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SE and EE Optimization for Cognitive UAV Network Based on Location Information

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ABSTRACT Unmanned Aerial Vehicle (UAV) aided communication has the potential to provide on-demand wireless services and improve the outdoor link throughput. Applications for UAVs are rapidly growing with the development of Internet of Things. Because of limited battery energy, the UAVs need time-limited spectrum access to complete data transmission. Hence there are two challenges for the UAV-based communication: 1) Spectrum-efficient design; 2) Energy-efficient design. In this paper, we investigate the optimization of spectrum efficiency (SE) and energy efficiency (EE) for cognitive UAV network based on location information. Because of high mobility, the cognitive radio (CR) based UAVs operate on different frequency bands that vary with time and space. Thus, one spectrum band that is available in one region may not be necessarily available in another region. Based on location information of the primary transmitter and the UAV, we propose a hybrid mode in which the sensing performance and UAV's transmit power can be adjusted simultaneously to satisfy the outage constraint of the primary user. The multi-objective optimization theory is used to solve the tradeoff between SE and EE. The UAV's transmit power, sensing time and sensing threshold are optimized jointly to solve the tradeoff problem. To further improve the SE and EE performance, we propose a multi-frame combined sensing scheme, in which multiple frames are bundled together. Simulation results are provided to show the SE-EE tradeoff design, to validate the effectiveness of the proposed hybrid mode, and to show the advantages of the multi-frame combined sensing scheme in EE performance.

INDEX TERMS UAV, spectrum efficiency, energy efficiency, cognitive radio, multi-frame combined sensing.

I. INTRODUCTION

Recently, Unmanned Aerial Vehicles (UAVs) have attracted much attention due to their wide use in many applications. Examples of the applications include: military operations, fire control, tracking and surveillance, wilderness search and many others [1]. The UAVs are equipped with cameras, sensors and communication equipment, which can be used for reconnoitering and monitoring purposes. With the advantages of high maneuverability and flexibility, the UAVs are widely used to assist the wireless devices on the ground [2]. UAV plays an important role in high-speed 5G wireless network. The network connection can be expanded from ground to air and various services can be provided for hot spots in different locations. Compared with terrestrial communication, UAV-assisted communication has the advantages of rapid deployment, high mobility and low operating costs [3].

Unlike traditional cellular networks, the UAVs can be used as mobile base stations such that the wireless services can be provided with no infrastructure constraint [4]. The UAV-assisted wireless network has attracted much attention by the academia and industry since it can alleviate urgent

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communication problems (e.g., natural disaster, hotspot, severe shadowing, etc.) effectively. The traffic offloading will be more efficient and flexible with UAV-assisted wireless network. In emergencies, the UAVs need to be deployed intensively to accommodate the sudden increase in traffic demand. The above situation is also a critical issue that should be addressed in 5G network [5].

In order to make full use of the potential capabilities, the UAVs need to communicate in an efficient way [6]. However, the UAVs usually operate on IEEE L-Band, IEEE S-Band, and on Industrial, Scientific, and Medical (ISM) band. Hence they will compete with many other devices, such as tablets and smartphones that are transmitting in popular networks (e.g., Bluetooth and WiFi coexist in the environment where UAVs operate) [7]. In addition, the development of new services in wireless networks is increased dramatically, which leads to increased utilization of these bands. Thus, the UAVs will suffer from interference caused by other devices and vice versa. Cognitive radio (CR) is considered as a promising technology to overcome the problem of spectrum overcrowding by utilizing the licensed spectrum opportunistically, and is becoming a key technology to meet the requirements of Internet of Things (IoT) [8]. The sensors equipped on the UAV can sense the wireless environment continuously, and make full use of the idle spectrum without interfering with the primary users (PUs). Then, the UAV network performance can be improved (such as lower contention with other devices, higher throughput, lower end-to-end delay, etc.).

The limitations of traditional spectrum monitoring become increasingly prominent. In order to improve the spectrum management capability, new spectrum sensing platform should be developed. The UAV can be equipped with spectrum monitoring equipment to test the electromagnetic environment and detect the air or ground signals. It provides a novel degree of freedom (DoF) for the spectrum monitoring network [4]. After the UAV lifts off, it is able to detect the radio signals that may not be received by the ground monitoring equipment [9]. The UAV-enabled communication has the advantages of dynamic deployment and reliable line-of-sight (LoS) link. Furthermore, the UAV has less shadowing and multipath effect, so it can obtain better sensing performance.

In traditional static scenarios, the severe fading and shadowing effect on the Ground-to-Ground channel should be considered. And most of existing works focus on spatial or temporal sensing in 2D spectrum space and assume that all the secondary users share the same opportunity to utilize the licensed channel. High mobility is one of the major characteristics of UAV, which brings new issues to the UAV communication [10]. The CR based UAVs fly on different frequency bands that vary with time and space. Thus, one spectrum band that is available in one region may not be necessarily available in another region. The UAV can utilize the licensed spectrum via spectrum sensing or power control. In the overlay mode, the UAV first senses the status of the PU and then transmits data if the PU is detected to be idle. In the underlay mode, the UAV does not perform spectrum sensing, and only needs to control its transmit power reasonably so that its interference to the PU is below a certain level.

With the explosive growth of mobile multimedia communication, the limited battery power has become the main consideration of UAV. The battery energy is mainly used for hovering and powering other devices (e.g., cameras, sensors, communication module, etc.). This limits the UAV's flying time and its communication capability [11]. Energy efficiency (EE), as one of the most important performance metrics in UAV communication network, has attracted more and more attention. Energy limitation is one of the bottlenecks in the development of UAV. Most UAVs are powered by batteries, and the limited energy is difficult to ensure that the UAV can work continuously for a long time. Therefore, how to improve the information transmission rate while reducing the energy consumption of UAV communication and prolonging the UAV's operating time is an important issue that should be addressed in the development of UAV network.

The research on cognitive UAV network is still at early stage [12]. Authors in [13] investigated the spectrum sharing between UAV and terrestrial wireless communication system. In the cognitive UAV communication system, the UAV communicates with the secondary ground receiver, and there are many terrestrial communication links working on the same frequency band. The power allocation and UAV trajectory design are optimized to maximize the transmission rate from UAV to secondary receiver while the air-to-ground interference to terrestrial users is effectively controlled. The spectrum sharing between UAV small cells and cellular networks was investigated in [14]. The optimal deployment density of the UAV small cells is derived to maximize the network throughput on the condition that the cellular network efficiency constraint is satisfied. In [15], authors proposed UAV based CR to improve the sensing performance and increase the probability of accessing the idle spectrum. The UAV flies around the PU and its flight cycle is divided into sensing radian and transmission radian. Virtual cooperative sensing is proposed to improve the sensing performance of UAV system, and the throughput is maximized by optimizing the sensing radian and number of slots.

In the literature, there are some related works which deal with EE optimization in cognitive UAV networks. An efficient spectrum and energy management solution in UAV-based CR network is proposed in [16]. The three-dimensional location of the UAV and resource allocation are optimized to minimize the energy consumption of the UAV while the data rate of primary transmission is guaranteed. In [17], the energy efficient management of UAV for underlay CR system is explored where the power allocation scheme is combined with 3D positioning optimization. The idea of the above two papers is to exploit the mobility of UAV to obtain additional DoF compared with ground nodes. Authors in [18] investigated the case that the UAV simultaneously communicates with the ground receiver and a relaying UAV. The EE is maximized subject to minimal rate constraint, power budget, and interference constraint.

A UAV-based mobile relaying system is studied in [19] and [20], where the UAV is used to assist wireless communication from the source to the destination on the ground. The SE and EE are maximized by optimizing the UAV's flying speed and trajectory together with the time allocation for relaying. There is a tradeoff between SE and EE maximization by exploiting the DoF of UAV trajectory design.

The trajectory of the UAV can be properly designed to improve the system performance. In [21], the average convert transmission rate is maximized by jointly optimizing the UAV's trajectory and transmit power while the covertness constraint and transmission outage constraint are satisfied. In [22], the authors investigated the optimization of trajectories and transmit power of the UAV base station and UAV jammer such that the average secrecy rate over all information receivers is maximized. The alternating algorithm and successive convex approximation technique are used to solve the optimization problem. In [23], the throughput, energy and delay tradeoffs in UAV-enabled wireless communication are analyzed. It is shown that the communication resource allocation can be jointly designed with the UAV's trajectory design to balance the throughput requirements of the users and the energy consumption of the UAVs. In [24], the authors investigated the minimization of the total UAV energy consumption while the throughput requirement of each ground node is satisfied. An efficient algorithm is proposed to optimize the hovering durations and locations as well as the UAV's trajectory.

In this paper, we focus on the SE and EE optimization for cognitive UAV system based on location information. Since the hovering power and transition power are usually fixed values, we only consider optimizing the transmit power of the UAV to balance the SE and EE for different locations of the UAV. When the UAV flies near to the PU, its data transmission may make the primary receiver (PR) in outage even if the transmit power is very low. In this case, the SE of the UAV will be low if the underlay mode is employed; however, if we use overlay mode, the UAV can easily detect the status of PT because of its high received signal-to-noise ratio (SNR), then the SE can be improved. When the UAV flies far away from the PU, the interference to PR will be small even if the UAV transmits signal with high power because of the influence of path loss. In this case, underlay mode can be employed because sensing is not necessary and will introduce additional time and energy overhead. To improve the SE and EE performance, different locations of UAV need different spectrum access modes. The main contributions of this paper are summarized as follows.

- Based on location information, we propose a hybrid mode in which the sensing performance and transmit power of UAV can be adjusted simultaneously to satisfy the outage constraint of PR. Simulation results show that the hybrid mode outperforms the overlay mode and underlay mode.
- The SE and EE are maximized by designing the system parameters of the UAV (including the sensing threshold, sensing time and transmit power of UAV) under the PR outage constraint. The multi-objective optimization theory is used to solve the tradeoff problem. Simulation results are provided to show the SE-EE tradeoff design.
- For the case that the PT's status remains unchanged for multiple frames, the conventional sensing frame structure may be inefficient. We propose a multi-frame combined sensing scheme, in which multiple frames are bundled together. Simulation results show the advantages of the multi-frame combined sensing scheme in both SE and EE.

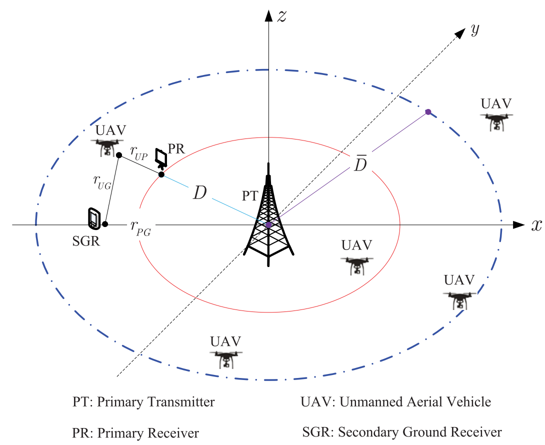

FIGURE 1. The UAV shares the spectrum with the primary network.

The remainder of this paper is organized as follows. The system model is introduced in Section II. Section III is devoted to the SE and EE analysis and problem formulation. Solutions of the optimization problems are given in Section IV. The multi-frame combined sensing scheme is proposed in Section V. Simulation results are provided in Section VI. Finally, Section VII summarizes this paper.

II. SYSTEM MODEL

In our system model, we consider that the UAV network needs to share the spectrum with the primary network, which is illustrated in Fig. 1. The micro rotary-wing UAV has CR function to opportunistically utilize the licensed spectrum. The UAV is battery powered and is equipped with a sensor to detect the status of the PT. The location of the PT is assumed to be known to the UAV network. For example, the PT is a TV transmitter, its parameters (location information, transmit power) are usually fixed [25]. In [26], the fusion center can use the energy levels sent by the secondary users to construct channel gain maps and estimates the PT locations and transmit power levels. The UAVs can make use of the location of PT to protect the PR. Since the operating time of the PT is unknown to the UAV, spectrum sensing should be conducted to decide whether the PT is idle or busy. Refer to Table 1 for main notations of this paper.

The protected boundary for the PR is determined by the SNR threshold of the received PU signal. It is assumed that

TABLE 1. Main notations and definitions.

Notation	Meaning
ρ_p	Transmit power of PT
D	Radius of protected boundary
ρ_u	Transmit power of UAV
ρ_s	Power for spectrum sensing
ρ_c	Circuit power of electronic devices
P_F	Probability of false alarm
P_D	Probability of detection
P_M	Probability of missed detection
ξ	Distance between PT and UAV
Υ	Average SE of UAV
Ω	Average EE of the CR module
p_{out}	Outage probability

the 3D geographical coordinates of PT is (0,0,0). The PT's transmit power is represented by ρ_p, the distance between PT and PR is r, then the received power of PR from PT is computed by

$$\rho_r = \frac{\rho_p h_p \mathrm{E}[g_p^2]}{r^\kappa}, \tag{1}$$

where κ is the path loss exponent, h_p is the gain of PU signal power accounting for the loss in near field, g_p is the channel response of PU signal at a particular location rm away from the PT. Suppose that the protected boundary is a circle, and its radius is D. For the PR located on the protected boundary, the received power from PT is given by

$$\rho_D = \frac{\rho_p h_p \mathrm{E}[g_p^2]}{D^\kappa}. \tag{2}$$

To guarantee the Quality-of-Service (QoS) of PU, the SNR of the PT's signal at the PR should be larger than or equal to β in the protected area, then the value of D is determined by β, which can be calculated as follows

$$D = \sqrt[\kappa]{\frac{\rho_p h_p \mathrm{E}[g_p^2]}{\beta \sigma_R^2}}, \tag{3}$$

where σ_R^2 is the noise power at the PR.

The UAV and the secondary ground receiver (SGR) are equipped with Global Position System (GPS), thus their geographical coordinates can be obtained. Let ρ_u denotes the transmit power of UAV, and r_{UG} denotes the distance between the UAV and the SGR, then the received power of SGR from UAV is $\rho_{r_{UG}} = \rho_u h_u g_{UG}^2 / r_{UG}^\kappa$, where h_u is the channel gain between the UAV and the SGR, g_{UG} is the channel response (UAV to SGR). When the PT is idle, the normalized transmission rate of the UAV system is [27]

$$\Phi_1 = \log_2\left(1 + \frac{\rho_{r_{UG}}}{\sigma_G^2}\right) = \log_2\left(1 + \frac{\rho_u h_u g_{UG}^2}{r_{UG}^\kappa \sigma_G^2}\right), \tag{4}$$

where σ_G^2 is the noise power at the SGR.

Let r_{PG} denotes the distance between PT and SGR, then the received power of SGR from PT is $\rho_{r_{PG}} = \frac{\rho_p h_p \mathrm{E}[g_p^2]}{r_{PG}^\kappa}$. When the PT is busy, the normalized transmission rate of the UAV system is [27]

$$\begin{aligned}\Phi_2 &= \log_2\left(1 + \frac{\rho_{r_{UG}}}{\rho_{r_{PG}} + \sigma_G^2}\right) \\ &= \log_2\left(1 + \frac{\rho_u h_u g_{UG}^2 r_{PG}^\kappa}{r_{UG}^\kappa(\rho_p h_p \mathrm{E}[g_p^2] + \sigma_G^2 r_{PG}^\kappa)}\right).\end{aligned} \tag{5}$$

By using the GPS, we obtain that the coordinates of the UAV and SGR are (x_u, y_u, z_u) and (x_G, y_G, z_G) respectively. The distance between PT and UAV is ξ, then it is derived that $\xi = \sqrt{x_u^2 + y_u^2 + z_u^2}$, $r_{PG} = \sqrt{x_G^2 + y_G^2 + z_G^2}$, $r_{UG} = \sqrt{(x_u - x_G)^2 + (y_u - y_G)^2 + (z_u - z_G)^2}$.

III. PROBLEM FORMULATION

The UAV flies around the PT and opportunistically utilize the licensed spectrum. When it flies to the protected area, it may interfere with the PR. Since the exact location of the PR is unknown to the UAV, we assume that the data transmission of UAV in the protected area can make the PR in outage. In this case, spectrum sensing should be performed to detect the PT's status. The UAV can transmit data only when the PT is detected to be idle [28]. We first analyze the SE and EE performance for the UAV in overlay mode.

A. OVERLAY MODE

The periodic sensing scheme in [29] is used for the overlay mode. In the frame structure, the sensing time is denoted as τ_s and the frame duration is denoted as τ. Let $\zeta = 0$ and $\zeta = 1$ denote the cases that the PT is actually idle and busy respectively. And λ is the probability of $\zeta = 0$, $1 - \lambda$ is the probability of $\zeta = 1$. Let $\bar{\zeta} = 0$ and $\bar{\zeta} = 1$ represent the cases that the PT is sensed to be idle and busy respectively. The false alarm probability and detection probability are, respectively [29]

$$P_F = \mathrm{P}_r\{\bar{\zeta} = 1 | \zeta = 0\} = \mathcal{Q}\left(\sqrt{\tau_s f_s}(\chi - 1)\right), \tag{6}$$

$$P_D = \mathrm{P}_r\{\bar{\zeta} = 1 | \zeta = 1\} = \mathcal{Q}\left(\sqrt{\frac{\tau_s f_s}{2\gamma + 1}}(\chi - \gamma - 1)\right), \tag{7}$$

where $\mathcal{Q}(\cdot)$ is the Gauss $\mathcal{Q}$-function, f_s is the sampling frequency, γ is the sensing signal-to-noise ratio (SNR), $\chi = \epsilon/\sigma_n^2$ is the normalized threshold of spectrum sensing. By combining (6) and (7), we have $P_F = \mathcal{Q}(\phi)$, where $\phi = \gamma\sqrt{\tau_s f_s} + \mathcal{Q}^{-1}(P_D)\sqrt{2\gamma + 1}$.

In the CR module of the UAV, the power for spectrum sensing is denoted as ρ_s, the circuit power of electronic devices is denoted as ρ_c. We analyze the power consumption of the CR module and the average SE of the UAV by considering the following four cases:

Case 1: $\{\zeta = 0, \bar{\zeta} = 0\}$, this case happens with probability $\lambda(1 - P_F)$, the power consumption of the CR module is $\frac{1}{\tau}[(\rho_s + \rho_c)\tau_s + (\rho_u + \rho_c)(\tau - \tau_s)]$, and the average SE for the UAV is $\Upsilon_1 = \Phi_1(1 - \frac{\tau_s}{\tau})$.

Case 2: $\{\zeta = 0, \bar{\zeta} = 1\}$, this case happens with probability λP_F, the power consumption of the CR module is $\frac{\tau_s}{\tau}(\rho_s + \rho_c)$, and the average SE for the UAV is 0.

Case 3: $\{\zeta = 1, \bar{\zeta} = 0\}$, this case happens with probability $(1-\lambda)(1-P_D)$, the power consumption of the CR module is $\frac{1}{\tau}[(\rho_s+\rho_c)\tau_s+(\rho_u+\rho_c)(\tau-\tau_s)]$, and the average SE for the UAV is $\Upsilon_2 = \Phi_2(1-\frac{\tau_s}{\tau})$.

Case 4: $\{\zeta = 1, \bar{\zeta} = 1\}$, this case happens with probability $(1-\lambda)P_D$, the power consumption of the CR module is $\frac{\tau_s}{\tau}(\rho_s+\rho_c)$, and the average SE for the UAV is 0.

From the above analysis, the SE of the UAV system is given by

$$\Upsilon = \lambda(1-P_F)\Upsilon_1 + (1-\lambda)(1-P_D)\Upsilon_2. \tag{8}$$

The average power consumed by the CR module is:

$$\mathbb{E} = \frac{\tau_s}{\tau}(\rho_s+\rho_c) + \frac{\tau-\tau_s}{\tau}(\rho_u+\rho_c)[\lambda(1-P_F)+(1-\lambda)(1-P_D)]. \tag{9}$$

In this paper, the energy efficiency of the CR module is defined as the ratio of the SE of the UAV system to the average power consumed by the CR module [30], which is given by

$$\Omega = \frac{\Upsilon}{\mathbb{E}}. \tag{10}$$

The energy of the UAV battery is usually limited. And the hover power is determined by the weight and altitude of the UAV. In this paper, we consider EE optimization for the CR module to improve the communication capability of the UAV. If the transmit power of the UAV is increased to enhance the SE, the average power consumed by the CR module will be increased; then the EE may not be necessarily increased. If more time is used to detect the PT's status, the sensing performance will be better, however, the SE of the UAV system and the power consumed by the CR module may not be necessarily increased because the time used for data transmission is decreased. Hence, there is a tradeoff between the EE and the SE when we design the system parameters of the UAV.

Our goal is to maximize the EE and SE by designing the system parameters of the UAV (including sensing threshold, sensing time and transmit power of UAV) on the condition that the PR outage constraint should be satisfied. By using multi-objective optimization theory [31], we combine the EE and SE into one single-objective function. The optimization problem is formulated as follows:

$$\mathcal{OP}1: \max_{\chi,\tau_s,\rho_u} \quad \Xi = \omega\Upsilon + (1-\omega)\Omega, \tag{11}$$

$$\text{s.t.}: \ \mathbb{C}_1, \mathbb{C}_2, \mathbb{C}_3 \tag{12}$$

where $0 \le \omega \le 1$, $\mathbb{C}_1$ is the PR outage constraint ($P_M = \alpha$), $\mathbb{C}_2$ is the sensing time constraint ($0 < \tau_s < \tau$), $\mathbb{C}_3$ is the transmit power constraint ($\rho_{u,\min} \le \rho_u \le \rho_{u,\max}$). The problem $\mathcal{OP}1$ will be solved in Section IV.

B. UNDERLAY MODE

When the UAV flies outside the protected area, we should consider the worst-case location of PR because the exact location of PR is unknown to the UAV. Suppose that the PR is located on the protected boundary, and its received power from the PT is ρ_D, which is computed by (2). Let r_{UP} denotes the distance between the UAV and the nearest PR, then the received power of the PR from the UAV can be computed by:

$$\rho_{r_{UP}} = \frac{\rho_u h_u g_{UP}^2}{r_{UP}^{\kappa}}, \tag{13}$$

where g_{UP} is the channel response (UAV to PR), and g_{UP}^2 is exponentially distributed with $\mathrm{E}[g_{UP}^2] = 1$.

In underlay mode, the UAV do not detect the PT's status and control the value of ρ_u to avoid interference to PR. When the UAV is transmitting data to the SGR, the PR will be in outage if the ratio of received UAV signal over primary signal is larger than a threshold δ. And the outage probability is calculated as:

$$\begin{aligned} p_{out} &= \mathrm{P}_r\left\{\frac{\rho_{r_{UP}}}{\rho_D} > \delta\right\} = \mathrm{P}_r\left\{\frac{\rho_u h_u g_{UP}^2 D^{\kappa}}{\rho_p h_p \mathrm{E}[g_p^2] r_{UP}^{\kappa}} > \delta\right\} \\ &= \exp\left\{-\frac{\rho_p h_p \mathrm{E}[g_p^2] r_{UP}^{\kappa}\delta}{\rho_u h_u D^{\kappa}}\right\}. \end{aligned} \tag{14}$$

To avoid the interference to PR, the outage probability should be smaller than or equal to a target value α, then we obtain that $\rho_u \le \rho_u^{\dagger}$, where

$$\rho_u^{\dagger} = \frac{\rho_p h_p \mathrm{E}[g_p^2] r_{UP}^{\kappa}\delta}{h_u D^{\kappa}\ln(1/\alpha)}. \tag{15}$$

If the UAV flies far away from the PU, the interference to the PR will be small. Due to the propagation loss, the UAV may transmit data with maximum power $\rho_{u,\max}$ while the outage constraint $p_{out} \le \alpha$ is still satisfied. In this case, when $\rho_u = \rho_{u,\max}$, according to (15), we can obtain that $r_{UP} \ge r_{UP}^{th}$, where

$$r_{UP}^{th} = D\sqrt[\kappa]{\frac{\rho_{u,\max} h_u \ln(1/\alpha)}{\rho_p h_p \delta \mathrm{E}[g_p^2]}}. \tag{16}$$

Let $\bar{D} = D + r_{UP}^{th}$, when $\xi \ge \bar{D}$, the UAV can transmit data to SGR with $\rho_{u,\max}$.

In underlay mode, sensing is not performed, hence the SE of the UAV system is $\tilde{\Upsilon} = \lambda\Phi_1 + (1-\lambda)\Phi_2$. The average power consumed by the CR module is $\tilde{\mathbb{E}} = \rho_u + \rho_c$, and the EE is $\tilde{\Omega} = \tilde{\Upsilon}/\tilde{\mathbb{E}}$. Similar to the analysis in subsection A, the optimization problem is maximizing $\tilde{\Xi} = \omega\tilde{\Upsilon} + (1-\omega)\tilde{\Omega}$ subject to the transmit power constraint of the UAV ($\rho_{u,\min} \le \rho_u \le \min(\rho_u^{\dagger}, \rho_{u,\max})$).

C. HYBRID MODE

When the UAV flies outside the protected area and the distance between PT and UAV satisfies $D < \xi < \bar{D}$, the PR will be in outage if missed detection occurs and the ratio of received UAV signal over primary signal is larger than the threshold δ. Let $p_{UP} = \mathrm{P}_r\{\frac{\rho_{r_{UP}}}{\rho_D} > \delta\}$, in hybrid mode, the outage probability is computed by:

$$p_{out} = P_M \cdot p_{UP} = P_M \mathrm{P}_r\left\{\frac{\rho_{r_{UP}}}{\rho_D} > \delta\right\} = (1-P_D)\exp\left\{-\frac{\rho_p h_p \mathrm{E}[g_p^2] r_{UP}^{\kappa}\delta}{\rho_u h_u D^{\kappa}}\right\}. \quad (17)$$

According to (17), the PR outage constraint ($p_{out} = \alpha$) can be satisfied by adjusting the detection probability P_D and the UAV's transmit power ρ_u. If ρ_u is increased to enhance the SE, the probability p_{UP} will be higher, then P_D should be larger to make sure that the outage probability is equal to α; If the detection capability of the CR module is limited, i.e., P_D is small, in this case, the UAV should control the transmit power ρ_u to satisfy the outage constraint. Given the transmit power of UAV, the missed detection probability is obtained as follows:

$$P_M = \alpha \cdot \exp\left\{\frac{\rho_p h_p \mathrm{E}[g_p^2] r_{UP}^{\kappa}\delta}{\rho_u h_u D^{\kappa}}\right\}. \quad (18)$$

In hybrid mode, the EE and SE optimization problem is formulated as follows:

$$\mathcal{OP}2: \max_{\chi,\tau_s,\rho_u} \ \Xi = \omega\Upsilon + (1-\omega)\Omega, \quad (19)$$

$$\text{s.t.}: \mathbb{C}_4, \mathbb{C}_5, \mathbb{C}_6, \mathbb{C}_7 \quad (20)$$

where $0 \leq \omega \leq 1$, $\mathbb{C}_4$ is the PR outage constraint (formula (18)), $\mathbb{C}_5$ is the sensing time constraint ($0 < \tau_s < \tau$), $\mathbb{C}_6$ is the transmit power constraint ($\rho_u^{\dagger} < \rho_u \leq \rho_{u,\max}$), $\mathbb{C}_7$ is the distance constraint ($D < \xi < \bar{D}$). The problem $\mathcal{OP}2$ will be solved in Section IV.

IV. SOLUTIONS OF THE OPTIMIZATION PROBLEMS

In this section, the EE and SE optimization problem is solved. In $\mathcal{OP}1$ and $\mathcal{OP}2$, ω is the factor that balances EE and SE. When $\omega = 0$, the optimization problem is actually EE maximization problem; when $\omega = 1$, the optimization problem is actually SE maximization problem; when ω varies from 0 to 1, the tradeoff between EE and SE can be obtained.

A. SOLUTIONS OF $\mathcal{OP}1$

In $\mathcal{OP}1$, it is difficult to analyze the relationship between the objective function Ξ and the UAV system parameters, so we first analyze the cases that $\omega = 0$ (Ω maximization) and $\omega = 1$ (Υ maximization), then the tradeoff between EE and SE is analyzed and $\mathcal{OP}1$ is solved.

1) ρ_u IS OPTIMIZED FOR GIVEN VALUES OF χ AND τ_S

Obviously, Υ increases with ρ_u because Υ is a logarithmic function of ρ_u. Then, we analyze the property of Ω over ρ_u, the first partial derivative of Ω with respect to ρ_u is $\frac{\partial\Omega}{\partial\rho_u} = \frac{\mathbf{U}}{\mathbb{E}^2}$, where

$$\mathbf{U} = \frac{\partial\Upsilon}{\partial\rho_u}\mathbb{E} - \frac{\partial\mathbb{E}}{\partial\rho_u}\Upsilon = \frac{\tau-\tau_s}{\tau^2}\frac{1}{\ln 2}\big\{\tau_s(\rho_s+\rho_c) + (\tau-\tau_s)(\rho_u+\rho_c)[\lambda(1-P_F)+(1-\lambda)(1-P_D)]\big\}$$
$$\times\left\{\frac{\lambda(1-P_F)h_u g_{UG}^2}{r_{UG}^{\kappa}\sigma_G^2+\rho_u h_u g_{UG}^2} + \frac{(1-\lambda)(1-P_D)h_u g_{UG}^2 r_{PG}^{\kappa}}{r_{UG}^{\kappa}(\rho_p h_p \mathrm{E}[g_p^2]+\sigma_G^2 r_{PG}^{\kappa})+\rho_u h_u g_{UG}^2 r_{PG}^{\kappa}}\right\}$$
$$-\frac{\tau-\tau_s}{\tau^2}[\lambda(1-P_F)+(1-\lambda)(1-P_D)]$$
$$\times[\lambda\Phi_1(1-P_F)(\tau-\tau_s)+(1-\lambda)\Phi_2(1-P_D)(\tau-\tau_s)]. \quad (21)$$

Then, $\partial\Omega/\partial\rho_u = 0$ is equivalent to $\mathbf{U} = 0$. It is derived that $\lim_{\rho_u\to 0}\mathbf{U} > 0$ and $\lim_{\rho_u\to\infty}\mathbf{U} = -\infty$. Since $\mathbb{E}^2 > 0$, we can conclude that Ω increases with ρ_u when ρ_u is a small value and decreases with ρ_u when ρ_u is larger than a certain value. To further investigate the property of Ω over ρ_u, we take the first partial derivative of $\mathbf{U}$ with respect to ρ_u and obtain that

$$\frac{\partial\mathbf{U}}{\partial\rho_u} = \frac{\partial^2\Upsilon}{\partial\rho_u^2}\mathbb{E} - \frac{\partial^2\mathbb{E}}{\partial\rho_u^2}\Upsilon$$
$$= -\frac{\tau-\tau_s}{\tau^2}\frac{1}{\ln 2}\big\{\tau_s(\rho_s+\rho_c)+(\tau-\tau_s)(\rho_u+\rho_c)$$
$$\times[\lambda(1-P_F)+(1-\lambda)(1-P_D)]\big\}\big\{\lambda(1-P_F)$$
$$\times\left(\frac{h_u g_{UG}^2}{r_{UG}^{\kappa}\sigma_G^2+\rho_u h_u g_{UG}^2}\right)^2 + (1-\lambda)(1-P_D)$$
$$\times\left(\frac{h_u g_{UG}^2 r_{PG}^{\kappa}}{r_{UG}^{\kappa}(\rho_p h_p \mathrm{E}[g_p^2]+\sigma_G^2 r_{PG}^{\kappa})+\rho_u h_u g_{UG}^2 r_{PG}^{\kappa}}\right)^2\Big\}. \quad (22)$$

From (22), we can easily derive that $\partial\mathbf{U}/\partial\rho_u < 0$, $\mathbf{U}$ is a decreasing function of ρ_u. Since $\lim_{\rho_u\to 0}\mathbf{U} > 0$ and $\lim_{\rho_u\to\infty}\mathbf{U} = -\infty$, it can be concluded that there is only one value of ρ_u (assumed to be $\bar{\rho}_u$) that can make $\mathbf{U} = 0$. Since $\mathbf{U}$ decreases with ρ_u, we can obtain that $\mathbf{U} \geq 0$ and $\partial\Omega/\partial\rho_u \geq 0$ for $\rho_u \in (0, \bar{\rho}_u]$, $\mathbf{U} < 0$ and $\partial\Omega/\partial\rho_u < 0$ for $\rho_u \in (\bar{\rho}_u, \infty)$. Thus, Ω is a unimodal function of ρ_u. The Newton-Rahpson algorithm [32] can be employed to obtain $\bar{\rho}_u$ by setting $\mathbf{U} = 0$.

It is difficult to analyze the relationship between Ξ and ρ_u, however, according to the analysis above, Ω increases with ρ_u for $\rho_u \in (0, \bar{\rho}_u]$. We consider the following three cases: 1) $\bar{\rho}_u > \rho_{u,\max}$, the optimal power that maximizes Ξ is $\rho_{u,\max}$; 2) $\rho_{u,\min} \leq \bar{\rho}_u \leq \rho_{u,\max}$, the optimal power that maximizes Ξ can be obtained by searching the range $[\bar{\rho}_u, \rho_{u,\max}]$ exhaustively; 3) $\bar{\rho}_u < \rho_{u,\min}$, in this case, we can derive the optimal transmit power of UAV by searching the range in (12).

2) χ AND τ_S ARE OPTIMIZED FOR A GIVEN VALUE OF ρ_u

The property of Υ over τ_s has been investigated in [29]. There is only one optimal value of τ_s (assumed to be $\tilde{\tau}_s$) that can maximize Υ. And the optimal sensing threshold is derived as follows:

$$\chi = \gamma + 1 + \mathcal{Q}^{-1}(P_D)\sqrt{\frac{2\gamma+1}{\tilde{\tau}_s f_s}}. \quad (23)$$

Then, we analyze the property of Ω over τ_s, the first partial derivative of Ω with respect to τ_s is $\frac{\partial \Omega}{\partial \tau_s} = \frac{\mathbf{V}}{\mathbb{E}^2}$, where

$$\begin{aligned}\mathbf{V} &= \frac{\partial \Upsilon}{\partial \tau_s}\mathbb{E} - \frac{\partial \mathbb{E}}{\partial \tau_s}\Upsilon \\ &= -\lambda\Phi_1\frac{\tau_s(\tau-\tau_s)}{\tau^2}(\rho_s+\rho_c)\frac{dP_F}{d\tau_s} - \lambda(\Phi_1-\Phi_2) \\ &\quad\times\frac{(\tau-\tau_s)^2}{\tau^2}(\rho_u+\rho_c)(1-\lambda)(1-P_D)\frac{dP_F}{d\tau_s} \\ &\quad-\frac{1}{\tau}(\rho_s+\rho_c)[\lambda\Phi_1(1-P_F)+(1-\lambda)\Phi_2(1-P_D)], \end{aligned} \tag{24}$$

and

$$\frac{dP_F}{d\tau_s} = -\frac{\gamma}{2}\sqrt{\frac{f_s}{2\pi\tau_s}}\exp\Big\{-\frac{1}{2}\phi^2\Big\}. \tag{25}$$

Then, $\partial\Omega/\partial\tau_s = 0$ is equivalent to $\mathbf{V} = 0$. It is derived that $\lim_{\tau_s\to 0}\mathbf{V} = +\infty$ and $\lim_{\tau_s\to\tau}\mathbf{V} < 0$. Since $\mathbb{E}^2 > 0$, it can be concluded that Ω increases with τ_s when τ_s is a small value and decreases with τ_s when τ_s is larger than a certain value. To further investigate the property of Ω over τ_s, we take the first partial derivative of $\mathbf{V}$ with respect to τ_s and obtain that

$$\begin{aligned}\frac{\partial \mathbf{V}}{\partial \tau_s} &= \frac{\partial^2 \Upsilon}{\partial \tau_s^2}\mathbb{E} - \frac{\partial^2 \mathbb{E}}{\partial \tau_s^2}\Upsilon \\ &= -\frac{1}{\tau^2}\lambda\Phi_1\tau_s(\rho_s+\rho_c)\Big[\frac{d^2P_F}{d\tau_s^2}(\tau-\tau_s) - 2\frac{dP_F}{d\tau_s}\Big] \\ &\quad-\frac{(\tau-\tau_s)^2}{\tau^2}\lambda(\Phi_1-\Phi_2)\frac{d^2P_F}{d\tau_s^2}(\rho_u+\rho_c)(1-\lambda)(1-P_D) \\ &\quad+\frac{(\tau-\tau_s)}{\tau^2}2\lambda(\Phi_1-\Phi_2)\frac{dP_F}{d\tau}(\rho_u+\rho_c)(1-\lambda)(1-P_D), \end{aligned} \tag{26}$$

where

$$\frac{d^2P_F}{d\tau_s^2} = \frac{\gamma}{4\tau_s}\sqrt{\frac{f_s}{2\pi\tau_s}}\Big[1+\gamma\phi\sqrt{\tau_s f_s}\Big]\exp\Big\{-\frac{1}{2}\phi^2\Big\}. \tag{27}$$

It can be derived that $\partial\mathbf{V}/\partial\tau_s < 0$, $\mathbf{V}$ is a decreasing function of τ_s. Since $\lim_{\tau_s\to 0}\mathbf{V} = +\infty$ and $\lim_{\tau_s\to\tau}\mathbf{V} < 0$, it is concluded that there is only one value of τ_s (assumed to be $\bar{\tau}_s$) that can make $\mathbf{V} = 0$. Since $\mathbf{V}$ decreases with τ_s, we can obtain that $\mathbf{V} \geq 0$ and $\partial\Omega/\partial\tau_s \geq 0$ for $\tau_s \in (0, \bar{\tau}_s]$, $\mathbf{V} < 0$ and $\partial\Omega/\partial\tau_s < 0$ for $\tau \in (\bar{\tau}_s, \tau)$. Thus, Ω is a unimodal function of τ_s. The Newton-Rahpson algorithm can be employed to obtain $\bar{\tau}_s$ by setting $\mathbf{V} = 0$.

Based on the properties of Υ and Ω over the sensing time, it can be concluded that Ξ is a increasing function of τ_s for $\tau_s \in (0, \min(\tilde{\tau}_s, \bar{\tau}_s)]$ and is a decreasing function of τ_s for $\tau_s \in [\max(\tilde{\tau}_s, \bar{\tau}_s), \tau)$. Thus, the optimal sensing time that maximizes Ξ can be obtained by searching the range $[\min(\tilde{\tau}_s, \bar{\tau}_s), \max(\tilde{\tau}_s, \bar{\tau}_s)]$ exhaustively.

Finally, an efficient algorithm is proposed to optimize the sensing time, the sensing threshold and the transmit power of UAV such that Ξ is maximized. The proposed Algorithm 1 iterates until Ξ converges to a maximum point in the 2-D space. Suppose that τ_s^*, χ^* and ρ_u^* are the converged values in Algorithm 1. When $\tau_s = \tau_s^*$ and $\chi = \chi^*$, $\Xi(\tau_s^*, \chi^*, \rho_u^*)$ is the maximal value across ρ_u dimension; when $\rho_u = \rho_u^*$, $\Xi(\tau_s^*, \chi^*, \rho_u^*)$ is the maximal value across τ_s and χ dimension. The proposed Algorithm 1 can converge to the global maximum value, which is shown in the simulations in Section VI.

Algorithm 1 Joint Optimization of χ, τ_s and ρ_u That Maximizes Ξ

Initialization: $i = 0$; $\rho_u(0) = \frac{\rho_{u,\min}+\rho_{u,\max}}{2}$; $\Xi(0) = 0$; tolerance level ϖ;

Repeat

1) Using Newton-Rahpson algorithm to find $\bar{\rho}_u$ by setting $\mathbf{U} = 0$;
 if $\bar{\rho}_u > \rho_{u,\max}$ **then**
 $\rho_u^* \leftarrow \rho_{u,\max}$
 else
 Searching the range $[\max(\rho_{u,\min}, \bar{\rho}_u), \rho_{u,\max}]$ to obtain the optimal power ρ_u^*;
 end if
2) $\rho_u(i+1) \leftarrow \rho_u^*$;
3) Compute the root $\tilde{\tau}_s$ of $\frac{\partial\Upsilon}{\partial\tau_s} = 0$ and obtain $\bar{\tau}_s$ by setting $\mathbf{V} = 0$ with $\rho_u(i+1)$; Find the optimal sensing time τ_s^* by searching the range $[\min(\tilde{\tau}_s, \bar{\tau}_s), \max(\tilde{\tau}_s, \bar{\tau}_s)]$;
 $\chi^* = \gamma + 1 + \mathcal{Q}^{-1}(P_D)\sqrt{\frac{2\gamma+1}{\tau_s^* f_s}}$;
4) $\tau_s(i+1) \leftarrow \tau_s^*$, $\chi(i+1) \leftarrow \chi^*$;
5) Compute $\Xi(i+1)$ with $\rho_u(i+1)$, $\tau_s(i+1)$ and $\chi(i+1)$;
5) $i \leftarrow (i+1)$;

until $|\Xi(i) - \Xi(i-1)| \leq \varpi$;

Output: $\rho_u(i)$, $\tau_s(i)$ and $\chi(i)$.

In Algorithm 1, the optimal transmit power of UAV is derived for a given sensing time and a given sensing threshold (Step 1); then the optimal sensing time and optimal sensing threshold are obtained for a given transmit power of the UAV (Step 3). Finally, these optimal system parameters are obtained by using an efficient iterative algorithm. Therefore, the computational complexity of the algorithm is easy to calculate, i.e., multiplying the complexity of Step 1 by the complexity of Step 3.

The complexity of Step 1 contains the complexity of the bisection method and the complexity of an exhaustive search (the range is $[\max(\rho_{u,\min}, \bar{\rho}_u), \rho_{u,\max}]$), of which $\lceil \log_2\{(\rho_{u,\max} - \rho_{u,\min})/\varpi\}\rceil$ is the number of iterations that bisection method takes to terminate and $\lceil x\rceil$ denotes the smallest integer not less than x. The complexity of Step 3 is similar to that of Step 1, and is not stated here.

In underlay mode, the UAV do not perform spectrum sensing and control the value of ρ_u to avoid the interference to the PR. The optimization problem is maximizing $\tilde{\Xi} = \omega\tilde{\Upsilon} + (1-\omega)\tilde{\Omega}$ subject to the transmit power constraint of

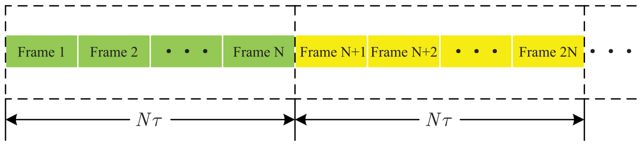

FIGURE 2. Multi-frame combined sensing scheme.

the UAV ($\rho_{u,\min} \le \rho_u \le \min(\rho_u^\dagger, \rho_{u,\max})$). The optimal value of ρ_u can be obtained similar to the analysis in subsection 1).

B. OPTIMIZATION OF $\mathcal{OP}2$

In hybrid mode, the PR outage constraint can be satisfied by adjusting the detection probability P_D and the UAV's transmit power ρ_u. The relationship between P_D and ρ_u is $P_D = 1-\alpha \cdot \exp\left\{\frac{\rho_p h_p \mathrm{E}[g_p^2] r_{UP}^\kappa \delta}{\rho_u h_u D^\kappa}\right\}$. Because of the coupling effect between P_F and P_D, and the complexity of $\mathcal{Q}^{-1}(x)$ function, the EE Ω may not be a unimodal function of ρ_u. For given values of χ and τ_s, finding an efficient algorithm that optimizes ρ_u is very difficult. However, we know the range of ρ_u lies between $\rho_u^\dagger$ and $\rho_{u,\max}$, thus a numerical search can be conducted to find the optimal transmit power of UAV.

For a given value of ρ_u, the optimization of τ_s and χ is similar to that of overlay mode. And the algorithm that optimizes the system parameters is similar to Algorithm 1. It should be noted that, in hybrid mode, the detection probability is computed by the following formula: $P_D = 1 - \alpha \cdot \exp\left\{\frac{\rho_p h_p \mathrm{E}[g_p^2] r_{UP}^\kappa \delta}{\rho_u h_u D^\kappa}\right\}$.

V. MULTI-FRAME COMBINED SENSING SCHEME

When the PT's status (busy or idle) remains unchanged for multiple frames, the conventional sensing frame structure may be inefficient. In this section, a multi-frame combined sensing scheme is proposed, in which N frames are bundled together, as is shown in Fig. 2. In the multi-frame combined sensing scheme, the duration of the combined frame is $N\tau$, in which τ_s is allocated for sensing, and the remaining time $N\tau - \tau_s$ is used for data transmission. Let Υ_{MF}, $\mathbb{E}_{MF}$ and Ω_{MF} represent the SE of the UAV system, the average power consumed by the CR module and the EE of the CR module for multi-frame combined sensing scheme, respectively. It is derived that

$$\Upsilon_{MF} = \lambda(1-P_F)\Phi_1\left(1-\frac{\tau_s}{N\tau}\right)+(1-\lambda)(1-P_D)\Phi_2\left(1-\frac{\tau_s}{N\tau}\right). \tag{28}$$

Let $\Delta\Upsilon = \Upsilon_{MF} - \Upsilon$, we have

$$\Delta\Upsilon = \lambda(1-P_F)\Phi_1\frac{(N-1)\tau_s}{N\tau}+(1-\lambda)(1-P_D)\Phi_2\frac{(N-1)\tau_s}{N\tau}. \tag{29}$$

Obviously, $\Delta\Upsilon > 0$, hence the SE of the multi-frame combined sensing scheme is higher than that of the conventional sensing. The EE of the CR module is $\Omega_{MF} = \Upsilon_{MF}/\mathbb{E}_{MF}$, where

$$\mathbb{E}_{MF} = \frac{\tau_s(\rho_s+\rho_c)}{N\tau} + \frac{(N\tau-\tau_s)(\rho_u+\rho_c)}{N\tau} \times \left[\lambda(1-P_F)+(1-\lambda)(1-P_D)\right]. \tag{30}$$

Let $\Delta\Omega = \Omega_{MF} - \Omega$, we have

$$\Delta\Omega = \frac{(N-1)\tau\cdot\tau_s(\rho_s+\rho_c)}{N\mathbb{E}\cdot\mathbb{E}_{MF}\tau^2} \times \left[\lambda(1-P_F)\Phi_1+(1-\lambda)(1-P_D)\Phi_2\right]. \tag{31}$$

Obviously, $\Delta\Omega > 0$, which means that the EE can be improved by employing the multi-frame combined sensing scheme. The larger the value of N, the higher the SE and the EE. However, the prerequisite of the multi-frame combined sensing scheme is that the PT's status (busy or idle) remains unchanged for N frames. For the case that the PT's status varies from frame to frame and short term service is provided, such as cellular system, the UAV can utilize the spectrum opportunities over the licensed band with smaller N. For the case that long term service is provided, a larger value of N can be selected. To achieve the EE and SE tradeoff for the multi-frame combined sensing scheme, the proposed algorithm in section IV can be used by replacing τ with $N\tau$.

TABLE 2. Simulation parameters.

Probability of $\zeta = 0$	λ	0.8
Frame duration	τ	20ms
Outage probability constraint	α	0.1
Sampling frequency	f_s	100000Hz
Transmit power of PT	ρ_p	5kW
Maximum transmit power of UAV	$\rho_{u,\max}$	4W
Minimum transmit power of UAV	$\rho_{u,\min}$	20mW
Outage SNR threshold	δ	-30dB
SNR threshold for protected area	β	5dB
Path loss exponent	κ	3.5
Noise power	σ_R^2, σ_G^2	-96dBmW
Power for spectrum sensing	ρ_s	0.3W
Circuit power of electronic devices	ρ_c	0.2W

VI. SIMULATION RESULTS

Simulation results are presented in this section to evaluate our proposed scheme and the tradeoff between EE and SE. The simulation parameters are shown in Table 2. We consider the scenario that the PT is a TV transmitter, and the transmit power of PT is set according to the product details [33] and reference [34].

When $\omega = 0$, the optimization problem becomes maximizing the EE of the CR module. Fig. 3 is illustrated to show the EE performance versus ξ for different modes, where ξ is the distance between the UAV and the PT. The radius of the protected area D is determined by the threshold β, in this simulation, it is derived that $D = 7.68$km. When $\xi < 7.68$km, the EE of the underlay mode is 0 since any transmission of the UAV can make the PR in outage. When the UAV flies outside the protected area and 7.68km$< \xi <$8.78km, the EE

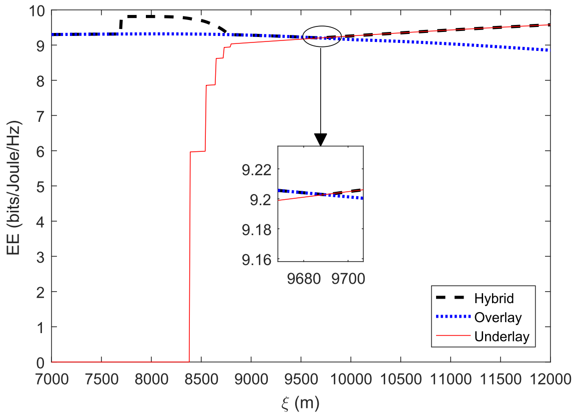

FIGURE 3. The EE versus ξ for different modes.

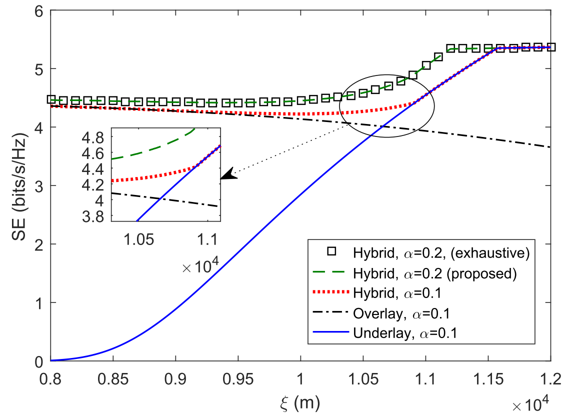

FIGURE 5. The SE performance comparison for different modes.

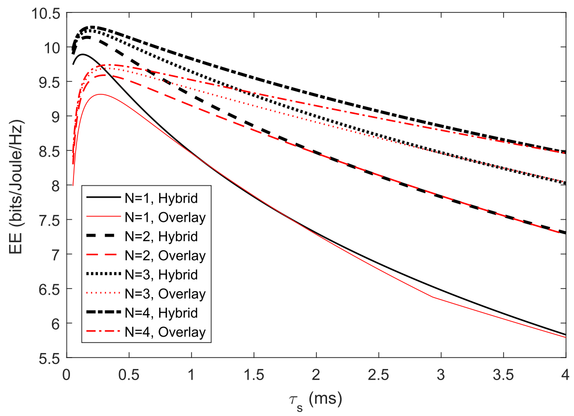

FIGURE 4. The EE versus sensing time for the multi-frame combined sensing scheme.

performance of hybrid mode outperforms the overlay mode and underlay mode. This is because the transmit power of UAV and detection probability can be adjusted according to the distance between the UAV and the PT in hybrid mode. When the UAV flies far away from the PT and ξ >9.69km, the overlay mode performs the worst, which indicates that spectrum sensing is not necessary in this case because it will introduce more time and energy overhead.

In Fig. 4, we present the EE of the CR module versus sensing time τ_s for the multi-frame combined sensing scheme with different values of N. In this simulation, the distance between the UAV and the PT is 8.5km. The multi-frame combined sensing scheme with $N = 1$ is equivalent to the conventional sensing scheme. It is seen that, in either hybrid mode or overlay mode, the EE is a unimodal (not convex) function of the sensing time and there is only one optimal value of τ_s that can maximize the EE. The maximum EE value of hybrid mode is larger than that of the overlay mode. We can also see clearly that the larger the value of N, the higher the EE, which is consistent with the theoretical analysis in Section V. However, the prerequisite of the multi-frame combined sensing scheme is that the PT's status remains unchanged for N frames. The maximum achievable EE can be improved with the value of N increasing especially when N changes from 1 to 2. And the improvement gain is decreased when N becomes larger.

In Fig. 5, we compare the three modes on the SE performance for the UAV. It is seen that the SE obtained by our proposed algorithm is the same as that using exhaustive search, which means that the proposed algorithm converges to the global maximum value. In the overlay mode, the SE decreases with ξ since the sensing performance becomes worse when the UAV flies far away from the PT. There is one intersection between the curves of underlay mode and overlay mode, which indicates that the UAV should select the optimal spectrum access mode according to its location information. When the UAV flies near to the PT (ξ ≤9.5km), the hybrid mode and overlay mode have similar SE performance. This is because the sensing SNR is high and the UAV do not need power control to protect the PR. When the UAV flies far away from the PT (ξ ≥10.9km), the hybrid mode and underlay mode have similar SE performance. This is because the UAV can transmit data with high power due to the influence of path loss (sensing is not necessary and will introduce additional time and energy overhead). For the case that 9.5km< ξ <10.9km, the SE performance of the hybrid mode outperforms both the overlay mode and underlay mode. It is also observed that the SE with $\alpha = 0.2$ is higher that with $\alpha = 0.1$, which means that strengthening the protection to PR will result in lower SE performance.

Fig. 6 is simulated to show the SE versus the sensing time τ_s and ξ. A 3D graph is illustrated. We can see clearly that, for a given value of $\rho_{u,\max}$, the SE of the hybrid mode is higher than that of the overlay mode. In the overlay mode, the UAV will transmit data with maximum power to optimize the SE, hence the SE increases with the value of $\rho_{u,\max}$. In the hybrid mode, when ξ is large and the sensing time τ_s is small, it is seen that the SE with $\rho_{u,\max} = 8$W is lower than that with $\rho_{u,\max} = 4$W. The reasons are as follows. According to formula (18), if the maximum power is used for data transmission, the larger the value of $\rho_{u,\max}$, the smaller the value of P_M, then P_F will be larger and the UAV has less opportunities to utilize the unlicensed spectrum. Thus, the SE may become lower.

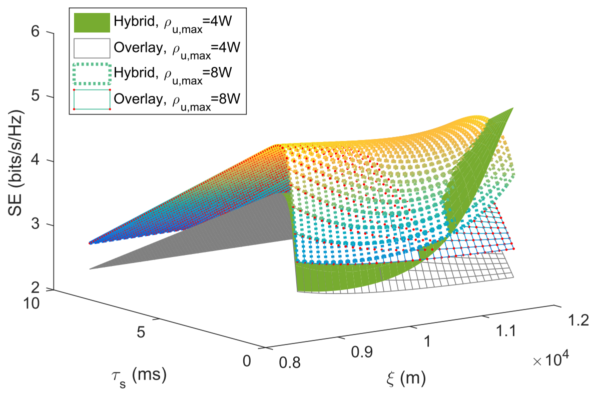

FIGURE 6. SE versus both the sensing time and ξ.

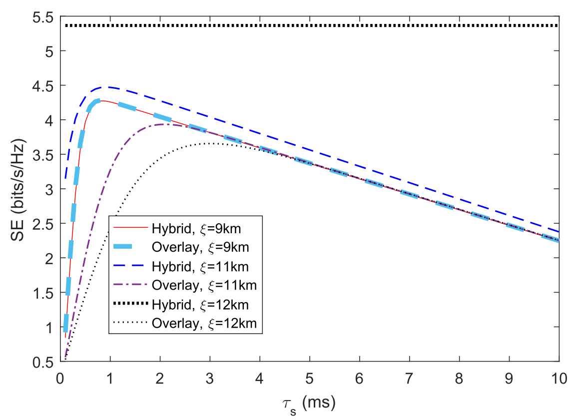

FIGURE 7. The SE versus sensing time at different UAV locations.

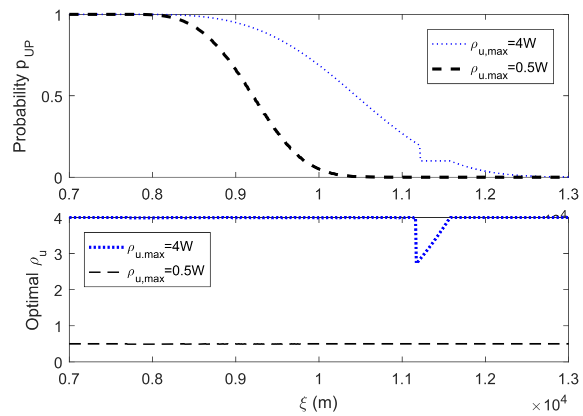

FIGURE 8. The probability p_{UP}, the optimal transmit power of UAV versus ξ in hybrid mode (SE is maximized).

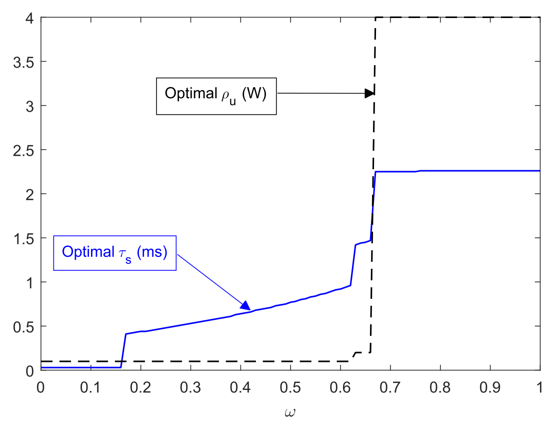

FIGURE 9. Optimal transmit power of UAV, optimal sensing time versus ω (Ξ is maximized).

The SE versus the sensing time τ_s at different UAV locations is illustrated in Fig. 7. In hybrid mode, the transmit power of the UAV is optimized. When $\xi = 9$km, the SE of overlay mode is almost the same as the hybrid mode, and there is only one optimal value of sensing time that can maximize the SE. When $\xi = 11$km, the hybrid mode significantly improves the SE compared with the overlay mode; The maximal SE of hybrid mode is approximately 4.48 bits/s/Hz, however, when the overlay mode is used, the maximal SE is approximately 3.94 bits/s/Hz. The optimal value of τ_s varies with different UAV locations. When $\xi = 12$km, the maximal SE of overlay mode is about 3.65 bits/s/Hz, which is much lower than that of hybrid mode (5.36 bits/s/Hz). This is because sensing is not necessary in this case and will introduce additional overhead.

When $\omega = 1$, the optimization problem becomes maximizing the SE of the UAV system. In Fig. 8, we show the probability p_{UP} and the optimal transmit power of UAV versus ξ in hybrid mode when the SE is maximized. The sensing time and sensing threshold are optimized in this simulation. When the UAV is near to the PT and is located in the protected area, p_{UP} is 1 since any transmission of the UAV will make the PR in outage. In this case, sensing is performed before transmission and $\rho_{u,\max}$ is chosen as the transmit power to maximize the SE. When $\rho_{u,\max} = 4$W, it can be seen that p_{UP} is 0.1 for 11.22km$< \xi <$11.56km, which means that sensing is not performed and power control is used to satisfy the outage constraint. In this case, the optimal transmit power is $\rho_u^\dagger$, which can be seen in the second subfigure. When $\xi >$11.56km, p_{UP} is less than 0.1 and decreases with ξ, the UAV transmits data to the SGR with maximal power $\rho_{u,\max}$ and the outage constraint is still satisfied. For the case that $\rho_{u,\max} = 0.5$W, the UAV will transmit data with $\rho_{u,\max}$ to maximize the SE whether it flies far or near from the PT.

Fig. 9 is simulated to show the optimal transmit power of UAV and optimal sensing time versus ω when the weighted sum Ξ is maximized. In this simulation, the distance between UAV and PT is 11.2km, and overlay mode is employed. The power ρ_u and sensing time τ_s should be carefully designed for different values of ω. When $\omega = 0$, the goal is to maximize the EE, smaller values of ρ_u and τ_s are selected. When $\omega = 1$, the goal is to maximize the SE, in this case, $\rho_{u,\max}$ is chosen as the optimal transmit power and the optimal sensing time is 2.26ms. This indicates that the maximum SE and maximum EE can not be achieved simultaneously, there is a tradeoff between them. To balance the SE and EE, a proper value of ω should be chosen and the optimal system parameters can be obtained with reference to Fig. 9.

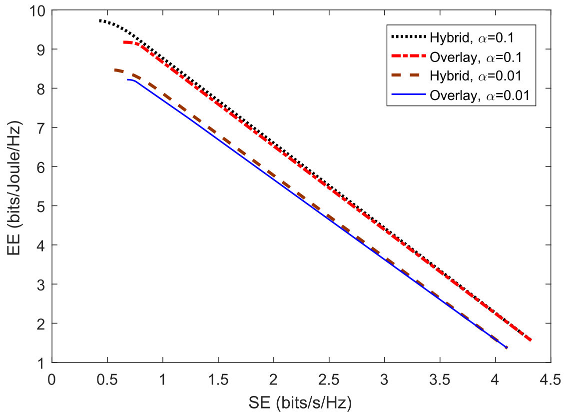

FIGURE 10. Tradeoff between EE and SE.

In Fig. 10, we show the EE versus SE for the hybrid mode and overlay mode. In this simulation, the sensing time, sensing threshold and transmit power of UAV are optimized to maximize the weighted sum Ξ. The distance between the UAV and PT is 8.5km. For a given ω, a pair of SE and EE can be derived by maximizing Ξ. When ω varies from 0 to 1, a tradeoff curve between them can be obtained. The hybrid mode outperforms the overlay mode in both SE and EE performance. In either hybrid mode or overlay mode, when the outage probability decreases from 0.1 to 0.01, both the SE and EE are reduced. The reason is that smaller value of α indicates stronger protection to PR and less spectrum access opportunities for the UAV, then the SE and EE performance is degraded.

VII. CONCLUSION

This paper investigates the spectrum sharing between the UAV network and terrestrial wireless network under different scenarios. We have addressed two major challenges in the UAV network: SE optimization and EE optimization. A hybrid transmission mode based on UAV's location is proposed, in which spectrum sensing and power allocation are adjusted simultaneously to protect the PU. To achieve the tradeoff between SE and EE, an efficient iterative algorithm is provided to obtain the system parameters (including sensing time, sensing threshold and UAV's transmit power). A multi-frame combined sensing scheme is proposed for the case that the PT's status remains unchanged for multiple frames. Computer simulations validate the proposed optimization strategy and illustrate the SE-EE tradeoff curves. It is shown that the hybrid mode outperforms the overlay mode and underlay mode in both SE and EE performance. By using the multi-frame combined sensing scheme, the EE performance can be further improved.

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