

Mode-Aware Anti-Jamming for Dynamic Spectrum Sharing UAV Networks: Joint Spectrum and Trajectory Optimization

Abstract—Unmanned aerial vehicle (UAV) communications under dynamic spectrum sharing are vulnerable to intentional jamming, especially when the jammer switches among different interference patterns such as constant, sweep, and random jamming. Existing learning-based approaches typically rely on implicit adaptation to interference, which often results in slow reaction and degraded reliability under abrupt jamming pattern transitions. To address this issue, we propose a mode-aware anti-jamming framework for dynamic spectrum sharing UAV networks. By exploiting short-window spectrum observations, the UAV explicitly estimates the belief state of the current jamming mode and incorporates it into a hybrid learning scheme that jointly optimizes spectrum allocation and UAV trajectory control. Specifically, Proximal Policy Optimization (PPO) is adopted for discrete spectrum allocation, while a continuous-control learning algorithm is used for trajectory optimization with a reliability-oriented reward design. Simulation results show that the proposed approach achieves faster throughput recovery and improved robustness under pattern-switching jamming compared with baseline methods.

Index Terms—UAV communications, dynamic spectrum sharing, anti-jamming, styling, reinforcement learning

I. INTRODUCTION

Unmanned aerial vehicles (UAVs) have become an important component of low-altitude wireless networks, enabling flexible and on-demand communication services such as emergency coverage, temporary hotspots, and aerial relaying. Due to the scarcity of dedicated spectrum, UAV systems often operate under dynamic spectrum sharing (DSS) frameworks, where secondary UAV links coexist with incumbent primary users (PUs). While DSS improves spectrum efficiency, it also exposes UAV communications to severe and highly dynamic interference, particularly in adversarial environments with intentional jamming. In practice, a jammer rarely adopts a fixed interference strategy. Instead, it may switch among multiple jamming patterns, such as constant jamming, sweep jamming, and random jamming, to increase uncertainty and disrupt adaptive communication schemes. Such pattern-switching jamming leads to abrupt and non-stationary interference dynamics, which can cause frequent quality-of-service (QoS) degradation and communication outages. For low-altitude UAV missions, ensuring fast recovery of communication quality after interference transitions is often more critical than optimizing long-term average throughput.

To address spectrum scarcity and interference, extensive research has investigated joint spectrum allocation and UAV trajectory optimization. By exploiting the UAV’s mobility

and flexible spectrum access, learning-based approaches can adapt resource allocation and flight trajectories in dynamic environments. In particular, reinforcement learning (RL) has been widely applied to handle the coupled discrete–continuous optimization inherent in spectrum assignment and UAV movement. However, most existing methods treat interference as an exogenous disturbance and directly include raw interference measurements in the state space, relying on the learning agent to implicitly infer jammer behavior from long-term reward feedback. Under pattern-switching jamming, this implicit learning results in an effectively non-stationary environment, where the learned policy tends to converge to conservative average-case behaviors and exhibits slow adaptation when the jamming pattern changes.

This observation reveals a key limitation of existing designs: the lack of explicit awareness of jamming patterns prevents fast reaction to abrupt interference transitions. In contrast to throughput-oriented formulations, anti-jamming UAV communications require rapid frequency agility and timely decision updates to restore link quality with minimal delay. Motivated by this challenge, we focus on a pattern-switching jamming scenario and investigate how explicit jamming cognition can be leveraged to improve the responsiveness and robustness of DSS-enabled UAV communications.

In this paper, we propose a mode-aware anti-jamming framework that explicitly decouples jamming cognition from control. The jammer behavior is modeled as a finite-mode pattern-switching process. Using short-window spectrum observations, the UAV rapidly estimates the posterior distribution of the current jamming mode, referred to as a belief state. This belief state is then incorporated into the decision-making process to condition both spectrum allocation and trajectory control, enabling instantaneous policy adaptation upon jamming mode transitions. Moreover, to capture practical frequency agility constraints, we explicitly introduce a frequency switching cost into the optimization objective, balancing fast reaction to interference and stable spectrum usage.

To solve the resulting problem, we develop a hybrid learning framework that jointly optimizes discrete spectrum allocation and continuous UAV trajectory control. A Proximal Policy Optimization (PPO) agent is employed to learn the spectrum allocation policy, while a continuous-control agent, such as TD3 or SAC, optimizes the UAV trajectory. Both agents are conditioned on the jamming mode belief and trained using a reliability-oriented reward that penalizes QoS outages and

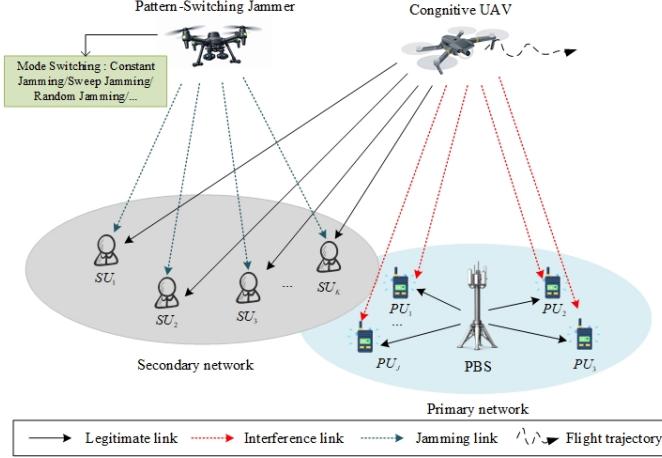


Fig. 1. Dynamic spectrum sharing UAV network under pattern-switching jamming, where the C-UAV performs jamming mode awareness and jointly optimizes spectrum allocation and trajectory to ensure reliable communications.

excessive frequency switching while ensuring PU protection. Simulation results under constant, sweep, and random pattern-switching jamming demonstrate that the proposed mode-aware approach achieves significantly faster throughput recovery and improved robustness compared with baseline schemes relying on implicit interference learning.

The main contributions of this paper are summarized as follows:

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The remainder of this paper is organized as follows. Section II introduces the system model, including the dynamic spectrum sharing UAV network and the pattern-switching jamming scenario. Section III presents the proposed mode-aware anti-jamming framework, including jamming mode recognition and the joint spectrum allocation and trajectory control scheme. Simulation results and performance evaluations are provided in Section IV. Finally, the paper concludes with Section V.

II. SYSTEM MODEL

A. Scenario Description

We consider a UAV-enabled dynamic spectrum sharing (DSS) network under intentional pattern-switching jamming, as illustrated in Fig. 1. The network consists of a primary network and a cognitive UAV-assisted secondary network, which coexist over a set of licensed spectrum bands.

The primary network includes a primary base station and J primary users (PUs). The PUs are indexed by $j \in \mathcal{J} \triangleq \{1, 2, \dots, J\}$. In order to serve more SUs and provide better services, a wideband spectrum is divided into M subcarrier spectrum bands. The spectrum bands are indexed by $m \in \mathcal{M} \triangleq \{1, 2, \dots, M\}$. Each PU is allocated one dedicated licensed spectrum band to avoid intra-primary interference. The secondary network comprises a cognitive UAV serving K ground secondary users (SUs). The SUs are indexed by

$k \in \mathcal{K} \triangleq \{1, 2, \dots, K\}$. The C-UAV operates as an aerial secondary base station, providing downlink communications to SUs by opportunistically accessing the licensed spectrum while ensuring that the interference inflicted on the primary network remains within acceptable limits.

A three-dimensional Cartesian coordinate system is adopted. The horizontal locations of the PBS, the j -th PU, the k -th SU, the C-UAV and the J-UAV at time slot n are denoted by $\mathbf{w}_b = (x_b, y_b)$, $\mathbf{w}_{p,j} = (x_{p,j}, y_{p,j})$, $\mathbf{w}_{s,k} = (x_{s,k}, y_{s,k})$, $\mathbf{q}_c = (x_c, y_c)$ and $\mathbf{q}_{jam} = (x_{jam}, y_{jam})$ respectively. These UAVs fly at a fixed altitude H_c . The total communication duration T is divided into N equal-length time slots, each with duration $\Delta t = T/N$. Due to the short duration of each slot, the C-UAV is assumed to be quasi-static within one slot. Let $n \in \mathcal{N} \triangleq \{1, 2, \dots, N\}$ denote the set of time steps. The dynamic positions of the SUs can be formulated as

$$\begin{aligned} x_{s,k}[n+1] &= x_{s,k}[n] + v_s \cos(\phi_{s,k}[n]), \\ y_{s,k}[n+1] &= y_{s,k}[n] + v_s \sin(\phi_{s,k}[n]), \end{aligned} \quad (1)$$

where $\phi_{s,k}[n] \in [-\pi, \pi]$ represents the direction of the k -th SU. The SUs move at a fixed speed v_s . Similarly, the dynamic position of the C-UAV can be formulated as

$$\begin{aligned} x_c[n+1] &= x_c[n] + v_c \cos(\phi[n]), \\ y_c[n+1] &= y_c[n] + v_c \sin(\phi[n]), \end{aligned} \quad (2)$$

where v_c is the constant flight speed, and $\phi[n]$ denotes the heading angle of the UAV at time slot n . The distance between the C-UAV and the k -th SU, and that between the PBS and the j -th PU at time slot n are respectively given as,

$$\begin{aligned} d_{c,k}[n] &= \sqrt{\|\mathbf{q}_c[n] - \mathbf{w}_{s,k}[n]\|^2 + H_c^2}, \\ d_{p,j}[n] &= \sqrt{\|\mathbf{w}_b[n] - \mathbf{w}_{p,j}[n]\|^2}, \end{aligned} \quad (3)$$

The wireless channel between the UAV and the ground users is dominated by the line-of-sight (LoS) link. Let β_{ref} represent the channel power gain at the reference distance of 1 m. Thus, the channel power gain from the C-UAV to the k -th SU can be expressed as

$$h_{k,n}^{\text{LoS}} = \beta_{ref} d_{c,k}[n]^{-2}, \quad (4)$$

where $d_{c,k}[n]$ represents the distance between the C-UAV and the k -th SU at time slot n . The channel model between the PBS and the ground users is different from that between the UAV and the ground users. It is required to consider both the distance-dependent path loss with exponent $\varphi \geq 2$ and small-scale Rayleigh fading. Thus, the channel power gains from the PBS to the j -th PU can be given as

$$h_{j,n}^g = \beta_{ref} d_{p,j}[n]^{-\varphi} \zeta_j, \quad (5)$$

where $d_{p,j}[n]$ is the distance between the PBS and the j -th PU at time slot n . The random variable ζ_j follows an exponential distribution with unit mean, which accounts for the Rayleigh fading.

Unlike conventional fixed or random jamming models, the J-UAV is assumed to adopt a pattern-switching strategy.

Let $z[n] \in \mathcal{Z} \triangleq \{\text{Constant, Sweep, Random}\}$ denote the jamming mode at time slot n , corresponding to constant jamming, sweep jamming, and random jamming, respectively. The jamming mode evolves over time according to a finite-state stochastic process. In particular, the mode transition is modeled as a first-order Markov chain, i.e.,

$$\Pr(z[n+1] = z' | z[n] = z) = \Pi_{z,z'}, \quad z, z' \in \mathcal{Z}. \quad (6)$$

where Π denotes the mode transition probability matrix. The transition probabilities are not known to the C-UAV, and the instantaneous jamming mode cannot be directly observed. The pattern-switching behavior of the jammer directly translates into time-varying and non-stationary interference across the spectrum.

Considering the sub-carrier allocation, the binary variables $\rho_{k,n}[m]$ and $\rho_{jam,n}[m]$ are introduced to characterize the spectrum usage of the SUs and the J-UAV, respectively. Specifically, $\rho_{k,n}[m] = 1$ indicates that the m -th sub-carrier is assigned to the k -th SU at time slot n , and $\rho_{k,n}[m] = 0$ otherwise. Each PU operates on a preassigned orthogonal sub-carrier with a fixed transmit power. The J-UAV dynamically occupies sub-carriers according to its current jamming mode, which is captured by the jamming indicator $\rho_{jam,n}[m]$. When $\rho_{jam,n}[m] = 1$, the m -th sub-carrier is subject to intentional interference from the jammer at time slot n . Based on the sub-carrier availability and the time-varying jamming condition, the C-UAV aims to dynamically adapt the spectrum allocation for the SUs, such that the communication quality can be rapidly restored after jamming pattern changes, while opportunistically accessing the licensed spectrum and guaranteeing the quality-of-service requirements of the primary network.

The SINR of the k -th SU and the j -th PU in the m -th sub-band can be respectively expressed as

$$\gamma_{m,k,n}^s = \frac{\rho_{k,n}[m] P_c h_{k,n}^{\text{LoS}}}{\sigma^2 + P_m^b h_{k,n}^g + \rho_n^{\text{jam}}[m] P_J h_{k,n}^{\text{LoS}}}, \quad (7a)$$

$$\gamma_{m,j,n}^p = \frac{P_m^b h_{j,n}^g}{\sigma^2 + \sum_{k=1}^K \rho_{k,n}[m] P_c h_{j,n}^{\text{LoS}} + \rho_n^{\text{jam}}[m] P_J h_{j,n}^{\text{LoS}}}, \quad (7b)$$

where P_c and P_J denote the transmission powers of the C-UAV and the jamming UAV, respectively, and P_m^b denotes the transmission power of the PBS in the m -th sub-band. Moreover, σ^2 is the noise power. Then, the achievable data transmission rate of the k -th SU and the j -th PU can be respectively expressed as

$$R_{m,k,n}^s = B \log_2 (1 + \gamma_{m,k,n}^s), \quad (8a)$$

$$R_{m,j,n}^p = B \log_2 (1 + \gamma_{m,j,n}^p), \quad (8b)$$

where B denotes the bandwidth for each sub-band.

B. Problem Formulation

In this paper, we address a joint spectrum allocation and UAV trajectory optimization problem in a dynamic spectrum sharing UAV network under pattern-switching jamming, aiming to achieve fast recovery and reliable communication for

secondary users while satisfying the primary user protection constraints. Accordingly, the optimization problem is formulated as follows:

$$\mathbf{P1 :} \max_{\rho, \phi} \quad \frac{1}{N} \sum_{n=1}^N \sum_{k=1}^K \sum_{m=1}^M R_{m,k,n}^s - \frac{\lambda_{\text{out}}}{N} \sum_{n=1}^N \sum_{k=1}^K \mathbb{I}_{k,n}^{\text{out}} \quad (9a)$$

$$\text{s.t.} \quad \sum_{m=1}^M R_{m,j,n}^p \geq R_j^{\min}, \quad \forall j \in \mathcal{J}, \quad \forall n \in \mathcal{N}, \quad (9b)$$

$$\rho_{k,n}[m] \in \{0, 1\}, \quad \forall k \in \mathcal{K}, \quad \forall m \in \mathcal{M}, \quad \forall n \in \mathcal{N}, \quad (9c)$$

$$\sum_{k=1}^K \rho_{k,n}[m] \leq 1, \quad \forall m \in \mathcal{M}, \quad \forall n \in \mathcal{N}, \quad (9d)$$

$$|\phi[n]| \leq \pi, \quad \forall n \in \mathcal{N}. \quad (9e)$$

where R_j^{\min} denotes the minimum transmission rate requirement of the j -th PU, and $\rho = \{\rho_{k,n}[m]\}_{k \in \mathcal{K}, m \in \mathcal{M}, n \in \mathcal{N}}$ represents the spectrum allocation policy for the SUs. Constraint (9b) guarantees the quality-of-service requirements of the PUs in the dynamic spectrum sharing environment. Constraints (9c) and (9d) indicate that each sub-carrier can be assigned to at most one SU at each time slot to avoid intra-secondary interference. Constraint (9e) specifies that the heading angle of the C-UAV is constrained within the interval $[-\pi, \pi]$, ensuring feasible UAV mobility.

III. OUR PROPOSED METHOD

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- Use a zero before decimal points: “0.25”, not “.25”. Use “cm³”, not “cc”).

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Number equations consecutively. To make your equations more compact, you may use the solidus (/), the exp function, or appropriate exponents. Italicize Roman symbols for quantities and variables, but not Greek symbols. Use a long dash rather than a hyphen for a minus sign. Punctuate

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$$a + b = \gamma \quad (9)$$

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- Do not use the word “essentially” to mean “approximately” or “effectively”.
- In your paper title, if the words “that uses” can accurately replace the word “using”, capitalize the “u”; if not, keep using lower-cased.
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- Do not confuse “imply” and “infer”.
- The prefix “non” is not a word; it should be joined to the word it modifies, usually without a hyphen.
- There is no period after the “et” in the Latin abbreviation “et al.”.

- The abbreviation “i.e.” means “that is”, and the abbreviation “e.g.” means “for example”.

An excellent style manual for science writers is [7].

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ACKNOWLEDGMENT

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