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Power Control and Trajectory Planning Based Interference Management for UAV-Assisted Wireless Sensor Networks

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ABSTRACT Wireless sensor networks are generally used to assist in collecting and transmitting data where humans cannot directly explore. But in a scenario with complex terrestrial environment, the ground communication links between sensors become so weak to provide reliable and high-speed services. Unmanned aerial vehicles (UAVs) can be used as flying relays to enhance connective reliability of terrestrial wireless sensor networks. However, in a UAV-assisted wireless senor network, if the UAV shares the same spectrum with sensors, the interference degrades the quality of communication links when sensors exist in pairs under co-channel conditions. Motivated thereby, we manage the interference by optimizing the transmit power of all communication nodes and planning the trajectory of UAV to achieve the goal of maximizing the sum throughput of the target sensor. Due to the nonconvexity of the optimization problems, we utilize difference of two convex functions (D.C.) programming and successive convex approximation to obtain the suboptimal solutions. Simulation results prove that the minimum signal-to-interference-plus-noise ratio (SINR) required by sensor pairs, flight altitude and maximum transmit power of the UAV can be carefully selected to maximize the sum throughput of target sensor, when the UAV's trajectory is pre-planned. The successive trajectory planning algorithm is also employed to significantly improve the sum throughput.

INDEX TERMS Wireless sensor network, UAV communication, throughput maximization, power control, trajectory planning.

I. INTRODUCTION

Wireless sensor nodes are often used to collect and transmit data in Internet of Things (IoT) applications where humans cannot directly explore. Wireless sensor network is a research hotspot integrating computer, communication, sensor, information fusion and other technologies, and widely applied in different fields i.e., military, medical testing and environmental monitoring [1]. However, in some emergent scenarios, after the ground infrastructure destroyed by natural disasters, or in areas with complex terrain, such as forests and remote areas, the ground sensor networks will not be able to communicate without manual intervention. Considering the complexity of the ground conditions, the deployment of unmanned aerial vehicle (UAV) is an efficient solution to enhance the network capability in emergency sensor communications.

Unprecedented advances in aeronautics and electronic technologies have led to a widespread deployment of UAVs, such as drones, aircrafts, balloons, and airships, etc., [2]–[4]. In particular, if properly planned and deployed, UAVs can provide reliable and cost-effective wireless communications solutions for a variety of scenarios. Therefore, attentions of UAVs from academia and industry are increasingly paid due to their high mobility, wide coverage and low cost. UAVs can be used as aerial base stations (BS) to provide reliable

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wireless communications to scenarios without infrastructure for wireless access. As mobile relays, they can rapidly provide wireless connectivity for ground-based wireless equipment and complement existing ground network by providing coverage in hard-to-reach rural areas.

With the advancement of technology, the data distribution and collection of UAV-assisted ground sensor networks has been widely used in critical situation [5]. In a common sensor network, the data transmission mode is usually passed from one sensor node to another, and finally reaches the destination receiver. However, the sensor nodes that are close to each other will interfere with each other, and even cause link interruption. Therefore, interference management is an important means to ensure reliable data transmission.

A. RELATED WORK

Compared with the traditional ground BS, the advantage of UAVs as a flying BS relies on its ability to adjust height, avoid obstacles and improve the possibility of establishing a line-of-sight (LoS) communication link with ground users. Power control and trajectory planning are often exploited in the research of UAV network performance [6]–[8]. In [6], the authors optimize flight trajectory of the UAV by considering the throughput of communication and the energy consumption of the UAV. Wu *et al.* [7] study the communication system of multiple UAVs, which serve a group of users on the ground. They jointly optimize the multiuser communication scheduling and association, the UAV's trajectory and power control to maximize the minimum throughput over all ground users. In [8], the authors propose an energy-aware path planning to minimize energy consumption of UAV under the constraint of coverage and resolution.

UAVs have many advantages over traditional relays, such as rapid deployment, and dynamic adjustment of positions based on system performance. Optimal deployment of UAV is critical to the performance of the network when the UAV hovers over the terrestrial network. Researches in [9], [10] analyze the optimal deployment of UAV from transmission and connectivity. Zhan *et al.* in [9] optimize the position of the UAV by maximizing the average rate while ensuring that the bit error rate does not exceed the specified threshold. De Freitas *et al.* in [10] study the use of UAV relay to enhance the connectivity of ground wireless networks, and obtain the optimal deployment position of UAV to ensure information reliability. Power control and trajectory planning are jointly utilized to increase throughput in [11]. The authors also analyze information causal constraints of the UAV under the actual movement constraints (the velocity of UAV and initial/final relay position). The terrestrial networks studied in [9]–[11] only contain one source and one terminal node, without considering the impact of the amount, locations and distribution of terminal nodes on the system performance. Due to the simplification of the model, the interference problems of other communication nodes on UAV and terminal nodes are not considered.

All the above researches on UAVs are conducted under the optimization framework in an interference-free environment. However, interference problems are inevitable in multi-user scenarios, because frequency resources is scarce and UAVs need to share spectrum with communication devices. Therefore, effective interference mitigation measures are required to improve the system performance and guarantee the reliability of communications. In [12], the authors consider a system where a collection of single antenna ground nodes communicate with UAVs via multiple access ground-to-air communication links and propose a beamforming algorithm to reduce the interference. In the emerging cellular-connected UAV communications, due to the strong LoS air-to-ground (A2G) channel, UAVs may cause more serious interference to terrestrial network. Weidong Mei et al. in [14] propose to apply the non-orthogonal multiple access (NOMA) technique to the uplink communication from a UAV to cellular BSs for interference mitigation. In [13], the authors propose an interference-aware path planning scheme for a network of cellular-connected UAVs. Each UAV is required to make a tradeoff between maximizing energy efficiency and minimizing wireless latency and interference. With the evolution of terrestrial networks, the interference problem of UAVs becomes more complicated.

In wireless sensor network, the interference problem is considered in terms of coding and energy [15]–[17]. In [15], authors consider complex field network-coded (CFNC) relay-assisted WSN communications, which remedies the problem of throughput inefficient. In [16], authors consider the influence of impulse noise on signal transmission and propose an effective channel coding scheme. Fateh and Govindarasu [17] propose a joint scheduling of tasks and messages for energy minimization in interference-aware real-time sensor networks. [15]–[17] all implement interference management from the traditional technical perspective, [18] utilizes cognitive radio (CR) to consider interference from another perspective, integrating CR principles into the lower layers of industrial wireless sensor networks can enable devices to detect and avoid interference. Reference [19] proposes a method to solve interference from the routing level, L Ye et al. present two channel hopping algorithms for multichannel, single-radio wireless sensor networks. Different from the above literature, the interference is processed and analyzed under the condition that the specific interference has been measured. Reference [20] presents a novel accuracy-aware approach to interference modeling and measurement for WSNs. To sum up, power control is rarely mentioned in WSNs. The combination of UAV and wireless sensor network increases the factors that affect interference. Therefore, we can analyze and solve the interference problem from more angles.

B. MOTIVATION AND CONTRIBUTIONS

Motivated by above works, in order to solve the co-channel interference problem in UAV-assisted wireless senor networks, where a UAV acting as a flying relay to forward information to the target sensor, and sensors existing in pairs in unicast mode, we investigate the power control and trajectory planning problems. The main contributions are summarized as follows.

- We introduce a system model that utilizing a UAV relay to assist poor communication scenario and simultaneously reduce the interference between the UAV and terrestrial sensor pairs. By managing the transmit power of all communication nodes and planning the UAV's trajectory, we maximize the sum throughput at the UAV's target sensor.
- We propose a successive convex algorithm to address the formulated power optimization problem by leveraging the D.C. (difference of two convex) programming. The lower bound of the optimal solution of this problem is given by an iterative algorithm.
- We analyze the trajectory optimization problem for given transmit power and flight range. The optimal solution of UAV position at each time slot is obtained by using successive convex approximation. The lower bound of the optimal trajectory increment of this problem is given.
- We present the effects of relative positions of the target sensor and sensor pairs based on power control and trajectory planning. Simulation results show the influence of the UAV's altitude, velocity, transmit power range and minimum SINR required by sensor receivers on the sum throughput.

The remainder of this paper is organized as follows. In Section II, we present the system model and problem formulations. Then, we propose a power control algorithm by leveraging D.C. programming in Section III. The trajectory planning with given power is investigated in Section IV. In Section V, simulation results are provided to verify the effectiveness of the proposed algorithms. Finally, the conclusion is given in Section VI. In addition, the key symbols used in this work are listed in TABLE 1 for the convenience of the readers.

II. SYSTEM MODEL

A. NETWORK MODEL

A UAV-assisted wireless sensor network is considered in Fig. 1. The mission critical sensor needs to complete the communication task with the target sensor (TS). In the meantime, other sensors on the ground exist in pairs (SP), each pair consists of a transmitter and a receiver. However, due to the poor communication link caused by terrestrial obstacles, the communication task required by the mission critical sensor is completed by one UAV relay. To this end, the mission critical sensor first sends information to the UAV, and then the UAV forwards the information to TS. Since the UAV shares the same spectrum resources with the ground sensors, the sensor transmitters (STs) will also send interference to the TS while transmitting messages to their receivers (SRs).

A three-dimensional (3D) Cartesian coordinate system is employed to describe the positions of terrestrial sensors

TABLE 1. Parameters summary.

Parameter	Description
H	The altitude of the UAV
T	The total flight time of the UAV
N	Set of time slot
τ	The time slot length
V	The velocity of the UAV
D	Set of sensor pairs
$\{x[n], y[n], H\}$	The location of the UAV at n-th time slot
$\{x_{ts}, y_{ts}, 0\}$	The location of the target sensor
$\{x_i^{st}, y_i^{st}, 0\}$	The location of the i-th sensor transmitter
$\{x_i^{sr}, y_i^{sr}, 0\}$	The location of the i-th sensor receiver
$d_i^{st,ts}$	The distance between the i-th sensor transmitter and target sensor
$d_{i,j}$	The distance between the i-th sensor transmitter and j-th sensor receiver
$d_i^{u,sr}[n]$	The distance between the UAV and i-th sensor receiver at the n-th time slot
$d_{u,ts}[n]$	The distance between the UAV and the target sensor at the n-th time slot
$g_i^{st,ts}$	The channel power gain from the i-th sensor transmitter to the target sensor
$g_{i,j}$	The channel power gain from the i-th sensor transmitter to the j-th sensor receiver
$g_{u,ts}[n]$	The channel power gain from the UAV to the target sensor at the n-th time slot
$g_i^{u,sr}[n]$	The channel power gain from the UAV to the i-th sensor receiver at the n-th time slot
β_0	The channel power gain at the reference distance
g_{SP}	The channel gain between the i-th sensor transmitter and the i-th sensor receiver
$\mathrm{SINR}_{ts}[n]$	The SINR received at target sensor
$\mathrm{SINR}_i^{sr}[n]$	The SINR received at the i-th sensor receiver
$p_u[n]$	Transmit power of the UAV at the n-th time slot
$p_i^{st}[n]$	Transmit power of the i-th sensor transmitter at the n-th time slot
$R_{\min}$	The minimum required data rate of the sensor pairs
$p_u^{\max}$	The maximum transmit power of the UAV
$p_{st}^{\max}$	The maximum transmit power of the sensor transmitter

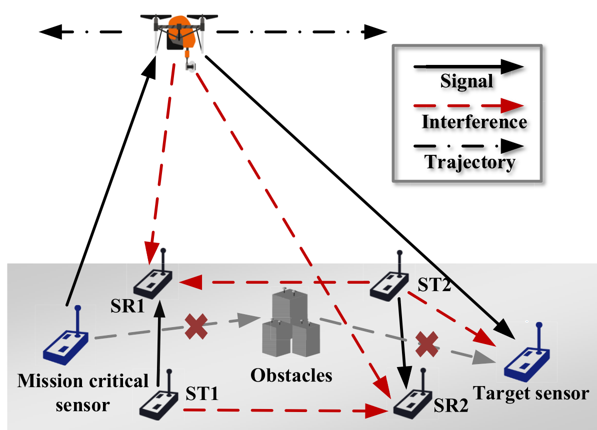

FIGURE 1. UAV-assisted wireless sensor network, where a UAV serves as a relay forwards the information to the target sensor, UAV and sensor pairs interfere with each other concurrently.

and UAV. As the number of ground communication nodes is larger than that in the air, we choose the mission critical sensor as the reference point, which is the origin of the coordinates (0,0,0). We assume that sensor pairs and the target sensor are distributed on a flat surface, let $\mathcal{D} = \{1, 2, \ldots, D\}$,

i represents the i-th pair of sensor pairs. Based on the relative position of each point to the mission critical sensor, their coordinates are $\{x_{ts}, y_{ts}, 0\}$, $\{x_i^{st}, y_i^{st}, 0\}$, $\{x_i^{sr}, y_i^{sr}, 0\}$, respectively.

The UAV flies horizontally from the starting point (the origin) to its destination node at a fixed altitude H in a limited time T, and thus the coordinate of the UAV is $(x(t), y(t), H)$ at time t. The fixed altitude H can select the minimum altitude to avoid collision according to the corresponding scene and terrain, which can reduce the energy consumed by frequent lifting and landing of the UAV [11]. The flight start and end of the UAV are usually planned in advance, so the start and end locations of the UAV are (x_S, y_S, H) and (x_E, y_E, H), respectively. In order to effectively design the flying trajectory, T is divided into N small time slots with each τ length, ie., $\tau = \frac{T}{N}$. Let n denote the n-th time slot, where $n \in \mathcal{N}$, $\mathcal{N} = \{1, 2, \ldots, n, \ldots, N\}$. Therefore, the UAV's location in time slot n is $\{x[n], y[n], H\}$. We assume that the UAV has a constant velocity of V in time T, the positions of the adjacent time slot of the UAV must be satisfied

$$(x[n]-x[n-1])^2+(y[n]-y[n-1])^2 \leq (V\tau)^2, \quad \forall n \in \mathcal{N} \tag{1}$$

where $x[0] = x_S$, $y[0] = y_S$, $x[N] = x_E$, $y[N] = y_E$.

B. CHANNEL MODEL

The distance between TS and the transmitter of i-th sensor pair is $d_i^{st,ts}$ and the distance between the i-th sensor transmitter and the j-th sensor receiver is $d_{i,j}$. The distance between UAV and the receiver of i-th sensor pair at time slot n is

$$d_i^{u,sr}[n] = \sqrt{\left(x[n]-x_i^{sr}\right)^2 + \left(y[n]-y_i^{sr}\right)^2 + H^2} \tag{2}$$

The distance between UAV and the TS is

$$d_{u,ts}[n] = \sqrt{(x[n]-x_{ts})^2 + (y[n]-y_{ts})^2 + H^2} \tag{3}$$

The channel power gains from the i-th sensor pair's transmitter to the TS $g_i^{st,ts}$, the i-th sensor pair's transmitter to the j-th sensor pair's receiver $g_{i,j}$ are modeled as statistically large scale path-loss. Referring to [22], [23], communication channel from UAV to terrestrial communication nodes is dominated by line-of-sight (LoS) link, which is therefore modeled by the free-space path loss model. As a result, the channel power gains from the UAV to the TS $g_{u,ts}[n]$, the UAV to the i-th sensor pair's receiver $g_i^{u,sr}[n]$ are

$$g_{u,ts}[n] = \beta_0 d_{u,ts}^{-2}[n] = \frac{\beta_0}{(x[n]-x_{ts})^2 + (y[n]-y_{ts})^2 + H^2} \tag{4}$$

and

$$g_i^{u,sr}[n] = \beta_0 d_i^{u,sr}[n]^{-2} = \frac{\beta_0}{\left(x[n]-x_i^{sr}\right)^2 + \left(y[n]-y_i^{sr}\right)^2 + H^2} \tag{5}$$

where β_0 is the channel power gain at the reference distance d_0. Both short dependent path loss and small scale fading effects are considered for the channel between i-th transmitter and i-th receiver, so the channel gain of the link between the i-th transmitter and the i-th receiver is given by

$$g_{SP} = \varphi \zeta_{SP}[n] \beta_0 \left(\mathrm{d}_{r,t}\right)^{-\alpha} \tag{6}$$

where φ is a constant determined by system parameters [24], ζ denotes the exponentially distributed random variable with unit mean accounting for Rayleigh fading, $d_{r,t}$ is the distance between the i-th transmitter and the i-th receiver, and α is the path loss exponent.

The transmit power of the UAV and the i-th SP transmitter are denoted as $p_u[n]$ and $p_i^{st}[n]$ at the n-th time slot. Furthermore, the signal to interference plus noise ratio (SINR) received at TS is expressed as

$$\mathrm{SINR}_{ts}[n] = \frac{p_u[n] g_{u,ts}[n]}{\sum_{i=1}^{D} p_i^{st}[n] g_i^{st,ts} + \sigma^2} \tag{7}$$

where σ^2 is the noise power. Moreover, the SINR received at the i-th receiver is

$$\mathrm{SINR}_i^{sr}[n] = \frac{p_i^{st}[n] g_{SP}}{I_i^{sr}[n] + \sigma^2} \tag{8}$$

where the interference received by the i-th SP receiver in the denominator is

$$I_i^{sr}[n] = \sum_{j \in \mathcal{D}, j \neq i} p_j^{st}[n] g_{j,i} + p_u[n] g_i^{u,sr}[n] \tag{9}$$

C. PROBLEM FORMULATIONS

Note that vector $\mathbf{x}[n] = \left(x[n], y[n], p_u[n], p_i^{st}[n]\right)$ and the sum throughput of TS underlaying UAV-assisted wireless network in time period T is thus given by

$$f(\mathbf{x}) = \sum_{n=1}^{N} \log_2\left(1 + \mathrm{SINR}_{ts}[n]\right) \tag{10}$$

Our aim is to maximize the target sensor's sum throughput by finding the optimal power allocation scheme, while satisfying the sensor pairs' minimum data rate requirements and the UAV's trajectory constraints. Mathematically, the optimization can be formulated as follows:

$$\begin{aligned} &\max_{\{x[n], y[n], p_u[n], p_i^{st}[n]\}} f(\mathbf{x}) \\ &s.t.\ C1: \log_2\left(1 + \mathrm{SINR}_i^{sr}[n]\right) \geq R_{\min} \\ &\quad C2: 0 \leq p_u[n] \leq p_u^{\max} \\ &\quad C3: 0 \leq p_i^{st}[n] \leq p_{st}^{\max} \\ &\quad C4: (x[n]-x[n-1])^2 \\ &\quad\quad + (y[n]-y[n-1])^2 \leq (V\tau)^2 \end{aligned} \tag{11}$$

where $R_{\min}$ is the required data rate of the sensor pairs, $p_u^{\max}$ and $p_{st}^{\max}$ are the maximum transmit power of the UAV and the sensor transmitters, respectively. $C1$ ensures that the rate requirements of the sensor receivers. $C2$ and $C3$ provide the transmit power limits for the UAV and sensor pairs, and constraint $C5$ characterizes the UAV's trajectory. Notably, the requirements of sensor receivers are taken into account since SP communications occupy the same spectrum band with the UAV.

Remark 1: The optimization problem in (11) differs from the most advanced research in the following aspects: i) it is a non-convex optimization due to the mutual interference between the UAV and sensor pairs, which cannot be solved directly by standard convex optimization method; ii) the variables that affect the objective function are related to the number of ground nodes and the UAV's trajectory, so the problem needs to be optimized in different situations; iii) the feasible region varies with time, which is non-convex, because the rate of the sensor receivers have to reach a certain requirement. With regards to this, we first study two subproblems: transmit power control with given trajectory investigated in Section III and trajectory planning with given transmit power investigated in Section IV. For the two subproblems, we proposed optimization methods respectively by analyzing the problem structure and leveraging the D.C. programming and successive convex approximation.

III. TRANSMIT POWER CONTROL WITH GIVEN TRAJECTORY

In addition to completing the original missions, the UAV can also serve third parties at the same time. Therefore, in these cases, the trajectory of the UAV is pre-planned. In this section, we study the transmit power control for a given trajectory. By analyzing the structure of the problem, it is shown that the non-convex optimization problem in (11) can be tackled by iteratively solving a series of convex problems.

Note that vector $\mathbf{p_n}[n] = \left(p_u[n], p_i^{st}[n]\right)$, the problem in (11) with given trajectory can be reformulated as follows:

$$\begin{aligned}\mathbf{P_{1.1}}: \quad & \max_{\mathbf{P}=(\mathbf{p_n}[1],\ldots,\mathbf{p_n}[N])} f(\mathbf{P}) \\ & s.t.\ C1: \log_2\left(1+\mathrm{SINR}_i^{sr}[n]\right) \geq R_{\min} \\ & \quad\ C2: 0 \leq p_u[n] \leq p_u^{\max} \\ & \quad\ C3: 0 \leq p_i^{st}[n] \leq p_{st}^{\max}\end{aligned} \tag{12}$$

The constraint C1 can be converted to the following equivalent expression:

$$\begin{aligned}C1: & \sum_{j\in\mathcal{D}, j\neq i} p_j^{st}[n] g_{j,i} + p_u[n] g_i^{u,sr}[n] \\ & \leq p_i^{st}[n] g_{SP} / \left(2^{R_{\min}}-1\right) - \sigma^2\end{aligned} \tag{13}$$

Therefore, all the constraints in (12) are convex. Nevertheless, even though the constraint C1 has been converted to convex, the objective function is not convex, and the optimization problem still cannot be solved. And then, we propose an efficient algorithm to address this problem by leveraging the D.C. programming [25].

The objective function is the difference of two functions:

$$f(\mathbf{P}) = l(\mathbf{P}) - h(\mathbf{P}) \tag{14}$$

where

$$l(\mathbf{P}) = \sum_{n=1} \log_2\left(\sum_{i=1} p_i^{st}[n] g_i^{st,ts} + p_u[n] g_{u,ts}[n] + \sigma^2\right) \tag{15}$$

and

$$h(\mathbf{P}) = \sum_{n=1} \log_2\left(\sum_{j\in\mathcal{D}, j\neq i} p_j^{st}[n] g_j^{st,ts} + \sigma^2\right) \tag{16}$$

$l(\mathbf{P})$ and $h(\mathbf{P})$ are concave functions. Further, we derive the following Lemma.

Lemma 1: The following concave function provides lower bound for $\log_2(1+\gamma_{ts}[n])$*:*

$$f_{tu}[n] = l(p_n[n]) - h(\overline{p_n}[n]) - \langle \nabla h(\overline{p_n}[n]), p_n[n] - \overline{p_n}[n]\rangle \tag{17}$$

where ∇ and $\langle\ \rangle$ are gradient and scalar product, respectively.

Proof: Based on the first-order Taylor approximation of a concave function, there is

$$\begin{aligned} l(\mathbf{p_n}[n]) &\leq l(\overline{\mathbf{p_n}}[n]) + \langle \nabla l(\overline{\mathbf{p_n}}[n]), \mathbf{p_n}[n] - \overline{\mathbf{p_n}}[n]\rangle \\ h(\mathbf{p_n}[n]) &\leq h(\overline{\mathbf{p_n}}[n]) + \langle \nabla h(\overline{\mathbf{p_n}}[n]), \mathbf{p_n}[n] - \overline{\mathbf{p_n}}[n]\rangle \end{aligned} \tag{18}$$

at the given point $\overline{\mathbf{p_n}}[n]$. Furthermore, $\log_2(1+\mathrm{SINR}_{ts}[n])$ can be transformed into

$$\begin{aligned} & \log_2(1+\mathrm{SINR}_{ts}[n]) \\ & = \log_2\left(1+\frac{p_u[n] g_{u,ts}[n]}{\sum_{i\in\mathcal{D}} p_i^{st}[n] g_i^{st,ts} + \sigma^2}\right) \\ & \overset{G}{=} \log_2\left(p_u[n] g_{u,ts}[n] + \sum_{i\in\mathcal{D}} p_i^{st}[n] g_i^{st,ts} + \sigma^2\right) \\ & \quad - \log_2\left(\sum_{i\in\mathcal{D}} p_i^{st}[n] g_i^{st,ts}[n] + \sigma^2\right) \\ & = l(\mathbf{p_n}[\mathbf{n}]) - h(\mathbf{p_n}[\mathbf{n}]) \end{aligned} \tag{19}$$

where G results from $\log(a/b) = \log(a) - \log(b)$. As a consequence, we get

$$\begin{aligned} \log_2(1+\gamma_{tu}[n]) &= l(\mathbf{p_n}[n]) - h(\mathbf{p_n}[n]) \\ &\geq l(\mathbf{p_n}[n]) - h(\overline{\mathbf{p_n}}[n]) \\ &\quad - \langle \nabla h(\overline{\mathbf{p_n}}[n]), \mathbf{p_n}[n] - \overline{\mathbf{p_n}}[n]\rangle \end{aligned} \tag{20}$$

and

$$\begin{aligned} f(\mathbf{p}) &= \sum_{n=1}^{N} \log_2(1+\mathrm{SINR}_{ts}[n]) \\ &= \sum_{n=1}^{N} l(\mathbf{p_n}[n]) - \sum_{n=1}^{N} h(\mathbf{p_n}[n]) \\ &= l(\mathbf{p}) - h(\mathbf{p}) \\ &\geq l(\mathbf{p}) - \left(h(\overline{\mathbf{p}}) + \langle \nabla h(\overline{\mathbf{p}}), \mathbf{p} - \overline{\mathbf{p}}\rangle\right) \end{aligned} \tag{21}$$

This is true when it satisfies $\overline{\mathbf{p}} = \mathbf{p}$. In addition, $f(\mathbf{p})$ is the sum of concave functions and linear functions, so it provides the concave lower bound. ■

Therefore, the objective function in $\mathbf{P_{1.1}}$ can be converted to the following function

$$f(\mathbf{p}, \overline{\mathbf{p}}) = l(\mathbf{p}) - \left(h(\overline{\mathbf{p}}) + \langle \nabla h(\overline{\mathbf{p}}), \mathbf{p} - \overline{\mathbf{p}}\rangle\right) \tag{22}$$

where the n-th component of the $\nabla h(\overline{\mathbf{p}})$ is derived as

$$\sum_{k\in\mathcal{D},k\neq i}\frac{g_{i,k}}{\sum_{j\in\mathcal{D},j\neq k}\overline{p_j^{st}}\tilde{g}_{j,k}+\sigma^2}\frac{1}{\ln 2},\quad n\neq 0,\ \overline{\mathbf{p}}=\mathbf{p}^k \tag{23}$$

On account of the above functions, the optimal solution to the problem in (12) is lower bounded by the following problem with any given $\overline{\mathbf{p}}$:

$$\begin{aligned}\mathbf{P_{1.2}}:\ &\max_{\mathbf{p}} f\left(\mathbf{p},\overline{\mathbf{p}}\right)\\ &s.t.\ C1:\sum_{j\in\mathcal{D},j\neq i}p_j^{st}[n]g_{j,i}+p_u[n]g_i^{u,sr}[n]\\ &\qquad\le p_i^{st}[n]g_{SP}/\left(2^{R_{\min}}-1\right)-\sigma^2\\ &\qquad C2:0\le p_u[n]\le p_u^{\max}\\ &\qquad C3:0\le p_i^{st}[n]\le p_{st}^{\max}\end{aligned}\tag{24}$$

which can be solved at each iteration. Let $\mathbf{p}^*$ be the optimal solution to the problem $\mathbf{P_{1.2}}$ with given $\overline{\mathbf{p}}$ and the corresponding value is $F\left(\mathbf{p}^*\right)$. According to Lemma1, the initial optimization problem was transformed into problem $\mathbf{P_{1.2}}$, and the complete algorithm process is shown in Algorithm 1. To prove that Algorithm 1 provides a series of nondecreasing solutions, we should verify whether the k-th optimal solution $(\mathbf{p_n}[1],\ldots,\mathbf{p_n}[N])^k$ is a feasible solution to the $(k+1)$-th optimization problem (24). If this is true, then we can prove that this is a series of nondecreasing solutions. The theorem 1 gives the solution idea of a successive convex optimization algorithm.

Theorem 1: The optimal solutions to the problem $\mathbf{P_{1.2}}$ are non-decreasing in each iteration, i.e., $F\left(\mathbf{p}^*\right)\ge F\left(\overline{\mathbf{p}}\right)$.

Proof: Denote $(\mathbf{p_n}[1],\ldots,\mathbf{p_n}[N])^k$ as the k-th optimal solution to the problem (24), i.e.,

$$\begin{aligned}&f\left(\mathbf{p},\overline{\mathbf{p}}^{(k-1)}\right)\\ &\quad= l(\mathbf{p})-\left(h\left(\overline{\mathbf{p}}^{(k-1)}\right)+\left\langle\nabla h\left(\overline{\mathbf{p}}^{(k-1)}\right),\mathbf{p}-\overline{\mathbf{p}}^{(k-1)}\right\rangle\right)\end{aligned}\tag{25}$$

$$\begin{aligned}&\max_{\mathbf{p}} f\left(\mathbf{p},\overline{\mathbf{p}}^{(k-1)}\right)\\ &s.t.\ C1:\sum_{j\in\mathcal{D},j\neq i}p_j^{st}[n]g_{j,i}+p_u[n]g_i^{u,sr}[n]\\ &\qquad\le p_i^{st}[n]g_{SP}/\left(2^{R_{\min}}-1\right)-\sigma^2\\ &\qquad C2:0\le p_u[n]\le p_u^{\max}\\ &\qquad C3:0\le p_i^{st}[n]\le p_{st}^{\max}\end{aligned}\tag{26}$$

It then follows that the $(k+1)$-th optimization problem is as follows:

$$f\left(\mathbf{p},\overline{\mathbf{p}}^k\right)=l(\mathbf{p})-\left(h\left(\overline{\mathbf{p}}^k\right)+\left\langle\nabla h\left(\overline{\mathbf{p}}^k\right),\mathbf{p}-\overline{\mathbf{p}}^k\right\rangle\right)\tag{27}$$

$$\begin{aligned}&\max_{\mathbf{p}} f\left(\mathbf{p},\overline{\mathbf{p}}^k\right)\\ &s.t.\ C1:\sum_{j\in\mathcal{D},j\neq i}p_j^{st}[n]g_{j,i}+p_u[n]g_i^{u,sr}[n]\\ &\qquad\le p_i^{st}[n]g_{SP}/\left(2^{R_{\min}}-1\right)-\sigma^2\\ &\qquad C2:0\le p_u[n]\le p_u^{\max}\\ &\qquad C3:0\le p_i^{st}[n]\le p_{st}^{\max}\end{aligned}\tag{28}$$

When there is $\mathbf{p}=\overline{\mathbf{p}}^k,\forall n\in\mathcal{N}$ in (24), we have the following:

$$\begin{aligned}&l(\mathbf{P})-h\left(\overline{\mathbf{P}}^k\right)\\ &\quad-\left\langle\nabla h\left(\overline{\mathbf{P}}^k\right),\mathbf{P}-\overline{\mathbf{P}}^k\right\rangle\\ &=l\left(\overline{\mathbf{P}}^k\right)-h\left(\overline{\mathbf{P}}^k\right)\\ &\ge l\left(\overline{\mathbf{P}}^k\right)-h\left(\overline{\mathbf{P}}^{(k-1)}\right)\\ &\quad-\left\langle\nabla h\left(\overline{\mathbf{P}}^{(k-1)}\right),\overline{\mathbf{P}}^k-\overline{\mathbf{P}}^{(k-1)}\right\rangle\end{aligned}\tag{29}$$

It means that the solution at the k-th iteration is also a solution at the $(k+1)$-th iteration. Therefore, the values of the Algorithm 1 must be non-decreasing. Further, since the solutions are non-decreasing over the iteration and the optimal solution is definitely upper-bounded, the algorithm 1 can be proved to be convergent. ■

Algorithm 1 Transmit Power Control With Given Trajectory

1: Input the UAV's trajectory $\{x[n],y[n],H\}$
Initialization:$k=0$, $\mathbf{P}^{(k)}=\left(\mathbf{p_n}[1]^{(k)},\ldots,\mathbf{p_n}[N]^{(k)}\right)$
2: **repeat**
3: Solving the problem $\mathbf{P_{1.2}}$ for any given $\mathbf{P}^{(k)}$ with standard convex optimization methods and obtain its optimal solution
$\mathbf{P}^\star=(\mathbf{p_n}^\star[1],\ldots,\mathbf{p_n}^\star[N])$
Update $\mathbf{P}^{(k+1)}=(\mathbf{p_n}^\star[1],\ldots,\mathbf{p_n}^\star[N])$
Update the iterative number $k=k+1$
4: **until** the stopping criterion $\left|\mathbf{P}^{(k+1)}-\mathbf{P}^{(k)}\right|\le e$ is met
5: Obtain optimal solutions:$p_u^\star[n]$, $p_i^{st\star}[n]$
6: Output the sum throughput at target user during the period T

IV. TRAJECTORY PLANNING WITH GIVEN TRANSMIT POWER

Consider such a scenario where the UAV receives a mission to the specified destination at the starting point without a planned trajectory, and simultaneously forwards the message to the target sensor. Limited by the energy of system, the transmit power of the UAV remains constant, and the transmit power of the sensor pairs on the ground are not controllable. Therefore, in order to ensure the maximum sum throughput of the target sensor during the period of T, trajectory planning of the UAV is required. As a consequence, we discuss the trajectory planning subproblem with given transmit powers in this section. Denote that

$\mathbf{w}[n] = (x[n], y[n])$, $\mathbf{z} = (\mathbf{w}[1], \ldots, \mathbf{w}[N])$, the problem can be written as follows:

$$\begin{aligned}
\mathbf{P_{2.1}}: \quad & \max_{\mathbf{z}=(\mathbf{w}[1],\ldots,\mathbf{w}[N])} f(\mathbf{z}) \\
& s.t.\ C1: \log_2\left(1+\mathrm{SINR}_i^{sr}[n]\right) \geq R_{\min} \\
& C2: x[n]^{\min} \leq x[n] \leq x[n]^{\max} \\
& C3: y[n]^{\min} \leq y[n] \leq y[n]^{\max} \\
& C4: (x[1]-x_S)^2 + (y[1]-y_S)^2 \leq (V\tau)^2 \\
& (x[n]-x[n-1])^2 + (y[n]-y[n-1])^2 \\
& \leq (V\tau)^2, \quad n = 2, \cdots, N-2 \\
& (x[N-1]-x_E)^2 + (y[N-1]-y_E)^2 \\
& \leq (V\tau)^2 \qquad (30)
\end{aligned}$$

The objective function in $\mathbf{P_{2.1}}$ can be further rewritten as

$$f(\mathbf{z}) = \sum_{n=1}^{N} R_{ts}[n] \qquad (31)$$

where

$$R_{ts}[n] = \log_2\left(1 + \frac{A}{\|\mathbf{w}[n]-w_{ts}\|^2 + H^2}\right) \qquad (32)$$

and

$$A = \frac{p_u[n]\beta_0}{\sum_{i\in\mathcal{D}} p_i^{st} g_i^{st,ts} + \sigma^2} \qquad (33)$$

$$\|\mathbf{w}[n]-w_{ts}\|^2 = (x[n]-x_{ts})^2 + (y[n]-y_{ts})^2 \qquad (34)$$

Obviously, $\mathbf{P_{2.1}}$ is a non-convex optimization problem due to the objective function and constraint $C1$. As a result, the optimal solution to the problem is difficult to obtain by traditional methods. In the following, we first introduce the slack variables $\{R[n]\}_{n=1}^{N}$, $\mathbf{P_{2.1}}$ can be reformulated as

$$\begin{aligned}
\mathbf{P_{2.2}}: \quad & \max_{\mathbf{z}=(\mathbf{w}[1],\ldots,\mathbf{w}[N]),R[n]} R[n] \\
& s.t.\ C1: R[n] \leq R_{ts}[n] \\
& C2: \log_2\left(1+\mathrm{SINR}_i^{sr}[n]\right) \geq R_{\min} \\
& C3: x[n]^{\min} \leq x[n] \leq x[n]^{\max} \\
& C4: y[n]^{\min} \leq y[n] \leq y[n]^{\max} \\
& C5: (x[1]-x_S)^2 + (y[1]-y_S)^2 \leq (V\tau)^2 \\
& (x[n]-x[n-1])^2 + (y[n]-y[n-1])^2 \\
& \leq (V\tau)^2, \quad n = 2, \cdots, N-2 \\
& (x[N-1]-x_E)^2 + (y[N-1]-y_E)^2 \\
& \leq (V\tau)^2 \qquad (35)
\end{aligned}$$

After introducing the slack variables, the constraints $C1$ and $C2$ are still not convex. Afterwards, we employ a successive convex optimization technique to get an efficient approximate solution to $\mathbf{P_{2.2}}$. By optimizing the incremental of the UAV's trajectory at each iteration, we successively maximize a lower bound of $\mathbf{P_{2.2}}$. Denote that $\delta x_k[n]$ and $\delta y_k[n]$ are the trajectory incremental from the k-th to the $(k+1)$-th iteration, i.e., $x_{k+1}[n] = x_k[n] + \delta x_k[n]$, $y_{k+1}[n] = y_k[n] + \delta y_k[n]$, $\forall n$. Next, we have the following Lemma.

Lemma 2: For any trajectory incremental $\delta x_k[n]$ and $\delta y_k[n]$, the following inequalities hold

$$\begin{aligned}
R_{ts,k+1}[n] &\geq R_{ts,k+1}^{lb}[n] \\
&\triangleq R_{ts,k}[n] - a_{ts,k}[n]\left(\delta x_k[n] + \delta y_k[n]\right) \\
&\quad - b_{ts,k}[n]\delta x_k[n] - c_{ts,k}[n]\delta y_k[n] \qquad (36)
\end{aligned}$$

where $a_{ts,k}[n] \geq 0$, $b_{ts,k}[n]$ and $c_{ts,k}[n]$ are coefficients given by (44).

Proof: From the proof of Lemma 2 in [11], we first define the function $f(x) \triangleq \log_2\left(1+\frac{\alpha}{\xi+x}\right)$, where α and ξ are constants. The function is shown to be convex with respect to $x \geq -\xi$. By leveraging the property that the first-order Taylor approximation of a convex function is a global under-estimator, for any given x_0, we have

$$f(x) \geq f(x_0) + f'(x_0)(x-x_0) \qquad (37)$$

where

$$f'(x_0) = \frac{-\left(\log_2 e\right)\alpha}{(\xi+x_0)(\xi+\alpha+x_0)} \qquad (38)$$

Let $x_0 = 0$, we have the following inequality

$$\log_2\left(1+\frac{\alpha}{\xi+x}\right) \geq \log_2\left(1+\frac{\alpha}{\xi}\right) - \frac{\left(\log_2 e\right)\alpha x}{\xi(\xi+\alpha)}, \quad \forall x \qquad (39)$$

The throughput $R_{ts,k+1}[n]$ can be expressed as

$$\begin{aligned}
&\log_2\left(1 + \frac{\alpha_{ts}[n]}{H^2 + (x_{k+1}[n]-x_{ts})^2 + (y_{k+1}[n]-y_{ts})^2}\right) \\
&= \log_2\left(1 + \frac{\alpha_{ts}[n]}{d_{uts,k}^2[n] + \Delta}\right) \qquad (40)
\end{aligned}$$

where

$$\alpha_{ts}[n] = A \qquad (41)$$

$$d_{uts,k}[n] \triangleq \sqrt{H^2 + (x_k[n]-x_{ts})^2 + (y_k[n]-y_{ts})^2} \qquad (42)$$

and

$$\begin{aligned}
\Delta \triangleq\ & \delta x_k^2[n] + \delta y_k^2[n] + 2\left(x_k[n]-x_{ts}\right)\delta x_k[n] \\
& + 2\left(y_k[n]-y_{ts}\right)\delta y_k[n] \qquad (43)
\end{aligned}$$

Due to $x_{k+1}[n] = x_k[n] + \delta x_k[n]$ and $y_{k+1}[n] = y_k[n] + \delta y_k[n]$, (36) follows from (39) by letting $\alpha = \alpha_{ts}[n]$, $\xi = d_{uts,k}^2[n]$ and $x = \Delta$, then the coefficients $a_{ts,k}[n]$, $b_{ts,k}[n]$ and $c_{ts,k}[n]$ in (36) can be obtained as

$$\begin{aligned}
a_{ts,k}[n] &= \frac{\alpha_{ts}[n]\log_2 e}{d_{uts,k}^2[n]\left(\alpha_{ts}[n] + d_{uts,k}^2[n]\right)} \\
b_{ts,k}[n] &= 2\left(x_k[n]-x_{ts}\right)a_{ts,k}[n] \\
c_{ts,k}[n] &= 2\left(y_k[n]-y_{ts}\right)a_{ts,k}[n], \quad \forall n \qquad (44)
\end{aligned}$$

■

Based on Lemma 2, the concave lower bounds of non-convex constraints $C1$ in (35) at given k-th $\{x_k[n], y_k[n]\}$ are obtained. Constraints $C1$ and $C5$ in (35) can be further written as

$$R_{ts}[n] \leq R_{ts,k+1}^{\mathrm{lb}}[n] \qquad (45)$$

and

$$\begin{aligned}&(x[1]+\delta x_k[1]-x_S)^2+(y[1]+\delta y_k[1]-y_S)^2\leq(V\tau)^2\\&(x[n]+\delta x_k[n]-x[n-1]-\delta x_k[n-1])^2\\&\quad+(y[n]+\delta y_k[n]-y[n-1]-\delta y_k[n-1])^2\leq(V\tau)^2\\&\quad n=2,\cdots,N-2\\&(x_E-x_k[N-1]-\delta x_k[N-1])^2\\&\quad+(y_E-y_k[N-1]-\delta y_k[N-1])^2\leq(V\tau)^2\end{aligned}\tag{46}$$

Furthermore, the constraint $C2$ in $\mathbf{P_{2.2}}$ can be transformed into the following equivalent expression:

$$(x[n]-x_{ts})^2+(y[n]-y_{ts})^2+H^2\geq L\tag{47}$$

where

$$L=\frac{\left(2^{R_{min}}-1\right)p_u[n]\beta_0}{p_i^{st}g_{SP}-\left(2^{R_{min}}-1\right)\left(\sum_{j\in\mathcal{D},j\neq i}p_j^{st}g_{j,i}+\sigma^2\right)}\tag{48}$$

The locations of sensor pairs and target sensor are fixed, and the transmit power of sensor pairs and UAV are fixed, so L is a constant. Obviously, the constraint $C2$ is not a convex set. To this end, we introduce another slack variables $\{S[n]\}_{n=1}^{N}$, $C2$ can be reformulated as

$$\begin{aligned}&S[n]\geq L-H^2\\&S[n]\leq\|\mathbf{w}[n]-\mathbf{w}_{ts}\|^2\end{aligned}\tag{49}$$

Since $\|\mathbf{w}[n]-\mathbf{w}_{ts}\|^2$ is a convex function with respect to $\mathbf{w}[n]$, we have the following inequality by applying the first-order Taylor expansion at the given point $\mathbf{w}_k[n]$,

$$S_k[n]\leq\|\mathbf{w}_k[n]-\mathbf{w}_{ts}\|^2+2\left(\mathbf{w}_k[n]-\mathbf{w}_{ts}\right)^T\times\left(\mathbf{w}_k[n]-\mathbf{w}_{ts}\right)\tag{50}$$

Finally, by tackling the non-convexity of the objective function and constraint $C1$ in $\mathbf{P_{2.1}}$, the original problem is approximated by a more tractable function at a given local point $\{x_k[n], y_k[n]\}$. The problem (30) is approximated as the following problem

$\mathbf{P_{2.3}}$:

$$\begin{aligned}\max_{\mathbf{w}_k[n],\{\delta x_k[n],\delta x_k[n]\}_{n=1}^N,R[n],S_k[n]}\quad & R[n]\\ s.t.\ C1:\ & R[n]\leq R_{ts,k+1}^{\mathrm{lb}}[n],\\ C2:\ & S_k[n]\geq L-H^2\\ C3:\ & S_k[n]\leq\|\mathbf{w}_k[n]-\mathbf{w}_{ts}\|^2\\ &+2\left(\mathbf{w}_k[n]-\mathbf{w}_{ts}\right)^T\times\left(\mathbf{w}_k[n]-\mathbf{w}_{ts}\right)\\ C4:\ & x[n]^{\min}\leq x_k[n]\leq x[n]^{\max}\\ C5:\ & y[n]^{\min}\leq y_k[n]\leq y[n]^{\max}\\ C6:\ & (x[1]+\delta x_k[1]-x_S)^2\\ &+(y[1]+\delta y_k[1]-y_S)^2\leq(V\tau)^2\\ &(x[n]+\delta x_k[n]-x[n-1]-\delta x_k[n-1])^2\\ &+(y[n]+\delta y_k[n]-y[n-1]-\delta y_k[n-1])^2\\ &\leq(V\tau)^2,\quad n=2,\cdots,N-2\\ &(x_E-x[N-1]-\delta x_k[N-1])^2\\ &+(y_E-y[N-1]-\delta y_k[N-1])^2\\ &\leq(V\tau)^2\end{aligned}\tag{51}$$

TABLE 2. Simulations parameters.

Parameter	Description	Value
T	25s	The total flight time of the UAV
N	5	Set of time slot
τ	5s	The time slot length
D	2	The number of sensor pairs
β_0	-60dB	The channel power gain at the reference distance
$d_{r,t}$	30m	The distance between the i-th sensor transmitter and receiver
σ^2	10^{-9} Watt	The system noise power

$\mathbf{P_{2.3}}$ is a convex quadratic programming problem, which can be efficiently solved by iterations. The optimization variables are the increments at each iteration in (51), which means that we can always get a series of non-decreasing solutions. In conclusion, the lower bound of $\mathbf{P_{2.1}}$ is obtained by updating the trajectory based on the optimal solutions to $\mathbf{P_{2.3}}$, which is summarized in Algorithm 2.

Algorithm 2 Trajectory Planning With Given Transmit Power

1: Input the transmit power $\left\{\mathbf{p}[n]=\left(p_u[n],p_i^{st}[n]\right)\right\}$
Initialization: $k=0$, $\{x_0[n],y_0[n]\}_{n=1}^N$
2: **repeat**
3: Solving the problem $\mathbf{P_{2.3}}$ with standard convex optimization methods and obtain its optimal incremental $\left\{\delta x_k^\star[n],\delta y_k^\star[n]\right\}_{n=1}^N$
Update the trajectory $x_{k+1}[n]=x_k[n]+\delta x_k^\star[n]$ and $y_{k+1}[n]=y_k[n]+\delta y_k^\star[n]$, $\forall n=1,\cdots,N$
Update the iterative number $k=k+1$
4: **until**
5: Obtain optimal solutions:$x^\star[n]$, $y^\star[n]$
6: Output the sum throughput at target sensor during the period T

V. SIMULATIONS AND DISCUSSIONS

A. SIMULATION ENVIRONMENT DESCRIPTION

For our simulations, the sensor pairs and target sensor are located within a geographical area of size 400×300 m^2. The main simulation parameters are listed in TABLE 2. The altitude of the UAV, the velocity of the UAV, the rate requirement of sensor pairs, the maximum transmit power of UAV and the transmit power of sensor transmitters change with the simulation scenes. The locations of the first SP transmitter and receiver are $(92,51,0)$ and $(68,69,0)$, respectively. The locations of the second SP transmitter and receiver are $(228,189,0)$ and $(252,171,0)$, respectively. UAV starts from the coordinate origin (0,0,H) and flies to the end point (400,300,H).

In order to better illustrate the effectiveness of the algorithm and investigate the impacts of system parameters, we consider the following three specific cases: Case I, the target sensor is located between two sensor pairs with coordinates of (128,132,0); Case II, the target sensor is located between the second sensor pair with coordinates of (240,180,0); Case III, where the target sensor is located

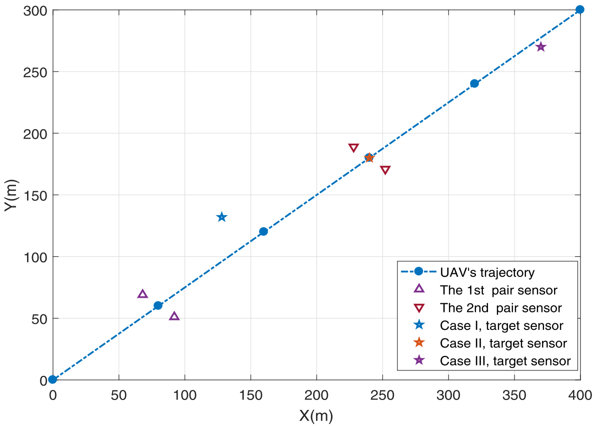

FIGURE 2. **The positions of the UAV, the sensor pairs and target sensors for three cases.**

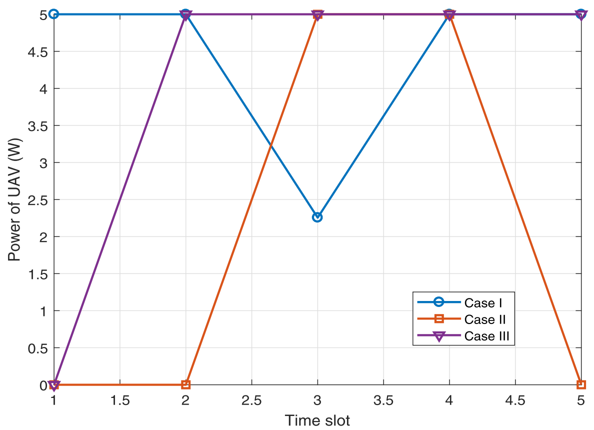

FIGURE 3. **The transmit powers of the UAV for three cases.**

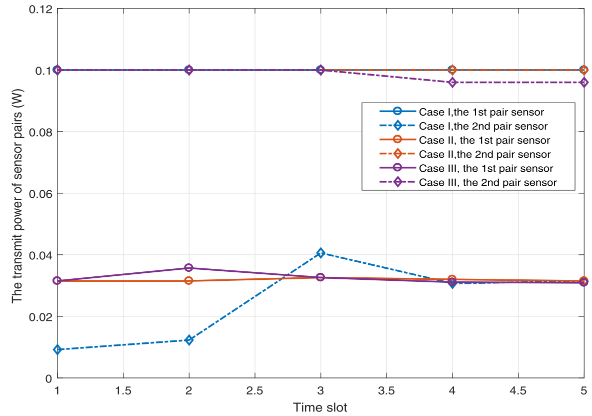

FIGURE 4. **The transmit powers of the sensor transmitters for three cases.**

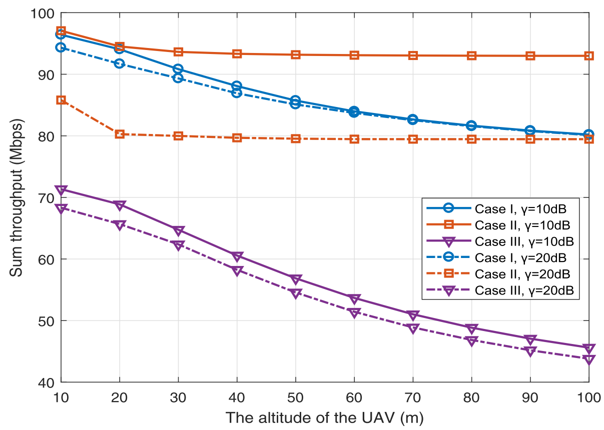

FIGURE 5. **The sum throughput versus the altitude of the UAV for three cases.**

outside the sensor pairs and closer to the end of the UAV with coordinates of (370,270,0). The position relationship of the UAV, sensor pairs and target sensors in the three cases is showed in Fig. 2. To accurately analyze the impact of target sensors' positions on system sum throughput, the altitude of the UAV is 20 m in Fig. 3, Fig. 4 and Fig. 7, the velocity is 20 m/s in Fig. 3-7, the maximum transmit power of the UAV is 5 W in Fig. 3 - Fig. 5, the maximum transmit power of sensor transmitters is 0.1 W in Fig. 3 - Fig. 7 and the required minimum rate of sensor receivers is 1 $Mbit/s$.

B. TRANSMIT POWER CONTROL WITH FIXED TRAJECTORY

Fig. 3 depicts the transmit power of the UAV varies with time slot for three cases. In Case I, from the second time slot to the third time slot, the UAV is far away from the target sensor and close to the 2nd SP, so the transmit power decreases. Until the fourth time slot, it is far away from the 2nd SP, the transmit power of the UAV is restored to the maximum. In Case II and Case III, due to the fact that at the first time slot, the UAV is far away from the target sensor and very close to the 1st SP. In order to ensure the communication quality of the 1st SP, the UAV chooses not to send a signal. In Case II, the UAV concentrates transmitting signals with maximum power at the third and fourth time slot, which can both reduce interference to sensor pairs and provide sufficient throughput.

Fig. 4 shows the variation of transmit power of sensor pairs under three cases. For Case I, at the third time slot, the UAV is far away from the target sensor and close to 2nd SP, and the transmit power of the UAV decreases, so the transmit power of 2nd SP increases. At the fourth time slot, the UAV's transmit power is restored to its maximum, and the transmit power of 2nd SP decreases accordingly. Since the target sensors of Case II and Case III are closer to 2nd sensor pair than 1st sensor pair, and the transmit power of the UAV reaches the maximum, the transmit power of the 1st sensor pair is smaller.

Fig. 5 further illustrates the relationship between sum throughput and UAV's altitude and sensor transmitter's power. For all cases, the sum throughput gradually decreases as the altitude of UAV increases. For Case I and Case III, with the increase of the minimum SINR required by sensor pairs, the transmit power of the UAV decreases, and the sum throughput decreases slightly. For Case II, the minimum SINR required by sensor pairs increases from 10 dB to 20 dB, which has the greatest impact on the UAV, so the sum throughput is greatly reduced. Fig. 6 illustrates the relationship between sum throughput and UAV's altitude and UAV's transmitter power. For all cases, the sum throughput increases as the transmit power of UAV increases from 2 W to 5 W. However, it can be seen from the simulation results

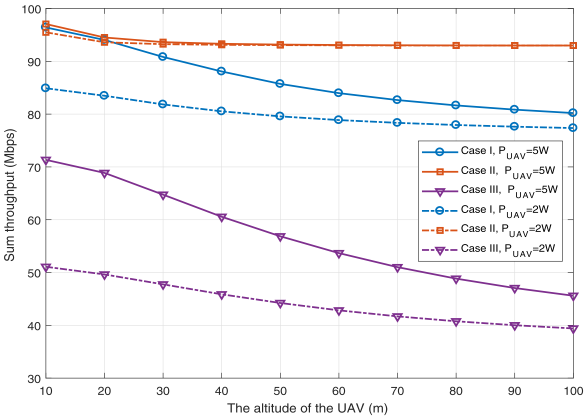

FIGURE 6. The sum throughput versus the altitude of the UAV for three cases.

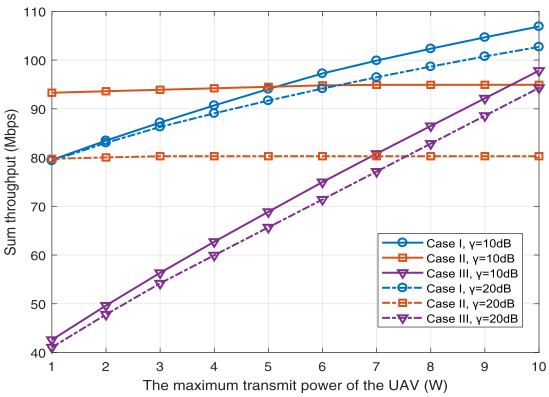

FIGURE 7. Throughput performance comparison among different cases versus the maximum transmit power of the UAV.

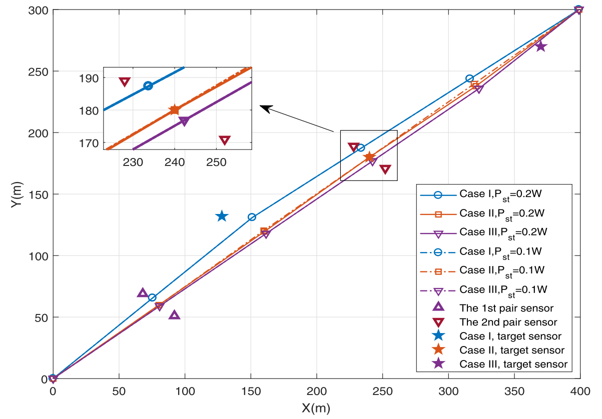

FIGURE 8. The UAV's trajectories comparison among different cases with different sensor transmitter's power.

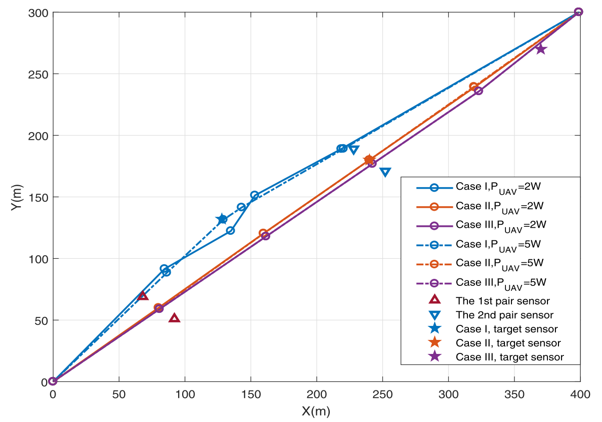

FIGURE 9. The UAV's trajectories for different cases with different UAV's transmit power.

that the increase of UAV's transmit power has little effect on Case II and the greatest effect on Case III. This is because the UAV only transmits signals at only two time slots. In Case III, the UAV does not transmit signals at the first slot, the power remains at its maximum at all other time slots as getting closer to the target sensor. Therefore, the power variation has the greatest influence on the throughput of the target sensor.

Fig. 7 shows the variation of sum throughput with the maximum transmit power of the UAV. Obviously, the sum throughput of the target sensor increases as the maximum transmit power of the UAV increases in Case I and Case III, the sum throughput hardly changes in Case II. When minimum SINR required by sensor receivers is 10 *dB*, and the maximum transmit power of the UAV is less than 5 W, the sum throughput of Case II is the highest and the sum throughput of Case III is the lowest. With SINR unchanged, Case I has the maximum sum throughput when the transmit power of the UAV is greater than 5 W and less than 7 W. When the transmit power of the UAV is around 10 W, the sum throughput of Case II is the lowest.

C. TRAJECTORY PLANNING WITH FIXED POWER ALLOCATION

Fig. 8 illustrates the trajectories obtained by the proposed algorithm for three cases with different sensor transmitter's power. For all cases, it can be seen that the six trajectories in the figure are highly similar, but in all three cases the UAV would like to fly closer to the target sensor. The increase of the maximum transmit power of sensor hardly affects the trajectory. Fig. 9 shows the UAV's trajectories for different cases with different UAV's transmit power. This is due to the fact that when the UAV flies away from the sensor pairs and gets closer to the target sensor, the increased transmit power of the UAV increases the interference to sensor pairs.

In Fig. 10, we present the sum throughput versus the altitude of the UAV with different transmit power of the UAV. It is easy to get the conclusion that the sum throughput of the target sensor becomes smaller and smaller as the altitude increases. After reaching a certain altitude, the sum throughput remains almost unchanged due to the large signal attenuation. From the perspective of power, it is obvious that the increase of UAV's power has greater effect on the sum throughput of target sensor for Case I and Case III, and has little effect for Case II. According to Fig. 9, the transmit power of the UAV increases from 2 W to 5 W, and the UAV's trajectory in Case I changes significantly, resulting in a significant increase in sum throughput.

In Fig. 11, we present the sum throughput versus the velocity of the UAV with different altitude of the UAV. Given the

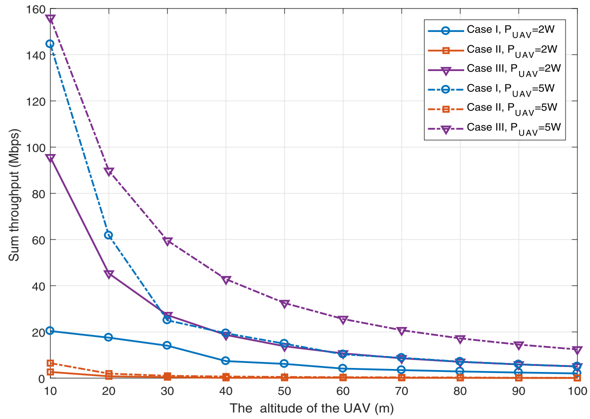

FIGURE 10. **The sum throughput versus the altitude of the UAV for three cases.**

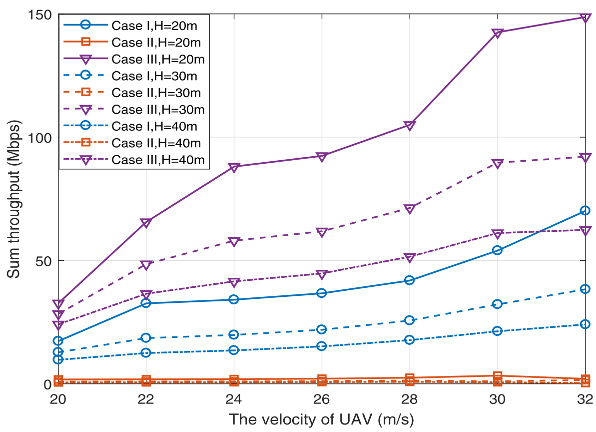

FIGURE 11. **The sum throughput versus the velocity of the UAV.**

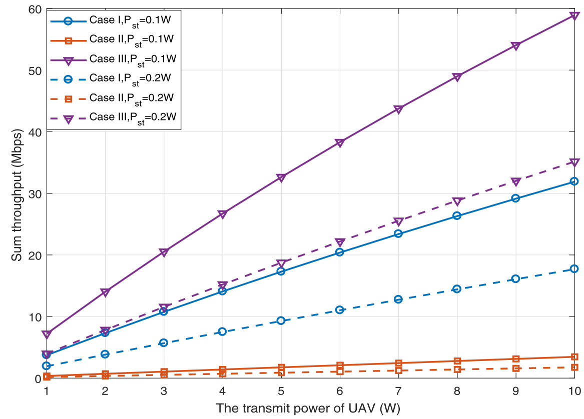

FIGURE 12. **The sum throughput versus the maximum transmit power of the UAV with different transmit power of the sensor pairs.**

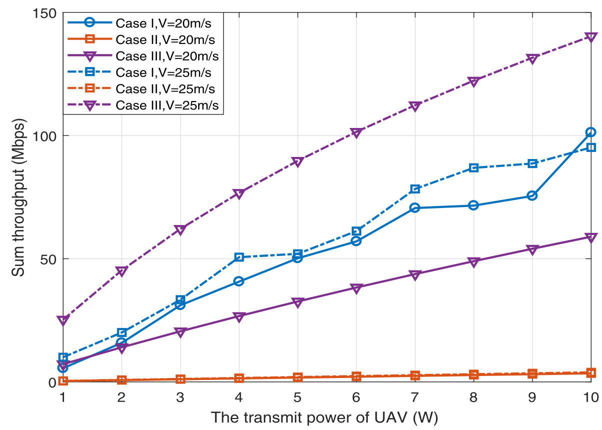

FIGURE 13. **The sum throughput versus the maximum transmit power of the UAV with different velocity of the UAV.**

same velocity and altitude of the UAV, the sum throughput of Case III is the highest and Case II is the lowest. When the UAV flies at the same altitude, the sum throughput increases as the velocity increases. For a certain case, the higher the flight altitude of the UAV maintains, the lower the sum throughput is obtained. This is due to the fact that the higher the altitude of the UAV, the greater the signal attenuation, thus reducing the sum throughput of the target sensor.

In addition, we also investigate that the sum throughput versus the maximum transmit power of the UAV in Fig. 12. For the same case, when the maximum transmit power of the sensor transmitter is fixed, with the increase of the maximum transmit power of the UAV, the sum throughput increases linearly. Similarly, the maximum transmit power of the UAV remains constant, and the bigger the maximum transmit power of sensor transmitter is, the lower the sum throughput is indicated. This stems from the fact that the promotion of sensors' transmit power results in the increase of interference, hence the sum throughput decreases. Compared among the three cases, the target sensor of Case III is the furthest away from the interference, while the target sensor of Case II is the closest to the interference. Therefore, with the same parameter setting, the sum throughput of Case III is the highest and that of Case II is the lowest.

Fig. 13 shows the variation trend of three cases' sum throughput capacities with transmit power of UAV at different UAV velocity. As can be seen that, the velocity of the UAV has a great influence on Case I and Case III. The higher the velocity of UAV, the greater the throughput of sum. In Case II, the velocity change of the UAV hardly affects the trajectory, so the change of sum throughput is also very small.

VI. CONCLUSION

This paper studies the interference management problem by optimizing the power control and trajectory planning in a UAV-assisted wireless sensor network to maximize the sum throughput of the target sensor under power constraints and flight coordinate constraints. Due to the non-convexity of the objective function, we decompose the original problem into two subproblems: the transmit power control with given trajectory and the trajectory planning with given transmit power. We utilize the D.C. programming and successive convex approximation to obtain the suboptimal solutions of the two subproblems. Numerical results show that the positional relationships between the target sensor and the ground sensor pairs play a crucial role in sum throughput. The UAV's velocity, altitude and SINR required by sensor receivers affect the sum throughput to varying degrees.

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