Joint Positioning of UAV and Power Control for Flying Base Stations in Mobile Networks

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***Abstract*—Deployment of unmanned aerial vehicles (UAVs) in future mobile networks has recently been considered as a reliable technique to enhance capacity of the network and to facilitate an efficient communication in emergency cases. The improvement provided by such network depends on the deployment of the UAVs with respect to users and also on the power consumption of the UAV. In this paper, we study the power consumption in the wireless networks equipped with the UAVs. We propose the novel solution in which the UAV can either change its transmitting power or relocate itself to a new position as the users move in order to guarantee quality of service to the users. We analytically find the transmitting power and an ideal position of the UAV to minimize the total consumed power by the UAV consisting of the power for communication and the power for a displacement of the UAV. According to the simulations, the proposed scheme brings up to 30% of total UAV power saving in the scenario with users moving in crowd.**

***Index Terms*—UAV, drones, transmission power control, propulsion power consumption, mobile users, mobile networks, 6G**

I. Introduction

The use of unmanned aerial vehicles (UAVs), such as drones, has recently attracted growing interest thanks to their inherent features of high-mobility and adaptability to an environment [1]. These features make the UAVs suitable for many applications including surveillance and monitoring of an area [2], emergency operations [3], collection of data from IoT devices [4],[5], offloading traffic from base stations (BSs) [6], enhancing network coverage [7]-[10], or improving quality of service for users [11]-[13]. The UAVs can be categorized into high altitude platforms (HAPs) and low altitude platforms (LAPs) based on their operational height [7]. The HAPs typically operate at altitudes of ten or more kilometers, and are quasi-stationary [14], [15]. In contrast, the LAPs can fly at altitudes from tens of meters up to a few kilometers. In addition, the LAPs are able to move quickly [15] and adjust their position according to the users' requirements [16]. Thus, in this paper we focus on the LAPs. In [17], the authors identify following key research challenges for the scenario when the UAVs serve users: find a suitable position of the UAVs so that they provide sufficient coverage for as many users as possible, reduce the power consumption of the UAVs to prolong their operational time, maximize the quality of service (e.g. throughput), etc. In [7], the authors study the problem of maximizing the coverage area associated with a single UAV. The authors in [9] analyze a similar scenario, where the objective function is to maximize the number of ground users within the coverage area. The maximization of the users satisfaction with experienced data rates is solved in [17] via evolutionary based algorithms.

In [10], the authors minimize the number of UAVs in a given area to ensure required service quality to all the ground users. The problem of maximizing the uplink throughput in a multiple-antenna UAV network is studied in [11]. However, in all these papers, the problem of power consumption is not considered.

The power consumption in the network with the fixed-altitude UAV along with the ground users is investigated in [18]. Then, in [19], the authors provide a reinforcement-learning framework to control the power consumption in the mobile networks equipped with multiple UAVs. However, in both [18] and [19], the impact of transmission power is ignored and only the propulsion energy spent for the UAV movement is considered. In [20], an algorithm for efficient 3D placement of the UAVs targeting a minimization of the transmission power while maximizing the number of covered users is proposed. In [8], the authors develop a framework to determine the optimal 3D locations of the UAVs with minimum transmission power in order to maximize the downlink coverage performance. The determination of the 3D position of the UAVs in order to maximize network throughput and to minimize energy consumption from the users' perspective is addressed in [21]. The authors employ genetic algorithms to solve the problem and to reduce the users' energy consumption while increasing network throughput. In [22], the deployment of cache-enabled UAVs is studied, with goal of maximizing the users' quality-of-experience (QoE) and by using minimum transmission power. The works [8], [20], and [22] are focused on a reduction of the UAVs' transmission power, but the power consumption due to movement of the UAV is not considered. The energy consumption caused by the UAV's movement as well as by transmission of data is considered in [23]. However, the authors are focused on completely different scenario in which the UAV tracks a mobile target.

In such scenario, the constraint on communication quality towards users is not considered at all.

The objective of our paper is to minimize the overall power consumed by the UAV serving ground users moving in a crowd. Thus, contrary to the related works, we consider both power spent for communication as well as for displacement of the UAV according to the users movement. To this end, we propose a novel solution where the UAV can adjust its position and/or the transmission power so that the downlink capacity of every user remains the same as the capacity offered by the static UAV. In other words, we combine the movement of the UAV with the transmission power control to reduce the power consumption by the UAV serving mobile users. In practical cases, this leads to a prolongation of the UAV's battery lifetime, which currently implies a critical limitation of the UAVs [16]. We express analytically the combined UAV transmission power and the power spent for the UAV movement as a function of the users' requirements on communication capacity and their relative location with respect to the UAV. Then, the minimum total power consumption of the UAV is derived as a closed form solution. Via simulations, we demonstrate an efficiency of the proposed solution and we illustrate its superior performance comparing to existing approaches.

The rest of the paper is organized as follow. In section II we present the system model. The proposed solution reducing power consumption via combined determination of the optimal 3D position of the UAV and the transmission power is presented in Section III. In section IV, we present simulation results and compare performance with existing solutions. Last section concludes the paper and outlines potential future research directions.

II. System model and formulations

In this section, we define the system model for the UAV positioning and power consumption. This model is exploited in following sections for derivation of the proposed solution. We consider a cell including n mobile users inside a circular area of a radius R_0 as illustrated in Fig. 1. The area is served with a UAV that can either hover or move over the area. All n users in the area communicate directly with the UAV.

Let $\{X(t), Y(t), H(t)\}$ denote the location of the UAV at the time t. In addition, $\{x_i(t), y_i(t), h_i(t)\}$ denote the coordinates associated with the i-th user's location at the time t. We assume $h_i(t) = h_j(t) = 0, \forall i, j \in \{1, 2, ..., n\}$, i.e., the height of all users is the same and we set it to zero for clarity of following derivations. However, note that an extension to any arbitrary height is easy and straightforward without impact on the derived solutions. Furthermore, let $d_i(t)$ denote Euclidian distance of the i-th user to the UAV.

We assume orthogonal channel allocation for all users. Hence, there is no interference among users' channels. Thus, according to the Shannon–Hartley theorem, the channel capacity of the i-th user is calculated as follow:

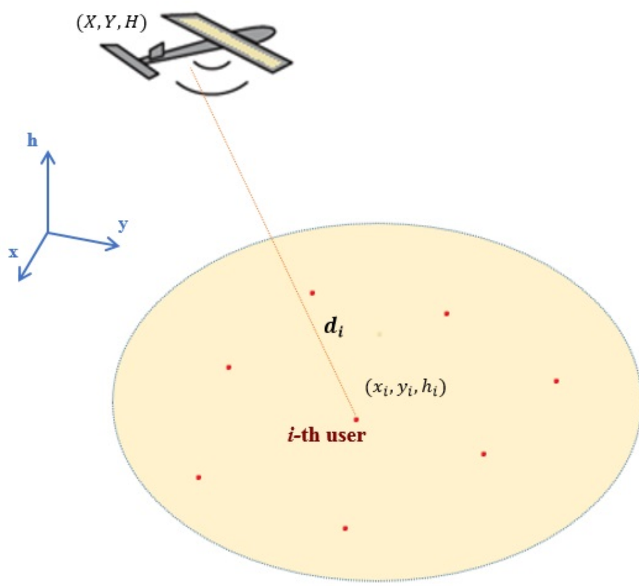

Fig. 1: UAV-enabled system model with multiple mobile users deployed within coverage area of the UAV.

$$C_i(t) = W_i \log_2(1 + \frac{p_i^R(t)}{N_i}), \tag{1}$$

where W_i denotes the bandwidth of the i-th user's channel, N_i represents the noise power at the channel associated with the i-th user, and $p_i^R(t)$ is the received power by the i-th user at the time t. According to the Friis' transmission equation, we get the transmission power of the UAV to the i-th user (p_i^T) as:

$$p_i^T = Q_i d_i^2, \qquad Q_i = \frac{p_i^R (4\pi f)^2}{D_i^T D_i^R c^2}, \tag{2}$$

where D_i^T is the gain of the UAV's antenna, D_i^R is the gain of the user's antenna (note that we assume the antennas of all users with the same gain), f is the frequency, and c is the speed of light (3×10^8 m/s). From (2), we can conclude that the power consumed by the UAV due to transmission power P_{TX} is expressed as a function of the coordinates of the users and the UAV as follow:

$$P_{TX}(X, Y, H) = \sum_{i=1}^{n} Q_i d_i^2 = \sum_{i=1}^{n} Q_i((X - x_i)^2 + (Y - y_i)^2 + H^2). \tag{3}$$

Note that the UAVs are supposed to operate outdoor and serve outdoor users. Thus, as in many related works, we can assume that the positions of the users are known to the UAV, and that the UAV can determine its own position (see, e.g. [7], [24], [25]). Now in order to formulate the required power for the UAV's movement, we note that the energy cost due to the movement is proportional to the distance between the point of origin and the destination. In particular, as the UAV moves from $\{X(t_k), Y(t_k), H(t_k)\}$ to the new location $\{X(t_{k+1}), Y(t_{k+1}), H(t_{k+1})\}$, the consumed propulsion energy is denoted by E_{pr}, and is rewritten as:

$$E_{pr}(X, Y, H, t_k, t_{k+1}) = \tag{4}$$
$$K\sqrt{(X(t_{k+1}) - X(t_k))^2 + (Y(t_{k+1}) - Y(t_k))^2 + (H(t_{k+1}) - H(t_k))^2},$$

where K is the constant indicating the cost of the UAV's movement for one meter (with a unit of J/m). The propulsion power P_{pr} is calculated by dividing E_{pr} with the duration of the UAV movement, i.e., with a time interval $\Delta t_{k+1} = t_{k+1} - t_k$. Mathematically, we have $P_{pr} = \frac{E_{pr}}{\Delta t_{k+1}}$.
The power optimization in case that there is no propulsion power, i.e., the UAV is stationary, or its consumed power is ignorable, the optimal coordinates of the UAV correspond to the center of gravity of the users' positions as shown in [16]:

$$X_G = \frac{\sum_{i=1}^{n} Q_i x_i}{\sum_{i=1}^{n} Q_i}, \quad Y_G = \frac{\sum_{i=1}^{n} Q_i y_i}{\sum_{i=1}^{n} Q_i}. \tag{5}$$

The required transmitting power to guarantee coverage to the users is increasing with the height H of the UAV. This implies that the infimum of P_{tr} occurs at $H_{opt} = H_{min}$, where H_{min} is the minimum permitted altitude of the UAV. The minimum permitted altitude is a function of the physical specifications of the UAV, legal regulations, and the environment's parameters, such as the urban area's topology, buildings' heights and their distribution over the region, and so on (for further details, see e.g., [15]).

III. Power optimization and UAV's positioning

In this section, we first formulate the problem of total UAV power consumption minimization, and then, we derive a closed form solution to our problem and we discuss it.

A. Problem formulation

Unlike other related works, we focus on the minimization of the sum of the communication power and the propulsion power (due to movement of the UAV) considering also the UAV's on-board circuits' consumption power (denoted by $P_{circuit}$) as well as the consumption power due to keeping the UAV in the air in one place (denoted by P_{hover}). Hence, we write the overall power consumption P_{tot} as:

$$P_{tot}(X, Y, H, k) = P_{hover} + P_{circuit} + P_{TX} + P_{pr} \tag{6}$$

According to models defined in Section II (more specifically in (3) and (4)), we can further define P_{tot} as:

$$P_{tot}(X, Y, H, k) =$$
$$P_{hover} + P_{circuit} + \sum_{i=1}^{n} Q_i((X - x_i)^2 + (Y - y_i)^2 + H^2) + \frac{E_{pr}}{(t_{k+1} - t_k)}$$
$$= P_{hover} + P_{circuit} + \sum_{i=1}^{n} Q_i((X - x_i)^2 + (Y - y_i)^2 + H^2) + \tag{7}$$
$$\frac{K}{\Delta t_{k+1}}\sqrt{(X(t_{k+1}) - X(t_k))^2 + (Y(t_{k+1}) - Y(t_k))^2 + (H(t_{k+1}) - H(t_k))^2}.$$

Note that $P_{circuit}$ in (7) depends on the UAV's computational (processing) and communication chips, hence, $P_{circuit}$ is regarded as a constant. Furthermore, P_{hover} is also independent of the UAV's movement and hence is considered as a constant. It is also notable that P_{hover} is equal to zero when the UAV moves. Now, we can formulate the problem of the total power consumption minimization as follow:

$$\begin{aligned} &\underset{X(t_{k+1}), Y(t_{k+1}), H(t_{k+1})}{\operatorname{argmin}} \quad P_{tot}, \\ &s.t. \quad C_j(t) = {C_j}^{min}, j \in \{1, ..., n\}, \forall t, \\ &\qquad ({x_j}^2 + {y_j}^2 \le {R_0}^2), \\ &\qquad H \ge H_{min}. \end{aligned} \tag{8}$$

The first constraint in (8) ensures that every user in the coverage area is receiving the minimum desired capacity (denoted by ${C_j}^{min}, j \in \{1, ..., n\}$) at all time. In our case, we define C_j^{min} as the capacity observed by the j-th user in case of the static UAV. The second constraint guarantees that the users remain within the coverage area. This is a reasonable assumption, as the UAV is supposed to supply communication service to the covered users only and the users who move out of this area are handed over to nearby base stations or other UAVs. The third constraint ensures that the UAV flies within the permitted range of altitude. It is notable that the maximum overall transmission power provided by the UAV is assumed to be greater than the experimental values for the overall transmission power which are presented later in section IV. Hence, we do not consider in (8) any constraints regarding the overall transmission power.

B. Closed form solution for UAV power optimization

From (1), it is concluded that in order to keep the capacity unchanged (i.e., to guarantee the first constraint in (8)), the received power p_i^R for all users must be constant. Any relative change in distance between any user and the UAV can imply that the UAV adjusts the transmission power so as to keep the power received by the users unchanged. This maintains the downlink channel capacity for each user. At the same time, the constant p_i^R can be achieved also via a displacement (movement) of the UAV to a new position.
Both transmission power control and the movement of the UAV are combined analytically together in our proposed solution to minimize the total consumed power P_{tot} as follows. The global minimum of P_{tot} can be found by studying P_{tot} at its critical points over the defined domain in (8). By calculating the critical points and evaluating P_{tot} at those, we can see that the objective function P_{tot} is always increasing with respect to H. Thus, the infimum of P_{tot} occurs at $H = H_{min}$.
After plugging $H = H_{min}$ into (7) it can be verified that the third term in (6) is not differentiable

at $(X(t_{k+1}), Y(t_{k+1})) = (X(t_k), Y(t_k))$. Also, For $(X(t_{k+1}), Y(t_{k+1})) \neq (X(t_k), Y(t_k))$, solving $\frac{\partial P_{tot}}{\partial X(t_{k+1})} = 0$ and $\frac{\partial P_{tot}}{\partial Y(t_{k+1})} = 0$ together yields the following critical points:

$$(X_{c_1}, Y_{c_1}) = \begin{cases} (X_G - X_S \times K, Y_G - Y_S \times K) & (X_G - X_S \times K) > X(t_k) \\ \emptyset & \text{otherwise}, \end{cases}$$
$$(X_{c_2}, Y_{c_2}) = \begin{cases} (X_G + X_S \times K, Y_G + Y_S \times K) & (X_G + X_S \times K) < X(t_k) \\ \emptyset & \text{otherwise}, \end{cases} \tag{9}$$

where $X_G = \frac{\sum_{i=1}^{n} Q_i x_i}{\sum_{i=1}^{n} Q_i}$ and $Y_G = \frac{\sum_{i=1}^{n} Q_i y_i}{\sum_{i=1}^{n} Q_i}$ represent optimal position of the UAV in case of no or negligible cost of the UAV's movement (i.e. propulsion power consumption is much smaller than transmission power consumption), and $X_S = \frac{1}{2\Delta t_{k+1}\sqrt{1+A^2}\sum_{i=1}^{n} Q_i}$ and $Y_S = \frac{1}{2\Delta t_{k+1}\sqrt{1+(\frac{1}{A})^2}\sum_{i=1}^{n} Q_i}$ are coefficients resulting from consideration of the transmission power, where

$$A = \frac{\sum_{i=1}^{n} Q_i Y(t_k) - \sum_{i=1}^{n} Q_i y_i(t_{k+1})}{\sum_{i=1}^{n} Q_i X(t_k) - \sum_{i=1}^{n} Q_i x_i(t_{k+1})}. \tag{10}$$

Then, the optimum X and Y coordinates of the UAV is selected out of the set of all critical points (denoted by D) as follows:

$$(X_{opt}, Y_{opt}) = \underset{X,Y \in D}{\operatorname{argmin}} P_{tot}(X, Y, H_{min}), \tag{11}$$
$$D = \{(X(t_k), Y(t_k)), (X_{c_1}, Y_{c_1}), (X_{c_2}, Y_{c_2})\}.$$

The calculated coordinates X_{opt} and Y_{opt} from (11) give closed form solution to the problem in (8). Thus, the UAV simply changes its position to the new coordinates whenever new coordinates are determined. Of course, there might be a delay between the determination of the new coordinates of the UAV and the time when the UAV reaches the new position. However, as in [17], [26], or [27], we focus on scenario with pedestrians and these move relatively very slow (speed around 1m/s) comparing to a speed of the UAV (typically around 15 or 20m/s). Thus, for sufficiently small interval between the determinations of the new positions (e.g., $\Delta t = 1s$), the expected movement of the UAV would be small (typically less than 1m considering the slow movement of the users) and the delay in the UAV movement becomes negligible. As the cost of the UAV movement K decreases, P_{tot} in (7) approaches $(P_{TX} + P_{circuit} + P_{hover})$. Therefore, considering $P_{circuit}$ and P_{hover} as constants, the solution to the optimization problem defined in (8) is close to the solution in (5), i.e., to optimum position disregarding power spent for the movement of the UAV. However, as K goes to infinity, the solution to (8) converges to $X_{opt}(t_{k+1}) = X(t_k)$, $Y_{opt}(t_{k+1}) = Y(t_k)$, and $H(t_{k+1}) = H(t_k)$. In other words, for a very large cost of the propulsion power, the UAV tends to remain inert and rather changes its transmitting power.

IV. Simulation Results

In this section we provide details of simulation scenario and models exploited to evaluate performance of the proposed joint movement of the UAVs and transmission power control to minimize the total power consumed by the UAV. We also demonstrate the advantages of the proposed scheme over the existing non-optimal scheme.

A. Simulation scenario and models

The simulations are performed using MATLAB. For simulations, n users are randomly located inside the coverage area of a radius $R_0 = 350$ m. We investigate performance for $n = 50$ and $n = 100$. We consider the users moving in a crowd. In such situation, the exploitation of the UAVs is the most beneficial and it is assumed, e.g., in [16], [28], [29]. In the crowd, all users move along the same direction (following the same crowd movement vector), but each user can move arbitrary along the crowd vector.

Table I shows the numerical values of the system parameters that we adopt in the simulations provided later in this section. For the wireless channel, we assume obstacle-free LOS (Free-Space Path Loss (FSPL)) model, and omnidirectional antennas with a gain of 0 dBi [30]. We set spectral density of noise to be -174 dBm/Hz. The radio frequency $f = 2.6$ GHz and the bandwidth $W = 10$ MHz [31] is selected. The minimum allowed flight altitude is set at $H_{min} = 200$ m [33].
Each simulation is of 180 s duration with a step of 1 s and the results are averaged out over 500 simulation drops (simulation runs).

TABLE I: Parameter Configurations

System Parameter	Numerical value
Number of users in the coverage area, n	50,100
Antenna gains, D_i^T,D_i^R	0 dBi [30]
Noise power spectral density, N_i	-174 dBm/Hz
Minimum capacity for the j-th user, C_j^{min}	1 Mbps
RF frequency, f	2.6GHz
Bandwidth	10 MHz [12]
Simulation step, Δt_k	1 second
Minimum allowed flying altitude, H_{min}	200 meters
Radius of the coverage area, R_0	350 meters
Maximum velocity of users, v_i	1 m/s
$P_{circuit}$	22 dBm [34]
P_{hover}	170 W [35]
Number of simulation drops	500

We investigate three different schemes: i) proposed Minimal P_{tot} scheme with the location of UAV determined from (9) and transmission power from (3) to obtain the minimum P_{tot}; ii) Minimal P_{TX} scheme where the location of UAV is derived as in (5) disregarding the power spent for the UAV movement (as it is done, e.g., in [8], [20], [22]); iii) Stationary UAV scheme, that is, the UAV does not move over the coverage area so there is no corresponding propulsion power consumption of the UAV and the UAV only adjusts the transmission power (as considered, e.g., in [32], [33]).

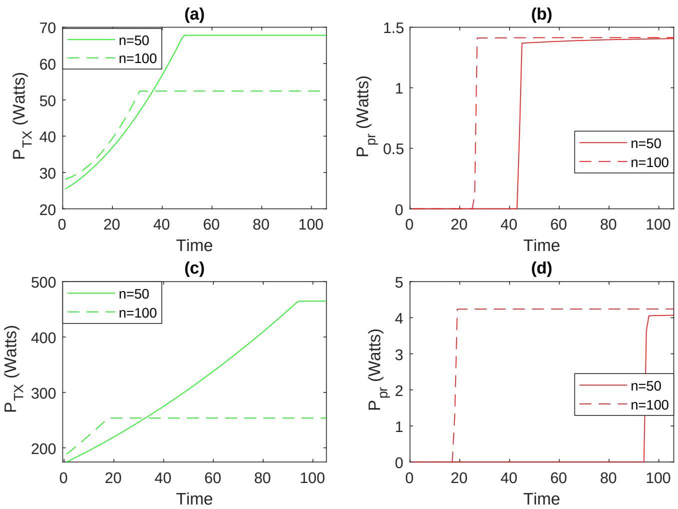

Fig. 2: (a) and (b): P_{TX} and P_{pr} of the UAV for K =5 in Minimal P_{tot} scheme. $n = 50, 100$, and $v_i \leq 1$ m/s, $(1 \leq i \leq n)$. (c), (d): P_{TX} and P_{pr} of the UAV for $K = 30$ in Minimal P_{tot} scheme. $n = 50, 100$, and $v_i \leq 1$ m/s, $(1 \leq i \leq n)$.

B. Simulation results and discussion

First, we show a sample of the transmission power and the propulsion power consumptions changing over time as the users move. This demonstrates complementarity of both approaches that we combine together. Fig. 2 illustrates the transmission power as well as the propulsion power in the Minimal P_{tot} scheme for the movement of crowd within a time interval of 100 seconds, and for $K = 5$ and $K = 30$. It is observed from Fig. 2 that, the UAV stays static for a while until the cost of transmission power becomes so large that it requires the UAV to start moving and keeping up with the crowd. From then on, the transmission power and the propulsion power begin to remain unchanged. It is notable that for larger values of K there is generally a longer delay before the UAV starts to move. It is also seen from Fig. 2 that, for larger K, the transmission power increases. This is because for the larger costs of movement, the UAV tends to remain idler, which brings additional transmission power. It is also seen from Fig. 2 that, for larger K, the transmission power consumption increases. This is because the UAV tends to remain idle for larger cost of movement and, hence, the transmission power is further increased.

Next, we study the effect of the cost of the UAV's movement and the number of users on the total power consumed power P_{tot}. Figs. 3, 4 and 5 illustrate average P_{tot} , average P_{pr}, and average P_{TX}, respectively, versus K for $n = 50$ and $n = 100$. Note that values plotted in these figures are averaged out over 500 simulation drops. It is seen that in Minimal P_{TX} scheme, the average total power generally increases with both n and K. This is because a higher number of users generally necessitates a higher overall transmission

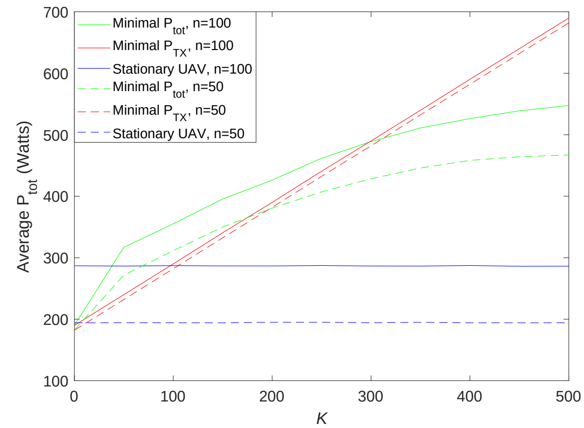

Fig. 3: Average total power vs. K, for $n = 50, 100$.

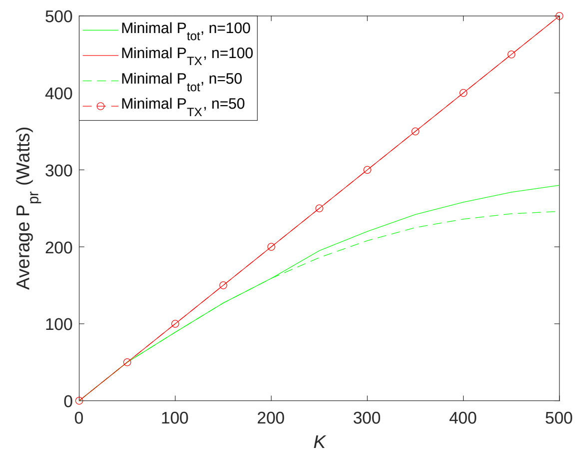

Fig. 4: Average propulsion power vs. K, for $n = 50, 100$.

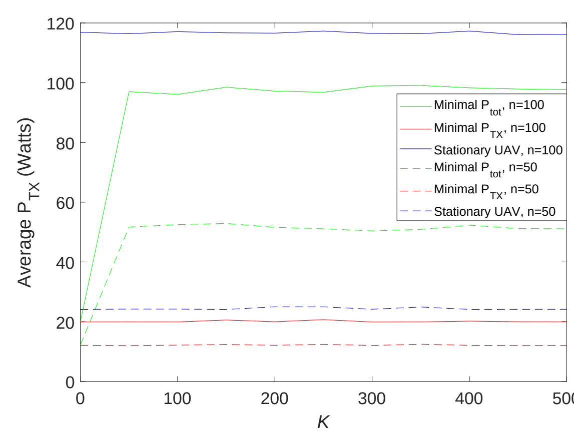

Fig. 5: Average transmission power vs. K, for $n = 50, 100$.

power (and so higher P_{tot}). In addition, a higher cost of the UAV's movement translates into a higher propulsion power consumption and consequently into a higher P_{tot}. According to Fig. 4, the average propulsion power is approximately the same for n=50 and for n=100 in Minimal P_{TX} scheme, because the UAV always reaches at the center of gravity of the system, and so is moving at the same speed as the crowd users, which costs the same cost of propulsion for different n. Also, we observe that, as K increases, the total power consumption in Minimal P_{tot} scheme starts increasing, and then at some point it becomes relatively independent of K. This is because for the higher costs of movement, the UAV in the proposed Minimal P_{tot} scheme- which is pursuing minimum total power, tends to move less, and so the behavior of P_{tot} approaches that in the stationary UAV -which is quite constant as well, according to Fig. 3. Note that the transmission power in Fig. 5 can be derived by subtracting $(P_{pr} + P_{circuit} + P_{hover})$ from P_{tot}.

V. Conclusions

In this paper, we have studied the problem of power optimization in future wireless networks with the UAVs. Contrary to existing papers, we consider that the total power consumed by the UAV includes both the transmission power of the UAV and the propulsion power spent for movement of the UAV. We derive a closed-form solution for the optimal location of the UAV and the transmission power of the UAV to minimize the total power consumed by the UAV. We show that the proposed joint transmission power control and UAV movement allows significant reduction in the total power consumed by the UAV while the capacity of the moving users is not degraded. In the future, the multiple UAV scenario should be studied. In this scenario, also association of the users to individual UAVs should be considered.

VI. Acknowledgment

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