leq i \leq N_{cu})$ for the user $u^G_{i,j}$ is expressed as:

$$\begin{gathered}\gamma^G_{1,j} = \frac{p^{G,R}_{1,j}}{\sigma^2}, \\ \gamma^G_{1,j} = \frac{p^{G,R}_{1,j}}{\sigma^2 + \sum_{l=1}^{i-1} p^{j,R}_{i,l,j}}, \\ (1 \leq i \leq N_{cu})\end{gathered} \tag{1}$$

where $p^{j,R}_{i,l,G}$ denotes the received signal power of the user $u^j_{l,G}$, and σ^2 denotes the noise's power. Now let $C^G_{i,j}$denote the channel capacity of the user $u^G_{i,j}$. According to the Shannon–Hartley theorem, the channel capacity $C^G_{i,j}$ is defined as:

$$C^G_{i,j} = B\log_2(1 + \gamma^G_{i,j}), \tag{2}$$

where B is the bandwidth assigned to each user and each cluster. Following [11], the channel's bandwidth as well as the noise's power are assumed to be equal for all clusters. The total transmission power of the FlyBS at the time t_k is expressed as:

$$P_{TX}(X, Y, H, t_k, G) = \sum_{j=1}^{N_{cl}} \sum_{i=1}^{N_{cu}} p^{j,T}_{i,G}, \tag{3}$$

where $p^{j,T}_{i,G}$ is the transmission power of the FlyBS to the $u^G_{i,j}$. According to the Friis' transmission equation, $p^{G,T}_{i,j}$ is determined as:

$$\begin{gathered}p^{j,T}_{i,G} = \frac{(4\pi f)^2}{D^{j,T}_{i,G} D^{j,R}_{i,G} c^2} p^{j,R}_{i,G} d^2_{i,j,G}, \\ 1 \leq i \leq N_{cu}, 1 \leq j \leq N_{cl},\end{gathered} \tag{4}$$

where $p^{j,R}_{i,G}$ is the received signal power by the user $u^G_{i,j}$, $\mathrm{D}^{j,T}_{i,G}$ is the gain of the FlyBS's antenna, $D^{j,R}_{i,G}$ is the gain of the user's antenna, $d_{i,j,G}$ is the distance between the FlyBS and the user $u^G_{i,j}$, f is the communication frequency, and $c = 3 \times 10^8$ m/s is the speed of light. The coefficient $\frac{(4\pi f)^2}{D^{j,T}_{i,G} D^{j,R}_{i,G} c^2}$ is substituted by Q in the rest of the paper for clarity and simplicity of the discussions. Using (4), the total transmission power of the FlyBS is rewritten as:

$$P_{TX}(X, Y, H, t_k, G) = \sum_{j=1}^{N_{cl}} \sum_{i=1}^{N_{cu}} Q p^{j,R}_{i,G} d^2_{i,j,G}, \tag{5}$$

By expanding (5) with the coordinates of the users and the FlyBS, we get:

$$\begin{gathered}P_{TX}(X, Y, H, t_k, G) = \\ \sum_{j=1}^{N_{cl}} \sum_{i=1}^{N_{cu}} Q p^{j,R}_{i,G} ((X(t_k) - x^G_{i,j}(t_k))^2 + (Y(t_k) - y^G_{i,j}(t_k))^2 + H(t_k)^2).\end{gathered} \tag{6}$$

B. Problem Formulation

Our goal is to find the position of the FlyBS jointly with the clustering of the users for NOMA purposes to minimize the transmission power of the FlyBS while guaranteeing a minimum capacity for the users. We formulate the joint problem of the transmission power minimization and users' clustering as:

$$\begin{aligned}&[G_{opt}, [X_{opt}(t_k), Y_{opt}(t_k)]] = \underset{[G,[X(t_k),Y(t_k)]]}{\operatorname{argmin}} P_{TX}, \forall k \\ &s.t. \quad C^G_{i,j}(t_k) \geq C_{min}, \forall j \in \langle 1, N_{cl} \rangle, \forall j \in \langle 1, N_{cu} \rangle, \forall k,\end{aligned} \tag{7}$$

where the constraint guarantees that every user receives at least the minimum required capacity C_{min} all the time. In line with [11], the minimum capacity is assumed to be the same for all the users. We note that, similar to many works (e.g., [14]-[17]) we do not consider the power consumption due to the FlyBS's movement (known as propulsion power). The problem of power optimization including the propulsion power is left for future work due to page limit of this paper.

III. Proposed optimal grouping of users for NOMA and positioning of FlyBS

In this section, we provide a novel method to solve (7) by finding the optimal grouping function G_{opt} as well as the optimal FlyBS's positions $[X_{opt}(t_k), Y_{opt}(t_k)]$ over time. From the definition of grouping, there are $\frac{N_u!}{N_{cl}!}$ different grouping options (grouping options that are obtained by switching the label (index) of clusters are considered the same). Thus, the number of options becomes extremely large for realistic values of N_u (it is about 17.2 million options even for only 14 users). This motivates us to find an analytical solution to grouping.

We start by deriving the conditions that yield the minimum transmission power, and then we find the position of FlyBS corresponding to the minimum transmission power. From the constraint in (7) and using (2), it is inferred that:

$$\gamma^G_{i,j} \geq \gamma_{min}, \tag{8}$$

where $\gamma_{min} = (2^{C_{min}/B} - 1)$ is a positive constant. Then, from (1), we rewrite (8) as:

$$\frac{p_{1,j}^{G,R}}{\sigma^2} \geq \gamma_{min}, \frac{p_{i,j}^{G,R}}{\sigma^2 + \sum_{l=1}^{i-1} p_{i,l,j}^{G,R}} \geq \gamma_{min}, \quad (2 \leq i \leq N_{cu}, 1 \leq j \leq N_{cl}). \tag{9}$$

Using (9), we find the conditions to reach the minimum transmission power as follows. Equation (9) is rewritten using (4) as:

$$\frac{\frac{p_{1,j}^{G,T}}{Qd_{1,j,G}^2}}{\sigma^2} \geq \gamma_{min}, \frac{\frac{p_{i,j}^{G,T}}{Qd_{i,j,G}^2}}{\sigma^2 + \frac{\sum_{l=1}^{i-1} p_{l,j}^{G,T}}{Qd_{i,j,G}^2}} \geq \gamma_{min} \quad (2 \leq i \leq N_{cu}, 1 \leq j \leq N_{cl}). \tag{10}$$

After several simple math operations, (10) is transformed to (assuming $\sum_1^0$ is equal to 0):

$$\gamma_{min} \sum_{l=1}^{i-1} p_{l,j}^{G,T} + \gamma_{min} Q d_{i,j,G}^2 \sigma^2 \leq p_{i,j}^{G,T}, \quad (1 \leq i \leq N_{cu}, 1 \leq j \leq N_{cl}). \tag{11}$$

Therefore, by writing down (11) for every $j \in \langle 1, N_{cl} \rangle$ and for all $i \in \langle 1, N_{cu} \rangle$, we get

$$\sum_{j=1}^{N_{cl}} \sum_{i=1}^{N_{cu}} p_{i,G}^{j,T} \leq \gamma_{min} Q \sigma^2 \sum_{j=1}^{N_{cl}} \sum_{i=1}^{N_{cu}} ((1+\gamma_{min})^{N_{cu}-i}) d_{i,j,G}^2. \tag{12}$$

The minimum in (12) is achieved when the equality in (11) holds for $1 \leq i \leq N_{cu}$, and $1 \leq j \leq N_{cl}$, that is, if:

$$\gamma_{min} \sum_{l=1}^{i-1} p_{l,j}^{G,T} + \gamma_{min} Q d_{i,j,G}^2 \sigma^2 = p_{i,j}^{G,T}, \quad (1 \leq i \leq N_{cu}, 1 \leq j \leq N_{cl}). \tag{13}$$

Hence, from (13), we derive $P_{TX}(X, Y, H, t_k, G)$ as:

$$\begin{aligned} P_{TX}(X, Y, H, t_k, G) &= \gamma_{min} Q \sigma^2 \sum_{j=1}^{N_{cl}} \sum_{i=1}^{N_{cu}} ((1+\gamma_{min})^{N_{cu}-i}) d_{i,j,G}^2 = \\ &\sum_{j=1}^{N_{cl}} \sum_{i=1}^{N_{cu}} ((1+\gamma_{min})^{N_{cu}-i})((X(t_k) - x_{i,j}^G(t_k))^2 + \\ &(Y(t_k) - y_{i,j}^G(t_k))^2 + H(t_k)^2). \end{aligned} \tag{14}$$

From (14), the FlyBS's position to achieve the minimum transmission power is derived for each grouping function G by evaluating the transmission power at its critical point(s). Thus, by solving equations $\frac{\partial P_{TX}}{\partial X} = 0$ and $\frac{\partial P_{TX}}{\partial Y} = 0$ with P_{TX} defined in (14), we get the following critical point:

$$X_{opt}^G = \frac{\sum_{j=1}^{N_{cl}} \sum_{i=1}^{N_{cu}} ((1+\gamma_{min})^{N_{cu}-i} x_{i,j}^G)}{\sum_{j=1}^{N_{cl}} \sum_{i=1}^{N_{cu}} ((1+\gamma_{min})^{N_{cu}-i})}, \quad Y_{opt}^G = \frac{\sum_{j=1}^{N_{cl}} \sum_{i=1}^{N_{cu}} ((1+\gamma_{min})^{N_{cu}-i} y_{i,j}^G)}{\sum_{j=1}^{N_{cl}} \sum_{i=1}^{N_{cu}} ((1+\gamma_{min})^{N_{cu}-i})}. \tag{15}$$

Knowing the coordinates X_{opt}^G and Y_{opt}^G and considering the definition of the total transmission power in (14), the corresponding minimum transmission power is determined by plugging (15) into (14). After a few simple math operations, the minimum transmission power corresponding to the grouping function G is rewritten as:

$$P_{TX}^{min}(G) = P_{TX}(X_{opt}^G, Y_{opt}^G, H, t_k, G) = \gamma_{min} Q \sigma^2 N_u H^2 + \gamma_{min} Q \sigma^2 (\delta_x^G + \delta_y^G), \tag{16}$$

where

$$\begin{aligned} \delta_x^G &= -\frac{(\sum_{j=1}^{N_{cl}} \sum_{i=1}^{N_{cu}} ((1+\gamma_{min})^{N_{cu}-i}) x_{i,j}^G)^2}{\sum_{j=1}^{N_{cl}} \sum_{i=1}^{N_{cu}} ((1+\gamma_{min})^{N_{cu}-i})} + \sum_{j=1}^{N_{cl}} \sum_{i=1}^{N_{cu}} ((1+\gamma_{min})^{N_{cu}-i} {x^2}_{i,j}^G), \\ \delta_y^G &= -\frac{(\sum_{j=1}^{N_{cl}} \sum_{i=1}^{N_{cu}} ((1+\gamma_{min})^{N_{cu}-i}) y_{i,j}^G)^2}{\sum_{j=1}^{N_{cl}} \sum_{i=1}^{N_{cu}} ((1+\gamma_{min})^{N_{cu}-i})} + \sum_{j=1}^{N_{cl}} \sum_{i=1}^{N_{cu}} ((1+\gamma_{min})^{N_{cu}-i} {y^2}_{i,j}^G). \end{aligned} \tag{17}$$

We note that for the movement in line with the system model, i.e., a crowd of users (e.g., vehicles) moving along the street in the direction of x-axis, the value of δ_x^G is significantly larger than δ_y^G in a system of vehicles at a road or a highway. This is mainly because δ_x^G and δ_y^G can be interpreted as a weighted sample variance of the x and y coordinates of the users' locations, respectively, and the range of x-coordinates corresponding to the vehicles is much larger than the range of y-coordinates (we do not show further details due to page limit). Therefore, we find the optimal grouping function by minimizing δ_x^G.

To minimize δ_x^G, we first derive an optimal grouping function G_{opt} via Theorem 1, that provides a necessary condition for G_{opt}.

Theorem 1. *Suppose that before grouping of users into clusters, the x-coordinates of the users are sorted as $X_{sorted} = \{x_{l_1}, \ldots, x_{l_{N_u}}\}$, such that $x_{l_1} < \ldots < x_{l_{N_u}}$. Then, for the grouping function that minimizes δ_x^G (i.e., the optimal grouping), the first users in each cluster (i.e., the users $x_{1,1}^{G_{opt}}, x_{1,2}^{G_{opt}}, \ldots, x_{1,N_{cl}}^{G_{opt}}$ should be N_{cl} consecutive users in the sorted sequence X_{sorted}, i.e., $\{x_{1,1}^{G_{opt}}, x_{1,2}^{G_{opt}}, \ldots, x_{1,N_{cl}}^{G_{opt}}\} = \{x_{l_r}, x_{l_{r+1}}, \ldots, x_{l_{r+N_{cl}-1}}\}$ for some $r \in \langle 1, N_u - N_{cl} + 1 \rangle$. Furthermore, the second users of each cluster (i.e., $x_{2,1}^{G_{opt}}, x_{2,2}^{G_{opt}}, \ldots, x_{2,N_{cl}}^{G_{opt}}$ should be N_{cl} consecutive users in the sorted sequence $X_{sorted} \backslash \{x_{1,1}^{G_{opt}}, x_{1,2}^{G_{opt}}, \ldots, x_{1,N_{cl}}^{G_{opt}}\}$, and so on and so forth for the rest of the users of all groups.*

Proof. We prove Theorem 1 using mathematical contradiction as follow: Suppose that $\{x_{1,1}^{G_{opt}}, x_{1,2}^{G_{opt}}, \ldots, x_{1,N_{cl}}^{G_{opt}}\} = \{x_{i_1}, \ldots, x_{i_{N_{cl}}}\}$ with $x_{i_1} < \ldots < x_{i_{N_{cl}}}$. Then, by contradiction, we assume that the users in $\{x_{i_1}, \ldots, x_{i_{N_{cl}}}\}$ are not consecutive in X_{sorted} and there exists x_j such that $x_{i_1} < x_j < x_{i_{N_{cl}}}$ and $x_j \notin \{x_{i_1}, \ldots, x_{i_{N_{cl}}}\}$ Also, we assume that, for G_{opt} , x_j is the s-th user in some cluster ($s > 1$).

Let G_1 denote the grouping function that is obtained by swapping x_{i_1} and x_j in G_{opt}. Similarly, G_2 denotes the grouping obtained by swapping $x_{i_{N_{cl}}}$ and x_j in G_{opt}. From the optimality of G_{opt} it is inferred that:

$$\begin{aligned} \delta_x^{G_{opt}} - \delta_x^{G_1} < 0, \\ \delta_x^{G_{opt}} - \delta_x^{G_2} < 0. \end{aligned} \tag{18}$$

Now, we rewrite the left-hand side terms in (18) in terms of the system parameters as follow:

$$\begin{aligned} \delta_x^{G_{opt}} - \delta_x^{G_1} = (x_{i_1} - x_j)((1+\gamma_{min})^{N_{cu}-1}x_{i_1} + (1+\gamma_{min})^{N_{cu}-1}x_j \\ -(1+\gamma_{min})^{N_{cu}-s}) - \alpha\beta, \\ \alpha = \frac{((1+\gamma_{min})^{N_{cu}-1} - (1+\gamma_{min})^{N_{cu}-s})}{\sum_{j=1}^{N_{cl}}\sum_{i=1}^{N_{cu}}((1+\gamma_{min})^{N_{cu}-i}}, \\ \beta = 2\sum_{j=1}^{N_{cl}}\sum_{i=1}^{N_{cu}}((1+\gamma_{min})^{N_{cu}-i}x_{i,j}^{G} - (1+\gamma_{min})^{N_{cu}-1}x_{i_1} - \\ (1+\gamma_{min})^{N_{cu}-1}x_j - (1+\gamma_{min})^{N_{cu}-s}x_{i_1} - (1+\gamma_{min})^{N_{cu}-s}x_j. \end{aligned} \tag{19}$$

Using the first inequality in (18) and using the fact that $x_{i_1} < x_j$, it follows from (19) that:

$$\begin{aligned} (\sum_{j=1}^{N_{cl}}\sum_{i=1}^{N_{cu}}(1+\gamma_{min})^{N_{cu}-i})((1+\gamma_{min})^{N_{cu}-1}x_{i_1} + \\ (1+\gamma_{min})^{N_{cu}-1}x_j - (1+\gamma_{min})^{N_{cu}-s}) - \\ ((1+\gamma_{min})^{N_{cu}-s})\beta > 0. \end{aligned} \tag{20}$$

A similar inequality to (20) can be derived from the second inequality in (18) (details omitted due to page limit). Then, by summing the respective sides in (20) and in the other derived inequality, it is concluded that:

$$\begin{aligned} (\sum_{j=1}^{N_{cl}}\sum_{i=1}^{N_{cu}}((1+\gamma_{min})^{N_{cu}-i})(1+\gamma_{min})^{N_{cu}-1}) + \\ ((1+\gamma_{min})^{N_{cu}-1} - (1+\gamma_{min})^{N_{cu}-s})^2 < 0. \end{aligned} \tag{21}$$

which is not correct, since the summands on the left-hand side in (21) are both positive, so this contradicts the initial assumption that the users in $\{x_{i_1}, ..., x_{i_{N_{cl}}}\}$ are not consecutive. Therefore, $\{x_{i_1}, ..., x_{i_{N_{cl}}}\}$ consists of consecutive users in X_{sorted}. By a similar procedure as above, we verify that the second users of all clusters should be consecutive values in $X_{sorted}\backslash\{x_{1,1}^{G_{opt}}, x_{1,2}^{G_{opt}}, \ldots, x_{1,N_{cl}}^{G_{opt}}\}$, and so on for the next users of all clusters. This completes the proof to Theorem 1. □

Theorem 1 provides a solution to choosing the optimal grouping function as follows: First, we sort the x-coordinates of users as $x_{l_1} < ... < x_{l_{N_u}}$, and list all possible sequences of length N_{cl} that consist of consecutive values in $X_{sorted} = \{x_{l_1}, \ldots, x_{l_{N_u}}\}$. There are $(N_u - N_{cl} + 1)$ of such sequences. According to Theorem 1, the set of first users of all clusters in the optimal grouping is one of those sequences in the list. Therefore, instead of considering all $\binom{N_u}{N_{cl}}$ of such possible subsets, we only have $(N_u - N_{cl} + 1)$ candidates. Of course, the optimal sequence cannot be determined until all of the N_u users are assigned to groups. Therefore, for each of the sequences in the first step, we list all sequences of N_{cl} consecutive users in the remaining set of users in X_{sorted}. Again, according to theorem 1, the set of second users of all clusters in the optimal grouping is one of these sequences. We repeat the procedure until there is no users left, that is, all the groups are completed. Next, we use (14) to evaluate the transmission power corresponding to every grouping completed in the procedure, and then choose the one that yields the minimum transmission power.

The size of the search space in the provided method is

$$\prod_{k=1}^{N_{cu}}(N_u - kN_{cl} + 1). \tag{22}$$

The search space is polynomial with N_u and N_{cl} and its size is significantly reduced with respect to search space of the exhaustive search, which is $\frac{N_u!}{N_{cl}!}$.

IV. Simulations and results

In this section, we provide details of models and simulations adopted for evaluation of the performance of the proposed optimization of the transmission power consumed by the FlyBS serving mobile users. We also demonstrate the advantages of the proposed scheme over existing state of the art schemes.

A. *Simulation scenario and models*

We consider a scenario where the FlyBS serves users represented by vehicles and/or users in vehicles during a busy traffic or a traffic jam at a road or a highway in a rural area. In such situation, the FlyBS is a suitable solution to improve the performance, since the conventional network is usually overloaded as plenty of active users are located in a small area with a limited network coverage (see, e.g., [20]).

The users are assumed to move on a 3-lane highway in the positive direction of x-axis. The users are distributed uniformly among all three lanes. Within one lane, the velocities of all users are the same so that the minimum regulated distance between the vehicles is kept all the time. More specifically, we set the two-second rule, that is, the minimum distance between two vehicles is equal to the distance moved by the vehicles within two seconds. The velocities are selected uniformly over interval {19-24} m/s, {17-19} m/s, and {14-16} m/s for the first, second, and third lanes, respectively. A common rotary-wing UAVs is considered to serve the users. Such UAV can fly typically with a maximum speed of about 25m/s [21], thus, the typical FlyBS is not efficient for higher speeds than 25 m/s as the FlyBS cannot follow the vehicles' movement.

We assume free space path loss (FSPL) model for the wireless channel, as the communication link between the FlyBS and the vehicles on the road is typically without any obstacles and the FSPL is a commonly adopted model in such cases ([8], [10], [18]). Omni-directional antennas with gains of 7 dBi and 0 dBi for the FlyBS and the users are considered, respectively, in line with [22]. The radio frequency $f = 2.6$ GHz and a bandwidth of 100 MHz are selected. Spectral

TABLE I: Parameter Configurations

System Parameter	Numerical value
Number of users in the coverage area, N_u	{30,60,90}
FlyBS's antenna gain, $D_{i,G}^{j,T}$	7 dBi
User's antenna gain, $D_{i,G}^{j,R}$	0 dBi
Noise power spectral density, N_i	–174 dBm/Hz
Minimum guaranteed capacity to each user C_{min}	15 Mbps
RF frequency, f	2.6 GHz
System bandwidth	100 MHz
Altitude of FlyBS, H	100 meters
Simulation Duration	600 s
Number of simulation drops	100

density of noise is set to –174 dBm/Hz. Following [18], the FlyBS's altitude is fixed at $H = 100$ m. The simulations are performed for the capacity required by each user $C_{min} = 15$ Mbps. Each simulation is of 600 seconds duration with the optimal grouping and transmission power calculated every second. The results are averaged out over 100 simulation drops. The system parameters are summarized in Table I.

Our proposal, which minimizes the FlyBS's transmission power consumption together with the FlyBS's positioning and determination of the optimal grouping of users for NOMA purposes (as elaborated in Section III) is compared with four most-related state of the art schemes: i) the algorithm introduced in [10] that provides a joint NOMA pairing and FlyBS's positioning for sum rate maximization (referred to as SRM in the later discussions in this paper), ii) an enhanced version of SRM in [10] (referred to as ESRM) that adopts the pairing scheme as in [10], but the position of FlyBS is enhanced by our proposed positioning according to (15) in order to achieve the minimum transmission power, as the solution in [10] targets a maximization of sum rate, iii) the algorithm developed in [12] that adopts the optimal grouping corresponding to the minimum transmission power in NOMA with static base station (referred to as SBS), and hence, does not provide any solution to the FlyBS's positioning, iv) an enhanced version of SBS (referred to as ESBS) that adopts the grouping scheme according to [12], but the positioning of the FlyBS is enhanced by our proposed positioning according to (15) to achieve the minimum transmission power consumption.

B. Simulation results

In this subsection, we present and discuss simulation results. First, we focus on an evolution of the transmission power consumption of the FlyBS over time to demonstrate the advantage of our proposed method over the existing solutions in terms of an efficient power management and consequent enhancement of coverage. Then, we compare the performance of the proposed scheme with existing solutions in terms of complexity and average power consumption.

Fig. 2 illustrates the transmission power of the FlyBS over time for $C_{min} = 15$ Mbps guaranteed to each user and for $N_u = 90$ (top subplot) and $N_u = 30$ (bottom subplot). In this figure, we assume NOMA is set so that users are paired

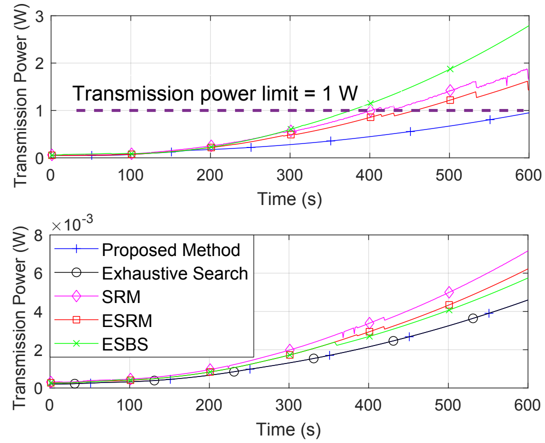

Fig. 2: Transmission power vs. operation time of the FlyBS for $N_u = 90$ (top subplot) and $N_u = 30$ (bottom subplot).

($N_{cu} = 2$), thus, two users share the same time-frequency resources. The transmission power consumption is increasing in general over time, for all solutions. This is due to a general increase in the relative distance between the first and the last vehicles in the scenario over time caused by diverse velocities of vehicles on different lanes causing a gradual expansion of the area demarcated by users covered by the FlyBS.

Fig. 2 further shows that the transmission powers corresponding to SRM, ESRM, and ESBS grow notably faster than for our proposed solution and the power is reduced roughly by 33%, 50%, and 66% with respect to SRM, ESRM, and ESBS, respectively for $N_u = 90$. We depict also the optimum power consumption determined via the exhaustive search. As the complexity of the exhaustive search does not allow to determine results for $N_u = 90$, we show it only for $N_u = 30$. The results confirm that the proposed solution reaches almost the optimum performance with totally negligible difference.

The efficiency of the proposed method is explained also in terms of the coverage as, in practice, the transmission power of the FlyBS is limited. Thus, the FlyBS may fail to guarantee C_{min} to all the users if the power limit is reached. In such case, a higher number of FlyBSs is required and the users should be associated to other FlyBSs to ensure a continuous coverage. In this sense, our proposed solution provides a higher coverage radius and less FlyBSs are needed to cover a specific area.

For example, if the transmission power of the FlyBS is limited to 1 Watt, Fig. 2 shows that the FlyBS is not be able to guarantee C_{min} to all users after 10 s, 380 s, 400 s, 450 s, and 600 s, for SBS, ESBS, SRM, ESRM, and the proposal, respectively. More specifically, compared with SBS, ESBS, SRM, and ESRM, the maximum covered area provided by the proposal is 155%, 36%, 26%, and 17% larger, respectively. Note that the transmission power reached by SBS (scheme iii, see previous subsection) is in the order of hundreds of watts, since the relative distance between the base station and the users increases notably due to immobility of the base station. Hence, the results of SBS are ommited in the rest of the paper.

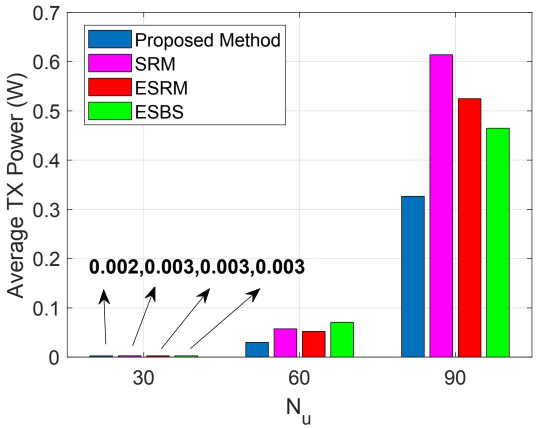

Fig. 3: Average transmission power achieved by individual schemes for various numbers of users N_u.

Next, we investigate an impact of the number of users on the transmission power in Fig. 3 (with $N_{cu} = 2$ for all schemes). It is observed that the average transmission power increases with the number of users, as a larger N_u results in less bandwidth available for each cluster of users, and so a higher transmission power is required to satisfy $C_{min} = 15$ Mbps. Our proposed solution reaches the lowest transmission power of the FlyBS disregarding the number of served users N_u. For $N_u = 90$, the transmission power is reduced by 48%, 38%, and 31% comparing to SRM, ESRM, and ESBS, respectively.

We also show the complexity of the proposed and state of the art solutions for joint users' pairing and the FlyBS's positions in Table II for $N_u = 90$. The complexity is defined as the number of calculations (math operations) performed by each solution. The results are shown for $N_{cu} = 2$, since ESRM is designed for $N_{cu} = 2$ and its extension to $N_{cu} > 2$ is not straightforward. Note that we do not include the complexity of SRM and ESBS, as the complexity of these is not easy to calculate, because the SRM and ESBS solutions are based on bisection search [10] and convex optimization, respectively. Table II confirms that the proposed optimization reduces the complexity significantly with respect to exhaustive search (2.7×10^{80} times) as well as with respect to ESRM (twice).

V. Conclusions

In this paper, we have studied the problem of joint FlyBS's positioning and transmission power minimization in future mobile networks based on NOMA. We formulate the transmission power minimization problem in terms of the grouping of users for NOMA purposes and determination of the FlyBS's positions over time as the users move. Then, we provided a solution to find the optimum grouping and the FlyBS's positions that yield the minimum transmission power while guaranteeing a minimum required capacity for all users. Furthermore, we show that the proposed solution reduces the transmission power consumed by the FlyBS by tens of percent while the required capacity of the moving users is always satisfied. Due to the efficient transmission power consumption in the proposed method, the coverage area of the FlyBS is significantly expanded.

In the future work, a scenario with multiple FlyBS should be studied. This scenario implies another dimension of the problem related to the user association to individual FlyBSs. Furthermore, the problem of power optimization with inclusion of propulsion power consumption should be considered.

TABLE II: Complexity of power optimization represented as the number of math operations required to obtain results.

Method	**Complexity**
Proposed transmission power optimization	46
ESRM	90
Exhaustive search	1.24×10^{82}

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