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Joint CoMP Transmission for UAV-Aided Cognitive Satellite Terrestrial Networks

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ABSTRACT This paper investigates a novel architecture of coordinated multi-point (CoMP) transmission in the cognitive satellite-terrestrial network associated with an unmanned aerial vehicle (UAV). We consider the downlink communication where the UAV and base station (BS) cooperatively serve the terrestrial user by sharing the licensed satellite network spectrum. The goal of this paper is to maximize the achievable rate of the terrestrial user by jointly optimizing BS/UAV transmit power allocation and UAV trajectory, subjecting to the interference temperature threshold imposed on satellite network as well as UAV mobility constraint. The formulated problem is shown in a complicated non-convex form, which is hard to tackle. To this end, we decompose the original problem into two sub-problems, and the block coordinate descent method is employed to solve the two sub-problems alternately. Specifically, for the first sub-problem, the optimal BS/UAV transmit power is obtained with a given UAV trajectory by using the Lagrangian dual method. For the second sub-problem, the UAV trajectory is attained with a given BS/UAV power allocation by using the successive convex approximation technique. Simulation results show that our proposed joint CoMP transmission scheme significantly improves the terrestrial network throughput compared with other benchmark schemes.

INDEX TERMS Unmanned aerial vehicle, satellite-terrestrial networks, UAV trajectory, coordinated multi-point.

I. INTRODUCTION

Historically, the satellites (SATs) have been primarily used in navigation, remote sensing, climate forecast and emergency communications since they have high link reliability and can provide wide coverage. However, due to the expensive cost of SATs and limited technical level, it is unable to provide high data rate like in terrestrial mobile communication network [1], [2]. Fortunately, with the continuous cost reduction and technique advancement, the SATs can now achieve higher rate by equipping advanced antenna as well as allocating more bandwidth [3]–[6]. Whereas, the spectrum resource is still scarcity in current SAT systems. In addition, the frequency reuse leads to severe co-channel interference on terrestrial cellular network. Kindly note that the satellite communication (SATCom) is not used to replace the existing terrestrial network. Instead, it aims at incorporating itself into the terrestrial network to further enhance the network robustness. In this regard, a useful technique called cognitive radio (CR) has been considered as a promising approach to improve the utilization of radio spectrum [7]–[9].

The increasing demand for seamless connectivity and high data rate transmission have propelled more and more researchers to investigate the cognitive satellite terrestrial networks, where the terrestrial users regarded as secondary users communicate over the same bandwidth allocated to the primary radio networks (satellite networks) [10]–[14]. Zhang *et al*. studied the information-theoretic limits of CR network and demonstrated that dynamic time-division multiple-access scheme was optimal strategy for the ergodic sum capacity of the cognitive broadcast channel [10]. Lagunas *et al*. proposed a resource allocation technique for cognitive satellite network where the satellite system exploited the spectrum allocation to terrestrial networks users without imposing harmful interference to them [11]. An uplink transmission cognitive SAT terrestrial network was considered in [12], and the authors proposed the optimal resource allocation to maximize the system throughput with interference temperature (IT) constraint. What's more, the physical layer security (PLS) was also considered in the cognitive SAT network [13], [14], where the secondary network can access the primarily network spectrum with the PLS requirement of the primarily network guaranteed.

However, the performance of primary network will drastically degrades when the IT imposed by the base station (BS) to primary users exceeds a predefined value [15], [16]. Especially, as the distance between primary user and BS is shorter than the distance between secondary user and BS, it is difficult to obtain high throughput in the secondary network by optimizing BS transmit power. Are there any other techniques to address the spectrum scarcity problem in the further network? The answer is yes. The use of low-cost and advanced unmanned aerial vehicles (UAVs) as mobile base stations are emerged as a promising solution to expand effective coverage range and improve the wireless network capacity [17]–[21]. The prominent advantage of UAV lies in its ability to freely move in the sky [22]–[26]. To effectively design the UAV trajectory, some works have been studied for the UAV trajectory optimization problem [27]–[29]. The work [27] studied a point-to-point downlink communication system, whose aim was to maximize the system' energy efficiency (defined as ratio of system throughput to UAV's energy consumption) by optimizing the UAV trajectory. Multiple UAVs to serve multiple users in the downlink scenario was studied in [28], where the goal of this paper was to maximize the minimum throughput over all users by jointly optimizing the multi-UAV trajectory and communication access scheme. Moreover, a new UAV-enabled wireless power transfer system was proposed in [29], where the UAV was equipped with energy transmitter to deliver wireless energy to the ground energy receivers for optimizing the total achieved energy by optimizing the UAV's mobility. Motivated by UAV-assisted wireless communications, the cognitive UAV communication paradigm was firstly proposed in [30]. In [30], the authors investigated a simple scenario where the UAV communicated with a secondary user in the presence of multiple primary ground users. Then, the problem was formulated to maximize the secondary user's average achievable rate by jointly optimizing UAV trajectory and power allocation along with the IT constraint at primary ground users, which was addressed by leveraging successive convex approximation (SCA) techniques.

In this paper, we consider a new UAV-enabled cognitive satellite-terrestrial network, where the coordinate multi-point (CoMP) technique is incorporated into cognitive system. In fact, CoMP technique is widely recognized as an effective mechanism for managing intercell interference and improving system throughput in cellular networks with frequency reuse [31]. Specifically, the BS and UAV transmit same data to the secondary user in the presence of satellite terrestrial user (primary user) with same bandwidth. For protecting the primary network performance, the interference imposed from BS and UAV transmit power to the primary user must be less than the predefined value for accessing the licensed satellite network spectrum, which means that BS/UAV transmit power as well as UAV trajectory should be carefully designed. On the one hand, when BS and UAV allocate more transmit power to secondary user, more interference will be imposed on primary user. On the other hand, if the UAV moves closer to secondary user, i.e., moving farther away from primary user, the UAV can use more power for secondary user to improve the cognitive network throughput. Based on this fact, our goal is to maximize the secondary user's achievable rate by jointly optimizing BS/UAV transmit power allocation and UAV trajectory with IT threshold constraint and UAV mobility constraint. However, the formulated problem is shown to be a non-convex and complicated expression, which has no standard method to solve. To tackle this challenge, we decompose the original problem into two sub-problems, and then a block coordinate descent method is used to solve the two sub-problems alternately. Specifically, for the first sub-problem, the optimal BS/UAV transmit power is obtained with given UAV trajectory by solving it using dual method, which has low computation complexity. For the second sub-problem, the UAV trajectory is obtained with given BS/UAV power allocation by solving it using SCA technique. Based on these, an iterative algorithm is proposed for solving original problem by alternately optimizing these two sub-problems. Finally, the numerical results show that the significant throughput gain are obtained by our proposed paradigm compared with other three benchmarks.

This paper is organized as follows. Section II introduces the system model and problem formulation. Section III consists of three subsections. In the first subsection, we obtain the optimal BS/UAV power allocation with given pre-determined UAV trajectory. In the second subsection, we design an algorithm for UAV trajectory with given BS/UAV power allocation. In the third subsection, we design a joint BS/UAV power allocation and UAV trajectory algorithm for our proposed scheme. The numerical results are presented in Section IV. Finally, the conclusion is given in Section V.

II. SYSTEM MODEL AND PROBLEM FORMULATION

We consider a UAV-enabled cognitive satellite-terrestrial network as shown in Fig. 1, where the SAT network corresponding to primary network shares the same spectrum with the UAV-aided terrestrial network corresponding to secondary network. The SAT transmits the signal to earth station (primary user, PU) while the BS and UAV jointly transmit same common data to the terrestrial user (second user, SU). We assume that the UAV can freely adjust its moving direction in a horizontal plane with fixed altitude H_u during time horizon T. The horizontal coordinate of the PU, SU and BS are respectively denoted as $\mathbf{w}_e$, $\mathbf{w}_m$ and $\mathbf{w}_b$. In addition, the altitude of BS is fixed with H_b. To make the problem more tractable, the continuous time T is approximately divided into

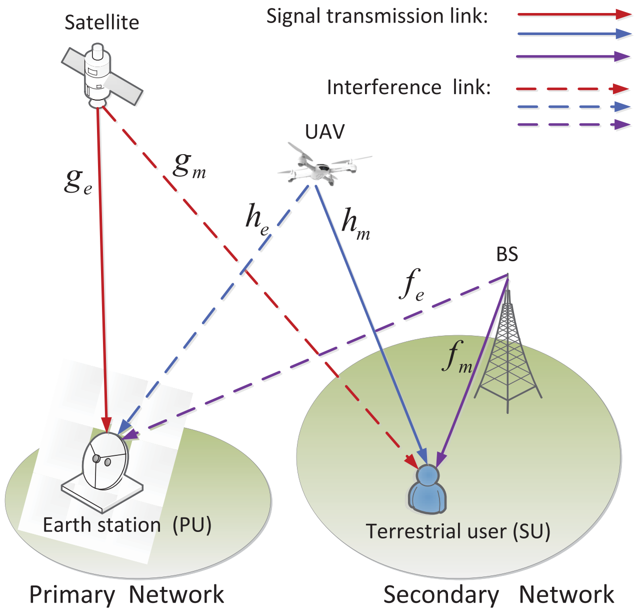

FIGURE 1. UAV-aided transmission in cognitive satellite terrestrial network.

N-length time slots with each time slot duration $\delta = T/N$. Thus, the horizontal coordinate of the UAV at time slot n can be denoted as $\mathbf{q}[n], \forall n$. kindly note that here, a rotary wing UAV is used in our system model for its high mobility and stationary properties.

A. BS-TERRESTRIAL USER CHANNEL MODEL

Assume that the links between BS and SU/PU undergo Rayleigh fading [19]. Thus, the channel power gain between BS and SU/PU can be modeled as

$$f_k = \frac{\beta_0}{\left(H_b^2 + \|\mathbf{w}_b - \mathbf{w}_k\|^2\right)^{\frac{\alpha}{2}}} \upsilon_k, \tag{1}$$

where $k \in \mathcal{K} \triangleq \{e, m\}$, β_0 represents the reference channel gain at distance 1m, α denotes path-loss exponent, and υ_k follows exponential distribution, which is given by $\upsilon_k \sim \text{EXP}(1)$. Note that the time slot n is omitted in (1) by assuming that within each time slot, the BS-SU/PU channel gain follows exponential distribution with same expectation.

B. UAV-TERRESTRIAL USER CHANNEL MODEL

For ease of exposition, a commonly-used air-to-ground (A2G) free-space path loss model is adopted [19], [27], [28]. It is worth noting that the free-space path loss model does not consider the small-scale fast fading since the UAV moves in a high altitude and the line-of-sight (LoS) is dominated. In addition, the Doppler effect due to the mobility of UAV is assumed perfectly compensated at the SU/PU [32]. Thus, the channel gain from UAV to SU/PU at time slot n can be expressed as

$$h_k[n] = \frac{\beta_0}{H_u^2 + \|\mathbf{q}[n] - \mathbf{w}_k\|^2}, \quad k \in \mathcal{K}. \tag{2}$$

C. SATELLITE-TERRESTRIAL USER CHANNEL MODEL

For the SAT channel links, the channel coefficients from SAT to SU/PU follow shadowed-Rician (SR) model [13], [33], which can be written as

$$\bar{g}_k = A\exp(j\phi) + Z\exp(j\varphi), \quad k \in \mathcal{K}. \tag{3}$$

where $\phi \in [0\ 2\pi]$ denotes the stationary random phase and φ denotes the deterministic phase of the LoS component. In addition, A and Z represent the amplitudes of the scattering and the LoS components, respectively. The distribution of the satellite channel follows $\bar{g}_k = (b, m, \Omega)$, where $2b$ represents the average power of multiple paths, m denotes the Nakagami channel with coefficient m, and Ω is the average power of LoS component.

Denote the transmit power of SAT as P_s, which is assumed to be invariant over each time slot. In addition, the transmit power of BS and UAV within time slot n are respectively denoted as $p_b[n]$ and $p_u[n]$. Therefore, the achievable rate of SU (bps/Hz) within time slot n can be expressed as

$$R_m[n] = \log_2\left(1 + \frac{G_u p_u[n]\, h_m[n] + G_b p_b[n] f_m}{G_s(\theta) P_s g_m + \sigma_m^2}\right), \tag{4}$$

where g_m represents the channel gain from SAT to SU and can be calculated as $g_k = |\bar{g}_k / D|^2, k \in \mathcal{K}$, where D denotes the distance between SAT and ground user. σ_m^2 denotes the power of additive Gaussian white noise at SU, G_u and G_b represent the UAV and BS directional antenna gain, $G_s(\theta)$ denotes the SAT's transmit antenna gain, which is determined by the angle between SAT and SU, and can be approximately represented as [34]

$$G_s(\theta) = G_{tx}\left(\frac{J_1(u)}{2u} + 36\frac{J_3(u)}{u^3}\right)^2 \tag{5}$$

where G_{tx} is a positive constant, $u = 2.07123 \sin\theta / \sin\theta_{3\text{dB}}$ ($\theta_{3\text{dB}}$ is the 3-dB angle, θ is the angle between SAT and SU), J_1 and J_3 are the first-kind Bessel function of order 1 and 3.

Thus, the received interference-to-noise-ratio (INR) from BS and UAV to PU within time slot n is denoted as $\gamma_e[n]$, which can be given by

$$\gamma_e[n] = \frac{p_b[n]\, G_b f_e + p_u[n]\, G_u h_e[n]}{\sigma_e^2}, \tag{6}$$

where σ_e^2 denotes the power of additive Gaussian white noise at PU.

Remark 1: Kindly note that from (4) and (6), we can see that both BS/UAV transmit power and UAV trajectory not only have a significant impact on the SU's achievable rate but also affect the interference of PU. Specifically, the increased BS/UAV transmit power will improve the achievable rate of SU while increases the interference at PU. Furthermore, as the UAV moves closer to PU, the received interference at PU will also increase. Based on the fact that the SU can access the licensed satellite spectrum resource as long as the interference imposed by the terrestrial network to the PU is lower than than the IT threshold vaule [11], [35]. Therefore, it has to carefully design the BS/UAV power allocation and UAV trajectory.

D. PROBLEM FORMULATION

Our objective is to maximize the SU's total achievable rate over a given horizon time T by jointly optimizing BS/UAV power allocation $\{p_b[n]\}_{n=1}^N$ and $\{p_u[n]\}_{n=1}^N$ as well as UAV trajectory $\{\mathbf{q}[n]\}_{n=1}^N$. Accordingly, the problem can be formulated as follows

$$\text{(P)} \quad \max_{p_b[n],p_u[n],\mathbf{q}[n]} \sum_{n=1}^{N} R_m[n]$$
$$\text{s.t. } P_r(\gamma_e[n] \le \gamma_{\text{th}}) \ge 1 - P_{\text{out}}, \quad \forall n, \quad (7)$$
$$\|\mathbf{q}[n+1] - \mathbf{q}[n]\| \le V_{\max}\delta, \quad n = 1, \ldots, N-1, \quad (8)$$
$$\mathbf{q}[1] = \mathbf{q}_0, \mathbf{q}[N] = \mathbf{q}_F, \quad (9)$$
$$\le p_b[n] \le p_b^{\max}, \quad \forall n, \quad (10)$$
$$\le p_u[n] \le p_u^{\max}, \quad \forall n, \quad (11)$$

where γ_{th} and P_{out} denote the IT threshold and interference constraint at the PU, respectively; (8) represents the UAV's mobility constraint with the maximum UAV speed $V_{\max}$; (9) denotes the UAV's initial location and final location constraint; (10) and (11) represent the maximum transmit power constraint over T, with $p_b^{\max}$ and $p_u^{\max}$ denoting the maximum power limits at BS and UAV, respectively.

III. PROPOSED SOLUTION

It is challenging to directly solve problem (P) due to the following two reasons. First, the BS/UAV power and UAV trajectory are coupled in objective function which yields a non-convex form. Second, the left hand side of constraint (7) is a complicated function. To this end, we first take some algebraic manipulations on constraint (7), we can rewrite it as

$$\begin{aligned} &P_r(\gamma_e[n] \le \gamma_{\text{th}}) \\ &= P_r\left(\frac{p_b[n]G_bf_e + p_u[n]G_uh_e[n]}{\sigma_e^2} \le \gamma_{\text{th}}\right) \\ &= P_r\left(f_e \le \frac{\gamma_{\text{th}}\sigma_e^2 - p_u[n]G_uh_e[n]}{p_b[n]G_b}\right) \\ &= P_r\left(\upsilon_e \le \frac{\gamma_{\text{th}}\sigma_e^2 - p_u[n]G_uh_e[n]}{p_b[n]G_b}\frac{\left(H_b^2 + \|\mathbf{w}_b - \mathbf{w}_e\|^2\right)^{\frac{\alpha}{2}}}{\beta_0}\right) \\ &\stackrel{a}{=} 1 - \exp\left(-\frac{\gamma_{\text{th}}\sigma_e^2 - p_u[n]G_uh_e[n]}{p_b[n]G_b}\frac{\left(H_b^2 + \|\mathbf{w}_b - \mathbf{w}_e\|^2\right)^{\frac{\alpha}{2}}}{\beta_0}\right), \end{aligned} \quad (12)$$

where inequality (a) holds since υ_e follows exponential distribution with expectation 1. By substituting (12) into constraint (7), we can easily obtain

$$\frac{\beta_0 p_u[n]}{H_u^2 + \|\mathbf{q}[n] - \mathbf{w}_e\|^2} \le \frac{G_b p_b[n]\ln(P_{\text{out}})}{G_u Q} + \frac{\gamma_{\text{th}}\sigma_e^2}{G_u}, \quad (13)$$

where $Q = \left(H_b^2 + \|\mathbf{w}_b - \mathbf{w}_e\|^2\right)^{\frac{\alpha}{2}}/\beta_0$. However, the reformulated new constraint constraint (13) is still non-convex due to the coupled UAV trajectory and UAV transmit power in the left hand side of (13).

To proceed, we first split the original problem into two sub-problems and then develop a block coordinate descent method to solve problem (P). Specifically, for the first sub-problem, denoted as (P1), the BS/UAV transmit power is optimized with given UAV trajectory relying on Lagrangian dual method. For the second sub-problem, denoted as (P2), the UAV trajectory is calculated with given BS/UAV power allocation by means of successive convex approximation (SCA) technique. Finally, an iterative algorithm is proposed for solving original problem (P) by alternately optimizing these two sub-problems.

A. BS/UAV POWER OPTIMIZATION

In this subsection, we consider the first sub-problem (P1) for optimizing BS/UAV power allocation $\{p_b[n], p_u[n]\}_{n=1}^N$ with given UAV trajectory $\{\mathbf{q}[n]\}_{n=1}^N$, which can be reformulated as

$$\text{(P1)} \quad \max_{p_b[n],p_u[n]} \sum_{n=1}^{N} R_m[n] \quad \text{s.t. } (10), (11), (13).$$

It can be verified that objective function and constraints in problem (P1) are all convex. Thus, problem (P1) can be efficiently solved by standard convex optimization techniques. Instead of relying on a generic solver, herein we propose a BS/UAV power allocation strategy based on dual method. It can be shown that problem (P1) satisfies the Slater's condition. That is, the strong duality is zero [36]. To this end, we introduce the dual variables $\{\lambda_n \ge 0\}_{n=1}^{n=N}$. Then, the corresponding partial Lagrangian function of problem (P1) can be expressed as (14), shown at the bottom of this page.

Accordingly, the dual function for (P1) is given by

$$g(\lambda_n) = \begin{cases} \max\limits_{p_u[n],p_b[n]} \mathcal{L}(p_u[n], p_b[n], \lambda_n) \\ \text{s.t. } (10), (11). \end{cases} \quad (15)$$

By applying the Karush-Kuhn-Tucker (KKT) conditions [36], the optimal BS and UAV power allocation to dual function

$$\mathcal{L}(p_u[n], p_b[n], \lambda_n) = \sum_{n=1}^{N} \log_2\left(1 + \frac{G_u p_u[n]h_m[n] + G_b p_b[n]f_m}{G_s(\theta)P_s g_m + \sigma_m^2}\right) + \sum_{n=1}^{N} \lambda_n\left(\frac{G_b p_b[n]\ln(P_{out})}{G_u Q} + \frac{\gamma_{th}\sigma_e^2}{G_u} - p_u[n]h_e[n]\right). \quad (14)$$

$g(\lambda_n)$ are respectively given by

$$p_u^{opt}[n]=\left[\frac{1}{\ln 2\lambda_n h_e[n]}-\frac{G_s(\theta)P_s g_m+\sigma_m^2+G_b p_b[n] f_m}{G_u h_m[n]}\right]_0^{p_u^{\max}}, \quad (16)$$

and

$$p_b^{opt}[n]=\left[-\frac{G_u Q}{G_b \lambda_n \ln(P_{out})} - \frac{G_s(\theta)P_s g_m+\sigma_m^2+G_u p_u[n] h_m[n]}{G_b f_m}\right]_0^{p_b^{\max}} \quad (17)$$

where $[x]^+ = \max\{x, 0\}$.

Next, we will address the corresponding dual problem, which is given by

$$(\text{P - D}) \min_{\lambda_n \geq 0} g(\lambda_n) \quad (18)$$

The dual problem (P-D) can be efficiently solved by the subgradient method and the update rule of parameters $\{\lambda_n\}$ is given by

$$\lambda_n^{t+1}=\left[\lambda_n^t-\pi_1\left(\frac{G_b p_b[n]\ln(P_{\text{out}})}{G_u Q}+\frac{\gamma_{\text{th}}\sigma_e^2}{G_u}-p_u[n] h_e[n]\right)\right]^+, \quad (19)$$

where the the superscript t denotes the iteration index, and π_1 is the positive step size. The detailed procedures for finding the optimal BS/UAV power allocation are summarized in Algorithm 1. Thus, the total complexity of the proposed Algorithm 1 is $\mathcal{O}(K_\lambda N)^2$, where N denotes the number of dual variables, and K_λ represents the required number of iterations for updating λ_n [37]–[39].

Algorithm 1 BS/UAV Power Allocation Optimization Using Subgradient Method

1: **Initialize** $\{\lambda_n\}^t \geq 0$, $\pi_1 \geq 0$, $t = 0$
2: **repeat**.
3: Obtain $p_u^{opt}[n]$ and $p_b^{opt}[n]$ using (16) and (17).
4: Compute the parameters $\{\lambda_n^{t+1}\}$ using (19).
5: $t = t + 1$.
6: **until** problem (P-D) converges to the required accuracy.
7: **Output:** $p_u^{opt}[n]$ and $p_b^{opt}[n]$ for $n = 1, \ldots, N-1$.

B. UAV TRAJECTORY OPTIMIZATION

In this subsection, we consider the second sub-problem (P2) for optimizing UAV trajectory with given BS/UAV power allocation. The problem (P) can be recast to

$$(\text{P2}) \quad \max_{\mathbf{q}[n]} \sum_{n=1}^{N} R_m[n] \quad \text{s.t. } (8),\ (9),\ (13).$$

One can see that the objective function of problem (P2) and constraint (13) is non-convex with respect to (w.r.t.) UAV trajectory $\mathbf{q}[n]$. In the following, we obtain an efficient approximation solution to (P2) based on SCA technique.

By defining $\mu_n = 1 + \frac{G_b p_b[n] f_m}{G_s(\theta)P_s g_m+\sigma_m^2}$ and $s[n] = \frac{G_u p_u[n]\beta_0}{G_s(\theta)P_s g_m+\sigma_m^2}$, the SU's achievable rate $R_m[n]$ can be rewritten as

$$R_m[n]=\log_2\left(\mu_n+\frac{s[n]}{\|\mathbf{q}[n]-\mathbf{w}_m\|^2+H_u^2}\right). \quad (20)$$

Although the $R_m[n]$ is not convex w.r.t. $\mathbf{q}[n]$, it is convex over $\|\mathbf{q}[n]-\mathbf{w}_k\|^2$. Therefore, with given local point $\|\mathbf{q}_l[n]-\mathbf{w}_k\|^2$ over l-iteration, the inequality holds in (21), as shown at the bottom of this page. It can be proved that the term $R_m^{lb}[n]$ is now convex w.r.t. the UAV trajectory $\mathbf{q}[n]$. Consequently, the objective function $R_m[n]$ can be replaced by its corresponding lower bound $R_m^{lb}[n]$.

To handle the non-convex constraint (13), we first reformulate it by introducing slack variables $\{Q_e[n]\}$ as

$$\frac{\beta_0 p_u[n]}{Q_e[n]+H_u^2} \leq \frac{G_b p_b[n]\ln(P_{\text{out}})}{G_u Q}+\frac{\gamma_{\text{th}}\sigma_e^2}{G_u}, \quad \forall n,$$
$$\Rightarrow \beta_0 p_u[n] \leq \left(\frac{G_b p_b[n]\ln(P_{\text{out}})}{G_u Q}+\frac{\gamma_{\text{th}}\sigma_e^2}{G_u}\right)(Q_e[n]+H_u^2), \quad (22)$$

with additional constraints

$$\|\mathbf{q}[n]-\mathbf{w}_e\|^2 \geq Q_e[n], \quad \forall n,$$
$$Q_e[n] \geq 0, \quad \forall n. \quad (23)$$

Remark 2: It can be shown that to achieve the optimal solution to problem (P2), we must have $\|\mathbf{q}[n]-\mathbf{w}_e\|^2 = Q_e[n], \forall n$. Otherwise, one can decrease $Q_e[n]$ until obtain a larger constraint set without decreasing the objective value.

It can be found that constraint (22) is convex while constraint (23) is non-convex. To solve it, the SCA technique is still applied. More precisely, with a given local point $\{\mathbf{q}_l[n]\}$

$$R_m[n] \geq \log_2\left(\mu_n+\frac{s[n]}{\|\mathbf{q}_l[n]-\mathbf{w}_m\|^2+H_u^2}\right)-\frac{s[n]}{\ln 2\left(\mu_n\|\mathbf{q}_l[n]-\mathbf{w}_m\|^2+\mu_n H_u^2+s[n]\right)\left(\|\mathbf{q}_l[n]-\mathbf{w}_m\|^2+H_u^2\right)} \times\left(\|\mathbf{q}[n]-\mathbf{w}_m\|^2-\|\mathbf{q}_l[n]-\mathbf{w}_m\|^2\right) \triangleq R_m^{lb}[n] \quad (21)$$

over l-iteration, we thus have

$$\begin{aligned} &\|\mathbf{q}[n]-\mathbf{w}_e\|^2 \\ &\quad\geq \|\mathbf{q}_l[n]-\mathbf{w}_e\|^2 + 2(\mathbf{q}_l[n]-\mathbf{w}_e)^{\mathrm{T}} \\ &\qquad\times(\mathbf{q}[n]-\mathbf{q}_l[n]) \triangleq \Phi^{lb}(\mathbf{q}[n]), \quad \forall n, \end{aligned} \tag{24}$$

As a result, the constraint (23) can be rewritten as

$$\begin{aligned} \Phi^{lb}(\mathbf{q}[n]) &\geq Q_e[n], \quad \forall n, \\ Q_e[n] &\geq 0, \quad \forall n. \end{aligned} \tag{25}$$

So, for a given local point $\{\mathbf{q}_l[n]\}$, the lower bound of (P2) is given by

$$\left(\mathrm{P}^{lb}2\right) \quad \max_{\mathbf{q}[n], Q_e[n]} \sum_{n=1}^{N} R_m{}^{lb}[n] \quad \text{s.t. } (8),\ (9),\ (22), (25).$$

Thus far, The problem ($\mathrm{P}^{lb}2$) is convex and can be efficiently solved by standard convex techniques. In other words, the problem (P2) can be approximately solved by successively updating the UAV trajectory based on the optimal solution to problem ($\mathrm{P}^{lb}2$). The detailed procedures are summarized in Algorithm 2. Note that the related problem ($\mathrm{P}^{lb}2$) is a convex quadratic programming problem, which involves $3N$ scalar real decision variables and $N-1$ quadratic constraints, and thus the computational complexity of ($\mathrm{P}^{lb}2$) is $\mathcal{O}\left((3N)^2(N-1)^{2.5}+(N-1)^{3.5}\right)$ [40].

Algorithm 2 UAV Trajectory Optimization With SCA Technique

1: **Initialize** $\{\mathbf{q}_l[n]\}_{n=1}^{N}$, $l=0$
2: **repeat**.
3: Obtain the optimal UAV trajectory, denoted as $\left\{\mathbf{q}^{opt}[n]\right\}_{n=1}^{N}$ by solving problem ($\mathrm{P}^{lb}2$).
4: Update the UAV trajectory $\mathbf{q}^{opt}[n]=\mathbf{q}_l[n], \forall n$.
5: $l=l+1$.
6: **until** the problem (P2) converges to the required accuracy.
7: **Output:**optimal UAV trajectory $\left\{\mathbf{q}^{opt}[n]\right\}_{n=1}^{N}$.

C. JOINT BS/UAV POWER AND UAV TRAJECTORY OPTIMIZATION

In this subsection, a block coordinate descent method is leveraged to solve the original problem (P) [41]. Specifically, based on the solutions to the two sub-problems, a block coordinate descent method is proposed for jointly optimizing problem (P1) and (P2), which is summarized in Algorithm 3. We optimize the two sub-problems alternately until it converges to a predefined accuracy. Note that after each iteration, the objective value of problem (P) is monotonically non-decreasing and the objective value of (P) is upper bounded by a finite value. Thus, the proposed method is guaranteed to converge. In addition, the overall computational complexity of Algorithm 3 is $\mathcal{O}\left(L\left((K_\lambda N)^2+(3N)^2(N-1)^{2.5}+(N-1)^{3.5}\right)\right)$, where L denotes the required number of iterations to converge.

Algorithm 3 Block Coordinate Descent Method For Solving Problem (P)

1: **Initialize** the UAV trajectory.
2: **repeat**.
3: Obtain the optimal BS/UAV power allocation by solving Algorithm 1.
4: Fix the BS/UAV power allocation, obtain the UAV trajectory by solving Algorithm 2.
5: **until** the problem (P2) converges to the prescribed accuracy.
6: **Output:** UAV trajectory $\left\{\mathbf{q}^{opt}[n]\right\}_{n=1}^{N}$ and BS/UAV power allocation $\{p_b^{opt}[n], p_u^{opt}[n]\}_{n=1}^{N}$.

IV. NUMERICAL RESULTS

In this section, the numerical simulations are provided to evaluate the performance of our scheme. The corresponding parameter values are summarized in Table 1. Unless otherwise specified, we set the locations of BS, SU and PU as $\mathbf{w}_b=(0,0)^{\mathrm{T}}$, $\mathbf{w}_m=(-400,0)^{\mathrm{T}}$ and $\mathbf{w}_e=(-200,0)^{\mathrm{T}}$, respectively.

TABLE 1. Simulation parameters.

Parameter	Value
Channel gain: β_0	-50dB
Channel path-loss exponent: α	3
Noise power: σ_m^2, σ_e^2	-110dBm
Duration of each time slot: δ	0.5s
UAV altitude: H_u	100m
UAV maximum transmit power: $p_u^{\max}$	1W
UAV maximum speed: V_{max}	30m/s
BS altitude: H_b	30m
BS maximum transmit power: $p_b^{\max}$	10W
IT threshold: γ_{th}	5×10^4
Interference constraint: P_{out}	5×10^{-3}
Beam angle from SAT to SU: θ	0.01° [33]
SAT link with average shadowing: (b, m, Ω)	$(0.126, 10, 0.835)$
SAT transmit power: P_s	80W [33] [34]
Antenna gains of UAV and BS: G_b, G_u	16dBi [33] [34]
Positive constant: G_{tx}	52dBi [33] [34]
Distance between UAV and terrestrial user: D	3.6×10^7m

We consider the first case where the distance between PU and BS station is relatively shorter than the distance between SU and BS station as shown in Fig. 2, namely $\mathbf{w}_m=(-400,0)^{\mathrm{T}}$ and $\mathbf{w}_e=(-200,0)^{\mathrm{T}}$. The impacts of the locations of SU and PU on UAV's power allocation will be discussed in Fig. 4. It can be seen from Fig. 2 that the UAV tends to move closer to SU to maximize the SU's achievable rate. The reason for this is that as the distance between UAV and SU becomes shorter, more power is allocated to SU. For describing the impacts of the locations of SU and PU on UAV's trajectory more explicitly, we consider the second case where the locations of SU and PU are respectively set to $\mathbf{w}_m=(-200,0)^{\mathrm{T}}$ and $\mathbf{w}_e=(-400,0)^{\mathrm{T}}$ as shown in Fig. 3.

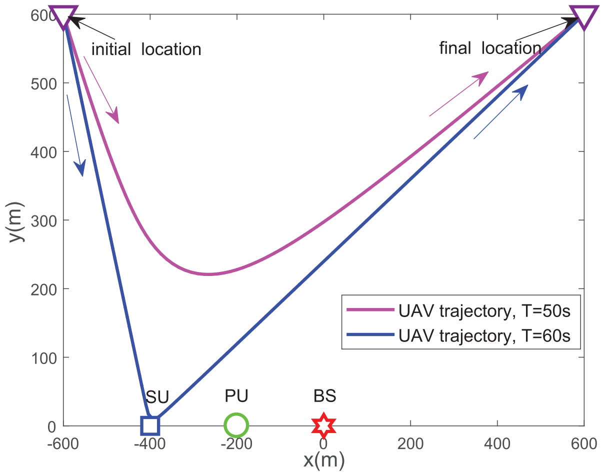

FIGURE 2. Position of BS, SU, PU and optimal UAV trajectory optimization obtained by our proposed scheme with different horizon time T, $\mathbf{w}_b = (-0, 0)^T$, $\mathbf{w}_m = (-400, 0)^T$, $\mathbf{w}_e = (-200, 0)^T$.

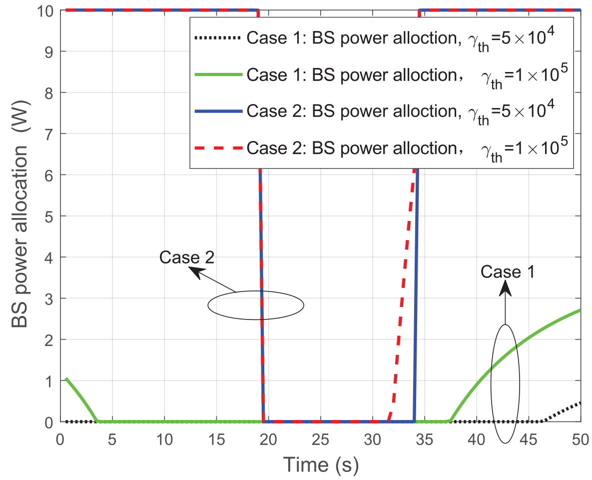

FIGURE 4. BS power allocation obtained by our proposed scheme with different locations of SU and PU .

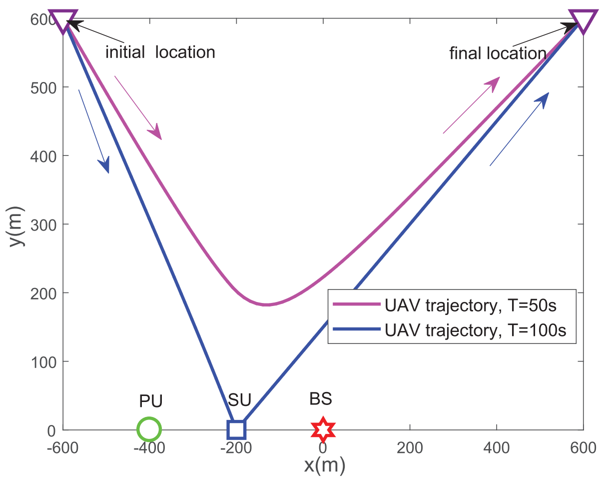

FIGURE 3. Position of BS, SU, PU and optimal UAV trajectory optimization obtained by our proposed scheme with different horizon time T, $\mathbf{w}_b = (-0, 0)^T$, $\mathbf{w}_m = (-200, 0)^T$, $\mathbf{w}_e = (-400, 0)^T$.

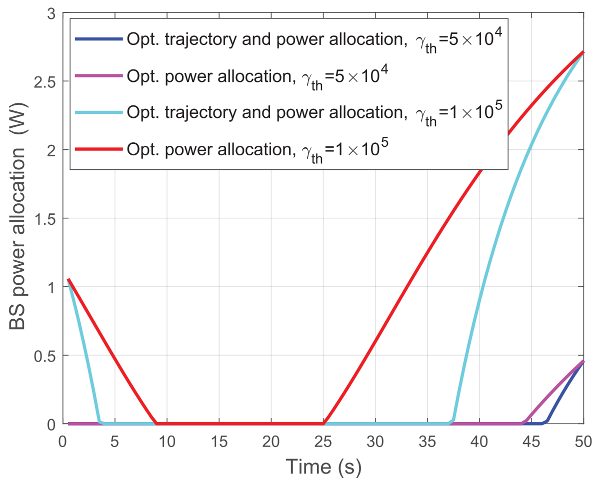

FIGURE 5. BS power allocation for the UAV trajectory of Fig. 2.

We can see from Fig. 3 that the distance between PU and BS station is longer than the distance between SU and BS station. Interestingly, we can still see that the UAV prefers to move closer to SU.

Fig. 4 shows the BS power allocation obtained by our proposed scheme with different locations of SU and PU, where case 1 and case 2 correspond to the first case and second case, respectively. For the given IT threshold at PU, we can observe that the BS transmit power of case 2 is higher than case 1 at any time. This can be attributed to the fact that since the PU is closer to BS in case 1 than that in case 2, less power should be transmitted to reduce the interference on the PU. Moreover, we depict the BS power allocation with different IT thresholds. It is observed from Fig. 4 that with same case, when the allowed IT threshold γ_{th} on PU increases, the more BS power is transmitted. This result can be easily explained that the larger IT threshold is allowed, the more BS power can be transmitted.

The impact of different IT thresholds on BS power allocation is plotted in Fig. 5. Two schemes are compared, i.e., our proposed scheme (opt. trajectory and power allocation) and UAV/BS power allocation with direct path from initial location to final location (opt. power allocation). With given IT threshold value, for example, $\gamma_{th} = 5 \times 10^4$, the BS power obtained by 'opt. trajectory and power allocation scheme' is smaller than the benchmark scheme 'opt. power allocation'. It is expected that as the UAV moves closer to PU, the interference will increase, which indicates that the BS should reduce power transmission for ensuing the IT threshold on PU below a prescribed value. Furthermore, with a larger IT threshold value, The BS power is expected to transmitted more power for boosting the SU's achievable rate. The UAV transmit power allocation is also plotted in Fig. 6. It can be seen that the UAV power obtained by our proposed scheme is smaller than the benchmark scheme. As well, UAV transmits more power as the IT threshold becomes larger.

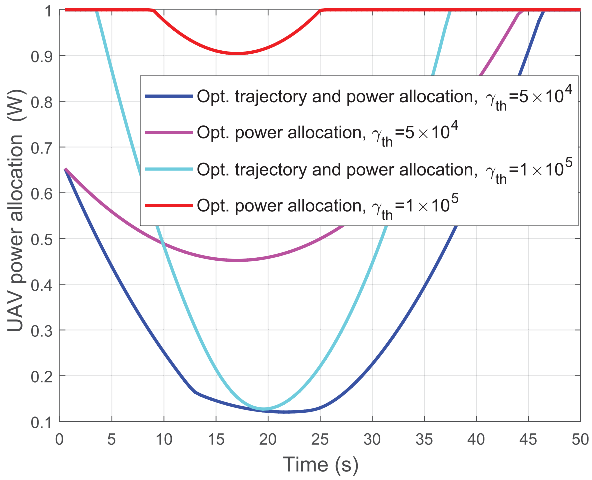

FIGURE 6. UAV power allocation for the UAV trajectory of Fig. 2.

To show the superiority of our proposed scheme, we compare our proposed scheme with other benchmarks, i.e., Opt. UAV/BS power with straight path scheme, Opt. BS power, no UAV scheme and Opt. UAV and BS power with fly-hover-fly path scheme in terms of SU's total throughput as shown in Fig. 7. The explicitly of explanations of these schemes are given as follows:

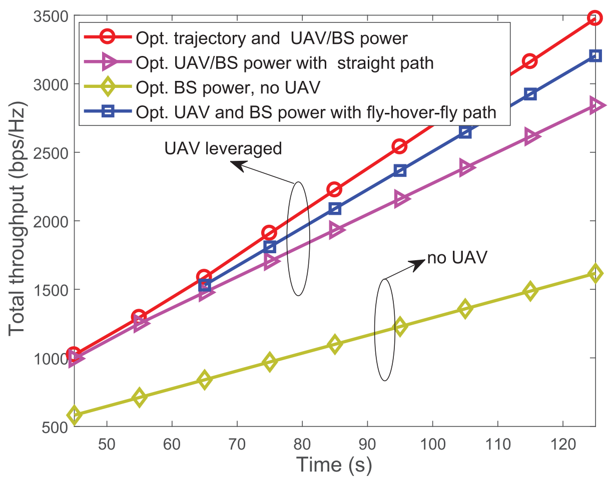

FIGURE 7. The total achievable rate of SU as a function of the deadline time T with different benchmarks.

- **Opt. trajectory and UAV/BS power scheme:** this is our proposed scheme which considers both UAV/BS power allocation and UAV trajectory. The UAV/BS power and UAV trajectory are optimized via solving Algorithm 3.
- **Opt. UAV/BS power with straight path scheme:** for this scheme, the UAV flies directly from the initial location to final location with constant speed $\frac{\|\mathbf{q}_F-\mathbf{q}_0\|}{T}$. What' more, the BS and UAV power allocation are optimized using Algorithm 1.
- **Opt. BS power, no UAV scheme:** for this scheme, we assume that there have no UAV, which indicates no UAV trajectory and UAV power are optimized. However, the BS power is still optimized to maximize the SU's total achievable rate.
- **Opt. UAV and BS power with fly-hover-fly path scheme:** for this scheme, we assume that the UAV first directly flies from the initial location to SU with maximum UAV flying speed, then hovers above the SU for staying with maximum allowed time, and finally directly flies from the SU to final location with maximum UAV flying speed. In addition, with the above UAV trajectory, the BS and UAV power allocation are optimized and can be efficiently solved by Algorithm 1.

From Fig. 6, it can be observed that as the time horizon T becomes larger, the SU's total throughput with UAV and BS joint transmission becomes more remarkable compared with only BS serving SU. Furthermore, we note that the significant gains are obtained by means of jointly optimizing UAV trajectory and BS/UAV power allocation. For example, for $T = 85s$, the SU's total throughput proposed by our scheme is 2225bps/Hz, 'Opt. UAV and BS power with fly-hover-fly path scheme' is 2089bps/Hz and 'Opt. UAV/BS power with straight path scheme' is 1933bps/Hz, whereas 'Opt. BS power, no UAV scheme' is only 1099bps/Hz, which implies a 6.1%, 13.1% and 50.6% increase of the SU's total throughput. In addition, we also see that the UAV trajectory optimization is more prominent than only optimizing UAV power allocation.

V. CONCLUSION

This paper studied the UAV-aided cognitive satellite terrestrial network, where the UAV and BS adopted joint transmission to enhance the terrestrial network performance. The objective of this paper was to maximize the terrestrial user's achievable rate by jointly optimizing BS/UAV transmit power allocation and UAV trajectory with the interference temperature threshold constraint and UAV mobility constraint. With the given UAV trajectory, the optimal BS and UAV transmit power were obtained by solving it using dual method, which yielded a low computation complexity algorithm. Besides, with given BS/UAV power allocation, the UAV trajectory was obtained by using successive convex approximation technique. Then, an iterative algorithm was proposed to jointly optimizing UAV trajectory and BS/UAV power allocation. Two main insights were extracted by the simulation results and our analysis: (1) the obtained total throughput of SU with UAV-aided transmission schemes was higher than only BS transmission scheme; (2) the UAV trajectory optimization was more prominent than optimizing UAV power allocation.

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