

Joint Optimization of User Association, Power Control, and Dynamic Spectrum Sharing for Integrated Aerial-Terrestrial Network

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Abstract—This paper proposes a novel integrated aerial-terrestrial multi-operator network in which each operator deploys a number of unmanned aerial vehicle-base stations (UAV-BSs) besides the terrestrial macro base station (MBS), where each BS reuses the operator’s licensed band to provide downlink connectivity for UAV-user equipment (UAV-UE). In addition, the operators allow the UAV-UE, whose demand cannot be satisfied by the licensed band, to compete with others to obtain bandwidth resources from the unlicensed spectrum. Considering inter-cell and inter-operator interference in the licensed and unlicensed spectrum, the user association, power allocation, and dynamic spectrum sharing are jointly optimized to maximize the network throughput while ensuring the UAV-UEs’ data rate requirements. The formulated optimization problem, which is an NP-hard problem, is divided into two sequential subproblems. We propose a distributed iterative algorithm composed of a matching game, coalition game, and successive convex approximation technique to jointly solve the user association and power control subproblems in the licensed spectrum. Afterwards, we propose a three-layer auction framework to allocate the unlicensed spectrum dynamically between operators. Simulation results show that the proposed algorithms with the additional use of the unlicensed spectrum achieve 86.8% higher system throughput than that of only using the licensed spectrum.

Index Terms—Integrated network, multi-operator, unmanned aerial vehicle, dynamic spectrum sharing.

I. INTRODUCTION

THE utilization of unmanned aerial vehicles (UAVs) is expected to witness significant growth in various applications such as aerial imaging, cargo transport, inspection, and intelligent agriculture [1], [2]. However, the current reliance of UAVs on direct communication with their ground control station (GCS) over the WiFi band, limited to visible line-of-sight conditions, poses constraints on the potential applications of future UAVs [3]. To facilitate the widespread deployment of UAVs, it is crucial to establish reliable and high-performance connectivity between UAVs and their GCS, enabling real-time

command and control for safe UAV operations, in addition to efficient data payload transmission [4]. Therefore, integrating UAVs into cellular networks as new aerial user equipment, referred to as cellular-connected UAVs, offers a promising solution that can significantly enhance performance in terms of reliability, coverage, and throughput. However, integrating UAVs into cellular networks presents several challenges that must be addressed for efficient implementation [5]. Specifically, UAVs encounter signal fluctuations due to the downtilt of macro base station (MBS) antennas, as the side lobes of these antennas primarily serve them. According to [6], UAVs flying at an altitude of 100 m suffer from a throughput reduction of factor 10 and a coverage drop from 76% to 30% compared to ground-based cellular users. Furthermore, UAVs at such heights may receive signals from MBSs located up to 10 kilometres apart, leading to significant uplink and downlink interference [7].

Several recent research works have tackled the coverage outage probability through UAV trajectory optimization [8], [9], [10], [11], and [12]. In [8], and [9], a deep reinforcement learning (DRL) approach was proposed to solve the trajectory optimization problem of the cellular-connected UAV to minimize the communication outage duration. In [10], the authors computed and optimized the aerial coverage probability and the UAV trajectory to maximize the minimal achievable signal-to-interference-plus-noise ratio (SINR) for a novel cellular network composed of traditional terrestrial BSs and dedicated BSs whose antennas are directed toward aerial users. In [11], the lower and upper bounds coverage probabilities were derived for a novel framework of a cluster of ground BSs serving a UAV-UE in a static or moving state through coordinated multi-point (CoMP) transmission. Simulation results in the mobile UAV-UE case showed that the UAV-UE spatial displacements and vertical motions affect their coverage probability and handover rate. Previous studies have primarily concentrated on optimizing the trajectory of a single UAV-UE with predetermined start and endpoints. However, there is a lack of research considering trajectory computation for a large number of UAV-UEs, the potential conflicts arising from these trajectories, and their impact on the terrestrial network. Furthermore, studies have highlighted the significant impact of UAV movement on coverage probability [11], [12]. Therefore, providing an aerial network that allows mobility freedom for cellular-connected UAVs without

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a trajectory restriction by providing broad coverage above the actual coverage height of Macro BS is a promising solution.

An aerial network architecture, in which UAV-BSs provide seamless connectivity for cellular-connected UAVs, was introduced in [13]. The authors proposed a three-dimensional (3D) network planning framework and provided a cell associations algorithm to minimize latency. In [14], a novel aerial network architecture reusing the licensed and unlicensed spectrum was proposed to maximize the network uplink sum rate while considering the QoS requirements of UAV-UEs, inter-cell interference (ICI), and the coexistence of both WiFi and terrestrial systems. However, these works focused on standalone aerial networks without exploring the potential benefits of integrating the aerial network with the terrestrial network to cater to cellular-connected UAVs at different altitudes. Moreover, the study conducted in [14] considered a single-operator scenario without considering the multi-operator scenario. When multiple operators operate in the unlicensed spectrum, it becomes crucial to address the challenge of sharing the spectrum among operators to mitigate inter-operator interference.

The 3rd Generation Partnership Project (3GPP) is developing and evolving 6G systems to accommodate non-terrestrial networks (NTNs) to extend global connectivity to regions and areas currently underserved by traditional terrestrial networks [15]. Although integrating the aerial network with the terrestrial network to serve the cellular-connected UAV has not been considered before, recent research works investigated this integration for ground cellular users in [16], [17], [18], and [19]. This paper [16] proposed a DRL-based positioning algorithm for multiple UAV-BSs to establish reliable mobile access networks for vehicle-to-everything (V2X) communications by jointly considering energy-efficient UAV operation and reliable wireless communication services. In [17], the authors formulated an optimization problem to maximize the number of users with a minimum data rate requirement in an integrated terrestrial and NTN where UAV-BSs are deployed to supplement the terrestrial MBS coverage. In [18], the authors jointly optimized the coupled effects of UAV-BS's longitudinal mobility, air-to-ground communication, and computation dynamics to maximize the overall energy efficiency of UAV for an air-ground cooperative networking scenario. In [19], the authors proposed a UAV-assisted cooperative transmission network, in which UAV location, UAV-user association, BS resource allocation, and the load allocation between the two systems were jointly optimized to maximize the energy efficiency of the network. However, previous studies have investigated the utilization of UAV-BSs in conjunction with cellular systems to extend cellular coverage for ground cellular users (CUs), not cellular-connected UAVs. Moreover, these studies have primarily focused on single-cell scenarios and have not thoroughly examined the implications of inter-cell interference among multiple base stations on network performance. Additionally, the coverage requirements for ground CUs in a two-dimensional (2D) space differ from those for UAV-UEs in a 3D space.

The New-Radio Unlicensed (NR-U) technology is expected to offload its traffic to an unlicensed spectrum, such as

the 5 GHz band, necessitating coexistence with existing WiFi networks. This paper [20] introduced an intelligent Listen-Before-Talk (LBT) based coexistence mechanism utilizing Q-learning to enhance fairness by optimizing the NR-U base station's maximum channel occupancy time in relation to WiFi access points and compared its performance with traditional LBT mechanisms. Existing studies primarily address the utilization of the unlicensed band during periods when WiFi access points are idle. Building upon the innovative work presented in [14], which demonstrated that the unlicensed band can be effectively employed within an aerial network while maintaining interference with WiFi network below a specified threshold, this research aims to enhance spectrum efficiency. Although the issue of aerial multi-operator networks in the unlicensed spectrum remains unexplored, some studies have investigated inter-operator interference in heterogeneous cellular networks [21], [22]. For instance, authors in [22] examined the joint allocation of unlicensed subchannels and the coexistence with WiFi, with the objective of maximizing network sum-rate while adhering to user QoS constraints. The authors proposed an iterative algorithm that employed a one-sided matching game to solve the resource allocation subproblem and a cooperative Nash bargaining game to address coexistence issues with WiFi access points. However, these approaches lack an incentive mechanism to ensure operators honestly submit their bandwidth demands from the unlicensed band. Consequently, there is a pressing need for an incentive-based spectrum management approach.

A. Contribution and Organization

This paper proposes a novel integrated aerial-terrestrial multi-operator network. We formulate a joint user association, power control, and dynamic spectrum allocation optimization problem to maximize the system sum rate, considering the UAV-UE data rate requirements and the inter-cell and inter-operator interference in the licensed and unlicensed spectrums. To the best of our knowledge, this is the first work to consider an integrated aerial-terrestrial network that considers multi-cell and multi-operator scenarios in licensed and unlicensed spectrums, respectively. The main contributions of this paper are as follows:

- We propose a novel integrated aerial-terrestrial multi-operator network in which each BS provides cellular connectivity to UAV-UEs by reusing the complete licensed spectrum (multi-cell scenario). In addition, network operators allow UAV-UE, whose achieved data rate from the licensed spectrum has not fulfilled its demand, to compete with others to obtain bandwidth from the unlicensed spectrum.
- Considering multi-cell and multi-operator scenarios in licensed and unlicensed spectrum, an optimization problem is formulated to maximize the network throughput by jointly optimizing the user association, power control, and dynamic spectrum management while ensuring the UAV-UE data rate requirement.
- To solve the coupling issue that arises due to considering the multi-cell scenario, we propose a distributed iterative algorithm based on a matching game, coalition game and

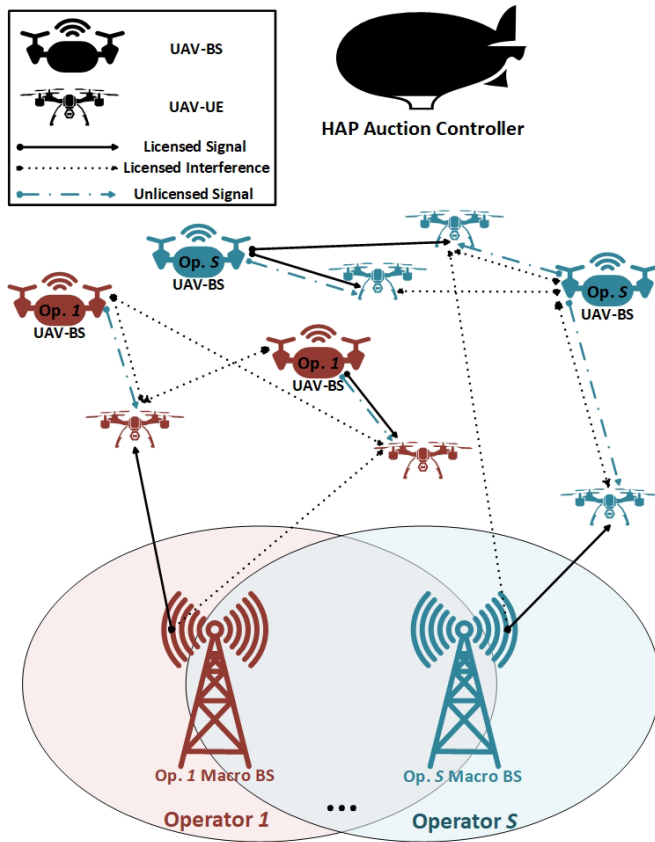


Fig. 1. Integrated aerial-terrestrial multi-operator network model.

successive convex approximation to solve the joint user association and power control subproblem in the licensed spectrum.

- To design dynamic spectrum management that solves the inter-operator interference issue in the unlicensed spectrum and overcomes the aerial network high dynamics, we propose a three-layer auction algorithm to allocate the unlicensed spectrum band dynamically among operators.
- Simulation results show that the proposed network and algorithms can significantly improve the operator's network throughput in the licensed band by 22% compared with the terrestrial network. In addition, the total network sum rate from licensed and unlicensed bands is 86.8% higher than using cellular service in licensed spectrum only.

The rest of this paper is organized as follows. Section II introduces the system model of the integrated aerial-terrestrial network. We provide the optimization problem formulation and decomposition in Section III. Section IV describes the solution algorithm of the joint user association and power control subproblem in the licensed spectrum. Section V illustrates the solution algorithm of the user association and dynamic spectrum allocation subproblem in the unlicensed spectrum. Simulation results are presented in Section VI. Section VII states the conclusion.

II. SYSTEM MODEL

A. Network Model

In the system model shown in Fig. 1, we consider an integrated aerial-terrestrial multi-operator network in the downlink

transmission. Each operator deploys multiple UAV-BSs, besides the terrestrial Macro BS (MBS), to provide efficient cellular services for UAV-UEs. Consider a set \mathcal{S} of S operators, in which the operator $s \in \mathcal{S}$ serves a set $\mathcal{N}^s = \{1, 2, \dots, N^s\}$ of N^s UAV-UEs and a set $\mathcal{M}^s = \{0, 1, 2, \dots, M^s\}$ of M^s BSs, where the MBS is indexed by 0 and the UAV-BSs are indexed by $(1, 2, \dots, M^s)$. We assume that for operator s , the location of MBS is $\{0, 0, z_{BS}\}$ and location of UAV-BS $m \in \mathcal{M}^s \setminus \{0\}$ is $\{x_m, y_m, z_m\}$. UAV-UEs can move freely at speeds ranging from $[0, v_{max}]$ during any time slot t . The time slot duration is selected to be sufficiently brief so that the positions of the UAV-UEs can be considered approximately constant within each time slot, even at the maximum speed of the UAV-UEs, as is commonly assumed in the literature [14], [23].

We assume each operator has its licensed spectrum, which is reused by all the BSs of the operator to fulfill the spectrum efficiency of next-generation networks. As a result, for operator s , the UAV-UE $n \in \mathcal{N}^s$ associated with the BS $m \in \mathcal{M}^s$ is suffered from inter-cell interference from all the other M^s cells. Due to the high demand data rate required by some applications (e.g. virtual reality, augmented reality, etc.) [24], the data rate over the licensed spectrum ($R_n^{l,s}$) could not attain the requested data rate ($R_n^{l,s} < R_n^{Req}$). Therefore, we assume that operators can compete to extend the service by reusing a total of B_{total}^U bandwidth from the unlicensed spectrum. In order to ensure the proposed architecture has a low impact on the existing WiFi system in the unlicensed spectrum, we assume that only the UAV-BSs can serve the UAV-UEs in the unlicensed spectrum [14]. In other words, the MBS can not operate in the unlicensed band due to its high transmit power and its antenna's down-tilt. Nevertheless, allowing multiple operators to access the unlicensed spectrum without management could severely degrade the performance due to the severe inter-operator interference among the operators. Since the operators need to compete to obtain the limited unlicensed spectrum for their potential UAV-UEs, a controller is needed to control the dynamic auction operation (DAO) to achieve efficient on-demand spectrum allocation. This controller could be a ground or an air unit based on the operators' methodology to provide backhaul connectivity to the aerial network. Since the aerial network could obtain the backhaul connectivity from either MBS or HAP, we set a HAP to provide the backhaul connectivity for the aerial network, where an auction controller (HAP-AC).

B. Channel Model

In our proposed network, we consider two different types of channel models as follows: (1) Air-to-Air (A2A) channel model (between UAV-BS and either HAP or UAV-UEs); and (2) Ground-to-Air (G2A) channel model (between MBS and UAV-UEs).

1) *A2A Channel Model*: The channels among UAV-BSs, HAP, and UAV-UEs are typically dominated by LoS links. Based on 3GPP TR 36.777, the path loss from UAV-BS $m \in \mathcal{M}^s \setminus \{0\}$ to UAV-UE $n \in \mathcal{N}^s$ during time slot t is given by:

$$PL_{mn}^{v,s}(t) = 30.9 + (22.25 - 0.5 \log_{10} |z_n(t) - z_m|) \cdot \log_{10} d_{mn}^s(t) + 20 \log_{10} f_c^v, \quad (1)$$

where $v \in \{l, u\}$ refers to licensed or unlicensed spectrum; $d_{mn}^s(t)$ is the 3D distance between UAV-BS m and UAV-UE n located at $\{x_n(t), y_n(t), z_n(t)\}$ within the operator s during time slot t , which is defined as $d_{mn}^s(t) = \sqrt{(x_m - x_n(t))^2 + (y_m - y_n(t))^2 + (z_m - z_n(t))^2}$; z_m is the UAV-BS m height; and f_c^v is the carrier frequency of licensed or unlicensed spectrum. The fading channel gain between UAV-BS $m \in \mathcal{M}^s \setminus \{0\}$ to UAV-UE n is shown as [25]:

$$g_{mn}^{v,s}(t) = h_{mn}^{v,s}(t) 10^{-PL_{mn}^{v,s}(t)/10}, \quad (2)$$

where $h_{mn}^{v,s}(t) \sim CN(0, \rho^2)$ is a random variable which represents the small-scale fading coefficient for the communication channel.

2) *G2A Channel Model*: According to [26], the downlink path loss between the MBS $m = \{0\} \subset \mathcal{M}^s$ and UAV-UE $n \in \mathcal{N}^s$ during time slot t can be calculated as:

$$PL_{mn}^{v,s}(t) = P_{LoS} PL_{mn}^{LoS}(t) + (1 - P_{LoS}) PL_{mn}^{NLoS}(t), \quad (3)$$

where the path loss in line-of-sight (LoS) and non-LoS (NLoS) cases can be calculated by:

$$\begin{aligned} PL_{mn}^{LoS}(t) &= 28.0 + 22 \log_{10}(d_{mn}^s(t)) + 20 \log_{10}(f_c^v), \quad (4) \\ PL_{mn}^{NLoS}(t) &= -17.5 + (46 - 7 \log_{10}(z_n(t))) \cdot \log_{10}(d_{mn}^s(t)) \\ &\quad + 20 \log_{10}(40\pi f_c^v/3), \quad (5) \end{aligned}$$

and the LoS probability is given by:

$$P_{LoS} = \frac{d_1}{d_{mn}^{2d}} + \exp\left(-\frac{d_{mn}^{2d}}{p_1}\right) \left(1 - \frac{d_1}{d_{mn}^{2d}}\right), \quad (6)$$

where d_1 and p_1 are altitude-dependent parameters with $d_1 = \max(460 \log_{10}(z_n(t)), 18)$ and $p_1 = 4300 \log_{10}(z_n(t)) - 3800$; and d_{mn}^{2d} is the 2D distance between MBS and UAV-UE n . The fading channel gain between the MBS $m = \{0\} \subset \mathcal{M}^s$ and UAV-UE $n \in \mathcal{N}^s$ during time slot t can be calculated as [25]:

$$g_{mn}^{v,s}(t) = h_{mn}^{v,s}(t) 10^{-PL_{mn}^{v,s}(t)/10}, \quad (7)$$

where $h_{mn}^{v,s}(t) \sim CN(0, \rho^2)$ is the corresponding small-scale fading coefficient.

C. Data Rate

1) *For Licensed Spectrum*: We assume that the spectrum efficiency per UAV-UE $n \in \mathcal{N}^s$ associated with BS $m \in \mathcal{M}^s$ of operator s in time slot t is as follows:

$$r_{mn}^{l,s}(t) = \log_2\left(1 + \frac{P_m^{l,s}(t) g_{mn}^{l,s}(t)}{\sum_{m' \in \mathcal{M}^s \setminus \{m\}} P_{m'}^{l,s}(t) g_{m'n}^{l,s}(t) + N_0}\right), \quad (8)$$

where $P_m^{l,s}(t)$ is the transmit power spectral density (PSD) at the BS m in the licensed band. $g_{mn}^{l,s}(t)$ is the channel gain between UAV-UE n and BS m , which can be calculated from equation (7) for $m = \{0\}$ and from equation (2) for $m \in \mathcal{M}^s \setminus \{0\}$. N_0 is the PSD of the noise, and $\sum_{m' \in \mathcal{M}^s \setminus \{m\}} P_{m'}^{l,s}(t) g_{m'n}^{l,s}(t)$ is the amount of inter-cell interference at UAV-UE n .

Let $B^{l,s}$ be the amount of licensed spectrum allocated for operator $s \in \mathcal{S}$. Then, the achievable transmission rate of

UAV-UE n associated with BS m from the licensed spectrum during time slot t can be expressed as:

$$R_{mn}^{l,s}(t) = \lambda_{mn}^{l,s} \cdot \frac{B^{l,s}}{\sum_{n \in \mathcal{N}^s} \lambda_{mn}^{l,s}} \cdot r_{mn}^{l,s}(t), \quad (9)$$

where $\lambda^{l,s}$ is the user association index of operator s in the licensed spectrum, in which $\lambda_{mn}^{l,s} = 1$ when UAV-UE n is associated with BS m of operator s , and $\lambda_{mn}^{l,s} = 0$ otherwise; and $\sum_{n \in \mathcal{N}^s} \lambda_{mn}^{l,s}$ is the number of UAV-UEs associated with BS m .

2) *For Unlicensed Spectrum*: we assume that the spectrum efficiency per UAV-UE $n \in \mathcal{N}^s$ under UAV-BS $m \in \mathcal{M}^s \setminus \{0\}$ of operator $s \in \mathcal{S}$ during time slot t is as following:

$$r_{mn}^{u,s}(t) = \log_2\left(1 + \frac{P_m^{u,s} g_{mn}^{u,s}(t)}{N_0}\right), \quad (10)$$

where $P_m^{u,s}$ is the transmit PSD at the UAV-BS m of operator s in the unlicensed band, which is fixed. $g_{mn}^{u,s}(t)$ is the channel gain between UAV-UE n and UAV-BS m in the unlicensed spectrum during time slot t , which can be derived from equation (2).

Thus, the UAV-UE n associated with UAV-BS m could achieve a data rate in the unlicensed spectrum during time slot t as expressed below:

$$R_{mn}^{u,s}(t) = \lambda_{mn}^{u,s} \cdot B_n^{u,s}(t) \cdot r_{mn}^{u,s}(t), \quad (11)$$

where $\lambda_{mn}^{u,s}$ is the association index between UAV-UE $n \in \mathcal{N}^s$ and UAV-BS $m \in \mathcal{M}^s \setminus \{0\}$ in the unlicensed spectrum; and $B_n^{u,s}(t)$ is the assigned unlicensed bandwidth for UAV-UE n during time slot t .

Finally, the achievable sum data rate of UAV-UE n over the licensed and unlicensed spectrum bands during time slot t is:

$$\mathcal{R}_n^s(t) = \sum_{m \in \mathcal{M}^s} R_{mn}^{l,s}(t) + \sum_{m \in \mathcal{M}^s \setminus \{0\}} R_{mn}^{u,s}(t). \quad (12)$$

III. PROBLEM FORMULATION AND DECOMPOSITION

Given the system model in section II, our goal is to maximize the total downlink sum rate of the network by jointly optimizing power control and user association in the licensed spectrum and dynamic spectrum allocation and user association in the unlicensed spectrum. Thus, the optimization problem is formulated as follows:

$$\begin{aligned} & \max_{(\lambda^L, P^L, \lambda^U, B^U)} \sum_{s \in \mathcal{S}} \sum_{n \in \mathcal{N}^s} \mathcal{R}_n^s(t), \\ & \text{s.t.}, \quad C_1 : \mathcal{R}_n^s(t) \geq R_n^{Req}, \quad \forall s \in \mathcal{S}, \quad \forall n \in \mathcal{N}^s, \\ & \quad C_2 : \sum_{m \in \mathcal{M}^s} \lambda_{mn}^{l,s} = 1, \quad \forall s \in \mathcal{S}, \quad \forall n \in \mathcal{N}^s, \\ & \quad C_3 : 0 \leq \sum_{s \in \mathcal{S}} \sum_{n \in \mathcal{N}^s} B_n^{u,s}(t) \leq B_{total}^U, \\ & \quad C_4 : \sum_{m \in \mathcal{M}^s \setminus \{0\}} \lambda_{mn}^{u,s} \leq 1, \quad \forall s \in \mathcal{S}, \quad \forall n \in \mathcal{N}^s, \\ & \quad C_5 : \lambda_{mn}^{l,s} \in \{0, 1\}, \quad \forall s \in \mathcal{S}, \\ & \quad \quad \forall n \in \mathcal{N}^s, \quad \forall m \in \mathcal{M}^s, \\ & \quad C_6 : \lambda_{mn}^{u,s} \in \{0, 1\}, \\ & \quad \quad \forall s \in \mathcal{S}, \quad \forall n \in \mathcal{N}^s, \quad \forall m \in \mathcal{M}^s \setminus \{0\}, \end{aligned}$$

$$C_7 : 0 \leq P_m^{l,s}(t) \leq P_m^{l,max},$$

$$\forall s \in \mathcal{S}, \forall m \in \mathcal{M}^s, \quad (13)$$

where constraint C_1 denotes that the achieved data rate through the licensed and unlicensed spectrum of each UAV-UE should meet the requested data rate; constraint C_2 ensures that each UAV-UE is associated with exactly one BS in the licensed spectrum; constraint C_3 guarantees that the total assigned unlicensed bandwidth resources must be less than or equal to the total available spectrum in the unlicensed band; constraint C_4 ensures that each UAV-UE is associated at most with one UAV-BS in the unlicensed spectrum; constraints C_5 and C_6 show that the user association coefficients in the licensed and unlicensed spectrum are binary; and $P_m^{l,max}$ is the maximum transmit PSD of BS m in the licensed spectrum.

The formulated problem is a non-convex mixed-integer non-linear programming (MINLP) optimization problem [27], which is generally NP-hard. Therefore, to solve this problem efficiently, we decouple the optimization problem into two sequence subproblems: the user association and power control in the licensed spectrum; and the user association and dynamic spectrum allocation in the unlicensed spectrum.

A. Stage One: Joint User Association and Power Control Subproblem in the Licensed Spectrum

The joint user association and power control subproblem in the licensed spectrum is written as:

$$\max_{(\lambda^L, P^L)} \sum_{s \in \mathcal{S}} \sum_{n \in \mathcal{N}^s} \sum_{m \in \mathcal{M}^s} R_{mn}^{l,s}(t),$$

$$s.t., \quad C_2, C_5, \text{ and } C_7. \quad (14)$$

Since each operator has a licensed spectrum band, we decompose subproblem (14) into S subproblems to decrease the computational complexity of the system. Each subproblem aims to independently maximize the operator's sum rate in the licensed spectrum. The optimization subproblem of operator $s \in \mathcal{S}$ is expressed as follows:

$$\max_{(\lambda^L, P^L)} \sum_{n \in \mathcal{N}^s} \sum_{m \in \mathcal{M}^s} \lambda_{mn}^{l,s} \cdot \frac{B^{l,s}}{\sum_{n \in \mathcal{N}^s} \lambda_{mn}^{l,s}} \cdot r_{mn}^{l,s}(t),$$

$$s.t., \quad C'_2 : \sum_{m \in \mathcal{M}^s} \lambda_{mn}^{l,s} = 1, \quad \forall n \in \mathcal{N}^s,$$

$$C'_5 : \lambda_{mn}^{l,s} \in \{0, 1\}, \quad \forall n \in \mathcal{N}^s, \quad \forall m \in \mathcal{M}^s,$$

$$C'_7 : 0 \leq P_m^{l,s}(t) \leq P_m^{l,max}, \quad \forall m \in \mathcal{M}^s, \quad (15)$$

where constraint (C'_2) emphasizes that each UAV-UE $n \in \mathcal{N}^s$ is associated with exactly one BS. Constraint (C'_5) indicates that the user association coefficient in the licensed spectrum $\lambda_{mn}^{l,s}$ can be only 0 or 1. Constraint (C'_7) ensures that the BS transmit PSD in the licensed spectrum remains in the required range.

B. Stage Two: Joint User Association and Dynamic Spectrum Allocation Subproblem in the Unlicensed Band

In this phase, we aim to maximize the network sum rate achieved from the unlicensed spectrum. After solving the previous subproblem, operators allow the UAV-UEs,

which achieved data rate from the licensed band ($R_n^{l,s} = \sum_{m \in \mathcal{M}^s} R_{mn}^{l,s}(t)$) less than the requested data rate ($R_n^{l,s} < R_n^{Req}$), to extend their cellular service to the unlicensed spectrum. As mentioned before, the MBS is not within the set of BSs that extend service to the unlicensed band to prevent the impact of coexistence interference on the WiFi system. However, the inter-operator interference issue in the unlicensed spectrum due to the multi-operator case will severely degrade the network performance if not managed. Due to the aerial network's high dynamics, a dynamic spectrum sharing mechanism is essential to ensure satisfactory system performance. Therefore, this subproblem aims to maximize the total sum rate in the unlicensed spectrum by optimizing the user association and dynamically allocating the unlicensed band between the operators, which is written as:

$$\max_{(\lambda^U, B^U)} \sum_{s \in \mathcal{S}} \sum_{n \in \mathcal{N}^s} \sum_{m \in \mathcal{M}^s \setminus \{0\}} \lambda_{mn}^{u,s} \cdot B_n^{u,s}(t) \cdot r_{mn}^{u,s}(t),$$

$$s.t., \quad C_1 : \sum_{m \in \mathcal{M}^s \setminus \{0\}} \lambda_{mn}^{u,s} \cdot B_n^{u,s}(t) \cdot r_{mn}^{u,s}(t)$$

$$\geq [R_n^{Req} - R_n^{l,s}]^+, \quad \forall s, \quad \forall n,$$

$$C_3 : 0 \leq \sum_{s \in \mathcal{S}} \sum_{n \in \mathcal{N}^s} B_n^{u,s}(t) \leq B_{total}^U,$$

$$C_4 : \sum_{m \in \mathcal{M}^s \setminus \{0\}} \lambda_{mn}^{u,s} = 1, \quad \forall s \in \mathcal{S}, \quad \forall n \in \mathcal{N}^s$$

$$C_6 : \lambda_{mn}^{u,s} \in \{0, 1\}, \quad \forall s \in \mathcal{S}, \quad \forall n \in \mathcal{N}^s, \quad \forall m \in \mathcal{M}^s \setminus \{0\}. \quad (16)$$

IV. USER ASSOCIATION AND POWER CONTROL IN THE LICENSED SPECTRUM

For operator $s \in \mathcal{S}$, the optimization subproblem (15) is still a non-convex MINLP optimization problem. Therefore, we decouple it into two sub-subproblems: user association sub-subproblem and power control sub-subproblem, which are respectively written below as:

$$\max_{\lambda^L} \sum_{n \in \mathcal{N}^s} \sum_{m \in \mathcal{M}^s} \lambda_{mn}^{l,s} \cdot \frac{B^{l,s}}{\sum_{n \in \mathcal{N}^s} \lambda_{mn}^{l,s}} \cdot r_{mn}^{l,s}(t),$$

$$s.t., \quad C'_2 \text{ and } C'_5, \quad (17)$$

and

$$\max_{P^L} \sum_{n \in \mathcal{N}^s} \sum_{m \in \mathcal{M}^s} \lambda_{mn}^{l,s} \cdot \frac{B^{l,s}}{\sum_{n \in \mathcal{N}^s} \lambda_{mn}^{l,s}} \cdot r_{mn}^{l,s}(t),$$

$$s.t., \quad C'_7. \quad (18)$$

In this section, we propose an efficient algorithm to obtain a sub-optimal solution to subproblem (15) by solving its two sub-subproblems (17) and (18) iteratively. A traditional matching game cannot solve the user association sub-subproblem (17) due to externalities, in which the choice of a UAV-UE by a BS is affected by the selection of the other UAV-UEs for that specific BS. Therefore, a matching and coalition game are proposed to cope with these externalities and solve this sub-subproblem efficiently. Then, a successive convex approximation method is utilized to solve the

non-convex power control sub-subproblem (18). In the following, the two sub-subproblems solution methods are discussed first, then we provide the iterative algorithm and discuss its convergence and complexity.

A. User Association

1) *Matching Game*: For operators $s \in \mathcal{S}$, we consider two disjoint finite sets of players, \mathcal{M}^s and \mathcal{N}^s . A matching game is defined as a function of $\Omega: \mathcal{M}^s \rightarrow \mathcal{N}^s$, such that:

- $\Omega(n) = m \iff \Omega(m) = n, \forall n \in \mathcal{N}^s, \forall m \in \mathcal{M}^s$.
- $|\Omega(n)| = 1, \forall n \in \mathcal{N}^s$.

The first item shows that if UAV-UE n is matched to BS m , then BS m is also matched to UAV-UE n . The second item implies that each UAV-UE is matched to one BS only.

Each UAV-UE of the set \mathcal{N}^s ranks the BSs of the set \mathcal{M}^s by preference relation $>$. The notation $\psi_{m_1}^n >_n \psi_{m_2}^n$ means that UAV-UE n prefers the BS m_1 over m_2 if $\psi_{m_1}^n > \psi_{m_2}^n$, where the utility (ψ_m^n) of UAV-UE n for BS m is calculated using equation (8).

Next, we propose a coalition game, along with UAV-UE transfer, to overcome the externalities of the matching game.

2) *Coalition Game*: For each operator $s \in \mathcal{S}$, we denote π_i as the coalition of the BS $i \in \mathcal{M}^s$ which is a set of UAV-UEs associated with this BS. The utility of UAV-UE n in the coalition π_i is calculated using equation (9). Since there are $M^s + 1$ BSs in the operator s network, the set of UAV-UEs \mathcal{N}^s , who are the players, is divided among the $|M^s + 1|$ coalitions. The formation of coalitions should satisfy the following constraints:

$$\mathcal{N}^s = \pi_0 \cup \pi_1 \cup \dots \cup \pi_{M^s}, \quad \pi_m \cap \pi_j = \emptyset, \quad \forall m, j \in \mathcal{M}^s \\ \text{and } m \neq j, \quad (19)$$

where $U(\pi_m)$ is the utility of coalition m that is written as:

$$U(\pi_m) = \sum_{n \in \pi_m} R_{mn}^{l,s}, \quad (20)$$

which represents the sum data rate in the licensed bands of all the UAV-UEs associated with the BS m .

Definition 1 (A Coalition Set Total Utility): The total utility of a coalitional set Θ , where $\Theta = \{\pi_0, \dots, \pi_{M^s}\}$, is calculated as:

$$U(\Theta) = \sum_{m=0}^{M^s} U(\pi_m), \quad (21)$$

which represents the sum data rate in the licensed spectrum band of all the UAV-UEs by the association defined by Θ .

The preference relation for UAV-UEs to choose whether to leave or join a coalition must be determined to maximize the operator's sum rate in the licensed spectrum. Instead of initial coalition set $\Theta = \{\pi_0, \dots, \pi_{M^s}\}$, a group of UAV-UEs choose to depart or enter a coalition, which forms a new coalition set $\tilde{\Theta} = \{\tilde{\pi}_0, \dots, \tilde{\pi}_{M^s}\}$, based on the utility comparison results between the initial and current coalition set [28], [29]. The utility relationship between the new and current coalition sets is defined as:

$$\sum_{m=0}^{M^s} U(\tilde{\pi}_m) > \sum_{m=0}^{M^s} U(\pi_m), \quad (22)$$

Thus, $U(\tilde{\Theta}) > U(\Theta)$ means that the coalition set $\tilde{\Theta}$ achieves a superior total utility than Θ .

Switching Rule: For any UAV-UE $n \in \mathcal{N}^s$ and $n \in \pi_m$, UAV-UE n strictly prefers to switch its coalition from π_m to coalition π_j ($\pi_j >_n \pi_m$), if and only if:

$$U(\{\pi_m \setminus n\}) + U(\{\pi_j \cup n\}) > U(\pi_m) + U(\pi_j), \quad \pi_m, \pi_j \subseteq \mathcal{N}^s, \\ \pi_m \neq \pi_j. \quad (23)$$

Therefore, the coalition set Θ is adjusted into a new coalition set as follows

$$\Theta = (\Theta \setminus \{\pi_m, \pi_j\}) \cup \{\pi_m \setminus n\} \cup \{\pi_j \cup n\}. \quad (24)$$

Theorem 1: The coalition game's final coalition set Θ_{final} is stable.

Proof. If the final coalition set Θ_{final} is not stable, then there must exist a UAV-UE $n \in \pi_p$ ($\pi_p \subseteq \Theta_{final}$) and another coalition $\pi_q \subseteq \Theta_{final}$ such that $\pi_q >_l \pi_p$. However, in this case, UAV-UE n will perform a switch operation to the available coalition forming a new coalition set based on the coalition game formulation [30]. Therefore, the final coalition set Θ_{final} is stable. ■

B. Power Control

The power control sub-subproblem (18) is still a non-convex optimization problem due to the ICI coupling between BSs. Therefore, we use the successive convex approximation (SCA) method to solve this sub-subproblem efficiently [31]. Based on [32], the SCA approach is guaranteed to converge in a finite number of iterations.

We first use the auxiliary variable $P_m^{l,s}(t) = e^{q_m^{l,s}(t)}$. Then, according to [33], $\hat{f}(x) = \xi \log x + v$ is the lower bound of $f(x) = \log(1+x)$, where $\xi = \frac{x}{1+x}$ and $v = \log(1+x) - \frac{x}{1+x} \log(x)$. Therefore, we can reformulate the sub-subproblem (18) as:

$$\max_{q^L} \sum_{n \in \mathcal{N}^s} \sum_{m \in \mathcal{M}^s} \lambda_{mn}^{l,s} \frac{B^{l,s}}{\sum_{n \in \mathcal{N}^s} \lambda_{mn}^{l,s}} [\xi^{l,s} \log_2(\gamma_{mn}^{l,s}) + v_{mn}^{l,s}] \\ \text{s.t.}, \quad q_m^{l,s}(t) \leq \ln(P_m^{L,max}), \quad \forall m \in \mathcal{M}^s, \quad (25)$$

where γ_{mn}^L is the signal-to-interference-plus-noise ratio (SINR) in the licensed spectrum, which is given by the following:

$$\gamma_{mn}^{l,s} = \frac{e^{q_m^{l,s}(t)} g_{mn}^{l,s}(t)}{\sum_{m' \in \mathcal{M}^s \setminus \{m\}} e^{q_{m'}^{l,s}(t)} g_{m'n}^{l,s}(t) + N_0}. \quad (26)$$

Theorem 2: Problem (25) is a convex optimization problem.

Proof. In order to check the convexity of the optimization sub-subproblem (25), we rearrange $\log_2(\gamma_{i,j}^{q,l})$ to be as follow:

$$\log_2(\gamma_{mn}^{l,s}) = \frac{\ln(\gamma_{mn}^{l,s})}{\ln(2)} = \frac{1}{\ln(2)} \left(\ln(g_{mn}^{l,s}(t)) + q_m^{l,s}(t) \right. \\ \left. - \ln\left(\sum_{m' \in \mathcal{M}^s \setminus \{m\}} e^{q_{m'}^{l,s}(t)} g_{m'n}^{l,s}(t) + \sigma^2\right)\right). \quad (27)$$

Based on [34], the above function is concave since the log-sum-exponential function is convex. Therefore, since the objective function of (25) is a combination of concave functions, the optimization sub-subproblem is convex. ■

Algorithm 1 Iterative User Association and Power Control Algorithm in the Licensed Spectrum for Operator s

```

1: Initialization:  $\mathcal{N}^s, \mathcal{M}^s, P_m^{L,max}$ 
   Step 1: Matching Game
2: Input:  $\mathcal{N}^s, \mathcal{M}^s$ .
3: Output: Initial user association  $\lambda_{ini}^L$ .
4: for each UAV-UE  $n \in \mathcal{N}^s$  do
5:   Calculate  $r_{mn}^{l,s}$  with the help of (8);
6:   Sort BSs according to  $r_{mn}^{l,s}$  in descending order;
7:   Match UAV-UE with the most preferred BS in its list.
8: end for
9: repeat
   Step 2: Coalition Game
10:  Input: Initial coalition set  $\Theta_{ini}$  from previous step
11:  Output: Coalition set  $\Theta_{final}$  (user association  $\lambda^L$ )
12:  while stable coalition set is not achieved do
13:    Choose a UAV-UE  $n \in \mathcal{N}^s$  randomly and refer to
    its current coalition as  $\pi_m \in \Theta$ ;
14:    Choose randomly another coalition  $\pi_j \in \Theta, \pi_j \neq$ 
     $\pi_m$ ;
15:    if Switch rule ( $\pi_j >_n \pi_m$ ) is fulfilled then
16:       $\Theta = (\Theta \setminus \{\pi_m, \pi_j\}) \cup \{\pi_m \setminus n\} \cup \{\pi_j \cup n\}$ 
17:    end if
18:  end while
   Step 3: Successive Convex Approximation
19:  Solve sub-subproblem (25) until convergence.
20: until Convergence
21: Output:  $\lambda^L, P^L$ 

```

C. Iterative User Association and Power Control Algorithm

Theorem 3: The convergence of Algorithm 1 is guaranteed.

Proof. Algorithm 1 determines near-optimal user association and power allocation in the licensed band, where each iteration includes a coalition game and SCA approach. Based on [31], the SCA approach guarantees the convergence to local optimum close to the global optimum. Besides, as proofed in Theorem 1, the coalition game would reach a stable coalition set. Therefore, the convergence of Algorithm 1 is guaranteed in a finite number of iterations since the operator's sum rate in the licensed spectrum has an upper bound and is improved in each iteration. ■

D. Computational Complexity Analysis

In this subsection, we analyze the computational complexity of the proposed Algorithm 1. For the user association sub-subproblem of operator s , we first use a matching game to initially associate UAV-UEs with BSs, with a complexity of $(\mathcal{M}^s \cdot \mathcal{N}^s)$ [35]. Afterwards, we introduce a coalition game to solve the externalities of the previous matching game. Based on the coalition game formulation, in the worst case, each UAV-UE needs to examine $|\mathcal{M}^s|$ of coalitions. Thus, the complexity of the coalition game is $O(\mathcal{M}^s \cdot \mathcal{N}^s)$. The optimal user association sub-subproblem could also be solved using the exhaustive search algorithm. However, the optimal algorithm has a computational complexity equal to $O((\mathcal{N}^s)^{|\mathcal{M}^s|})$, which is exceptionally high. The power control

sub-subproblem is solved efficiently using the CVX package since the problem is convex. Based on [31], the SCA method solves the optimization problem iteratively by updating the points of interest till convergence, which iterate for at most $O(\mathcal{M}^s)$ times. Therefore, the computational complexity for the proposed algorithm 1 is $O((\mathcal{M}^s \cdot \mathcal{N}^s) + K \times (\mathcal{M}^s \cdot \mathcal{N}^s + \mathcal{M}^s))$, where K denotes the number of iterations that the SCA method and coalition game would iterate before convergence, which is a finite constant.

V. DYNAMIC UNLICENSED SPECTRUM ALLOCATION AND USER ASSOCIATION

To solve the subproblem (16) of user association and dynamic spectrum allocation in the unlicensed band, we decouple it into two sub-subproblems: user association sub-subproblem and dynamic spectrum allocation sub-subproblem; which are respectively written below as:

$$\begin{aligned} \max_{\lambda^U} \sum_{s \in \mathcal{S}} \sum_{n \in \mathcal{N}^s} \sum_{m \in \mathcal{M}^s \setminus \{0\}} \lambda_{mn}^{u,s} \cdot B_n^{u,s}(t) \cdot r_{mn}^{u,s}(t), \\ \text{s.t., } C_4 \text{ and } C_6, \end{aligned} \quad (28)$$

and

$$\begin{aligned} \max_{B^U} \sum_{s \in \mathcal{S}} \sum_{n \in \mathcal{N}^s} \sum_{m \in \mathcal{M}^s \setminus \{0\}} \lambda_{mn}^{u,s} \cdot B_n^{u,s}(t) \cdot r_{mn}^{u,s}(t), \\ \text{s.t., } C_1 \text{ and } C_3. \end{aligned} \quad (29)$$

In order to decrease the computational complexity of the system, the user association sub-subproblem (28) is divided into $|\mathcal{S}|$ sub-subproblems; thus, each operator independently uses a matching game to associate the UAV-UEs with UAV-BS. For the dynamic spectrum allocation sub-subproblem (29), UAV-UEs need to compete with each other to strive for the limited unlicensed spectrum, which is hard to fulfill all the bandwidth requirements of UAV-UEs. Thus, we propose a three-layers auction framework to dynamically allocate the unlicensed spectrum among operators to prevent inter-operator interference.

A. Matching Game

Similar to the matching game used in the licensed spectrum, two disjoint finite sets of players, $\mathcal{M}^s \setminus \{0\}$ and \mathcal{N}^s , are considered. We define the matching game as a function of $\Omega: \mathcal{M}^s \setminus \{0\} \rightarrow \mathcal{N}^s$, such that:

- $\Omega(n) = m \iff \Omega(m) = n, \forall n \in \mathcal{N}^s, \forall m \in \mathcal{M}^s \setminus \{0\}$.
- $|\Omega(n)| = 1, \forall n \in \mathcal{N}^s$.

Each UAV-UE of the set \mathcal{N}^s ranks the UAV-BSs of the set $\mathcal{M}^s \setminus \{0\}$ by preference relation $>$, in which the utility ψ_m^n of UAV-UE n for UAV-BS m is calculated using equation (10).

B. Dynamic Auction Operation

This subsection proposes a three-layers dynamic auction operation (DAO) to solve the dynamic spectrum allocation sub-subproblem in the unlicensed spectrum (29). The three layers are the UAV-UEs layer, the Operators layer, and the HAP-AC layer. The dynamic auction operation coordinates competition relations between operators for the supply-demand of unlicensed bandwidth.

1) *The UAV-UEs Layer:* In the auction process, each UAV-UE $n \in \mathcal{N}^s$ associated with UAV-BS $m \in \mathcal{M}^s \setminus \{0\}$, $\forall s \in \mathcal{S}$, calculates $de_n^s(t)$, which denotes the bandwidth demand from the unlicensed spectrum based on

$$de_n^s(t) = \frac{[R_n^{Req} - R_n^l]^+}{r_{mn}^{u,s}(t)}. \quad (30)$$

Afterwards, the UAV-UE submits its demand priority pair (a_n^s, de_n^s) , where a_n^s is a predetermined value that indicates the maximum acceptable price of UAV-UE n under operator s and is related to (10). We use a_n^s to determine the demand priority degree, in which as the a_n^s increases, the bandwidth demand priority degree is higher.

Define q_n^s as the UAV-UE layer's received unlicensed bandwidth resources, where $q_n^s \in [0, B_{total}^U]$. $q_n^s > 0$ means UAV-UE $n \in \mathcal{N}^s$ actually obtained unlicensed bandwidth, while $q_n^s = 0$ means the bid is failed.

2) *The Operators Layer:* We define the dynamic bidding matrix as $B(t) = \{b_s(t), s = 1, 2, \dots, S\}$, where $b_s(t) \in [0, B_{total}^U]$. $b_s(t) > 0$ means operator $s \in \mathcal{S}$ can help UAV-UEs bid for the unlicensed bandwidth of HAP-AC; otherwise, $b_s(t) = 0$. The dynamic bidding matrix values are expressed as

$$b_s(t) \in [0, B_{total}^U], \quad \forall s \in \mathcal{S}, \quad (31)$$

$$\sum_{s=1}^S b_s(t) \leq B_{total}^U. \quad (32)$$

We consider that only \mathcal{N}_{new}^s UAV-UEs with $R_n^{l,s} < R_n^{Req}$ and $a_n^s > P_A$ are qualified to engage in this auction. Thus, we can update the current bandwidth demand of operator s to be:

$$b_s(t) = \sum_{n \in \mathcal{N}_{new}^s} de_n^s(t). \quad (33)$$

We define the operators' layer's unlicensed spectrum allocation matrix as $Q(t) = \{q_s^{op}, s = 1, 2, \dots, S\}$, where $q_s^{op} = \sum_{n \in \mathcal{N}^s} q_n^s$. The unlicensed spectrum allocation matrix is defined as:

$$q_s^{op} \in [0, B_{total}^U], \quad \forall s \in \mathcal{S}, \quad (34)$$

$$\sum_{s=1}^S q_s^{op} \leq B_{total}^U. \quad (35)$$

3) *The DAO Mechanism:* We design the operator $\mathcal{U}_s^S(t)$ and HAP-AC $\mathcal{U}^C(t)$ layers' utility functions to ensure competition in the DAO. When operator s assists UAV-UE n to bid, the operator-UAV link utility function is expressed as $U_n^s = a_n^s - P_A$, where P_A implies the current price of the DAO.

Therefore, the operator layer utility function is defined as:

$$\mathcal{U}_s^S(t) = \sum_{n \in \mathcal{N}_{new}^s} U_n^s \cdot de_n^s(t) = \sum_{n \in \mathcal{N}_{new}^s} (a_n^s - P_A) \cdot de_n^s(t), \quad (36)$$

and the HAP-AC side utility function can be expressed as:

$$\mathcal{U}^C(t) = \sum_{s=1}^S (P_A - P_{base,s}) \cdot b_s(t), \quad (37)$$

where $P_{base,s}$ represents the cost of the operator s to provide the unlicensed bandwidth resource unit for UAV-UE. Thus, we consider $P_{base,s}$ as the minimum price of the operator s bidding. We can observe that $a_n^s > P_{base,s}$ is guaranteed for each UAV-UE $n \in \mathcal{N}_{new}^s$ in the bidding procedures.

Therefore, the dynamic spectrum allocation sub-subproblem optimal solution refers to the solution of spectrum band allocation that maximizes social welfare, which is formulated as a linear programming optimization problem:

$$\begin{aligned} \max_{q_n^s} \quad & \sum_{s \in \mathcal{S}} \sum_{n \in \mathcal{N}^s} (a_n^s - P_A) \cdot q_n^s, \\ \text{s.t.}, \quad & C_1 : q_n^s \geq de_n^s(t), \forall s \in \mathcal{S}, \forall n \in \mathcal{N}^s, \\ & C_2 : \sum_{s \in \mathcal{S}} \sum_{n \in \mathcal{N}^s} q_n^s \leq B_{total}^U. \end{aligned} \quad (38)$$

Instead of submitting comprehensive bidding information for all UAV-UEs to HAP-AC, which presents a highly intricate process, our proposal introduces a low-complexity DAO approach. In this approach, HAP-AC only receives bidding requests from operators. The primary concept revolves around operators assisting their respective UAV-UEs in obtaining unlicensed spectrum resources from HAP-AC. To begin, UAV-UEs submit demand priority pairs, denoted as (a_n^s, de_n^s) , to their respective operators. Subsequently, each operator updates its current bandwidth demand, represented as $b_s(t)$, and utility function, denoted as $\mathcal{U}_s^S(t)$, based on the prevailing auction price. This update is performed using equations (33) and (36), respectively.

The determination of the deal price, denoted as P_A^* , occurs when the condition $[\sum_{s=1}^S b_s(t) - B_{total}^U] < \Delta$ is satisfied. Here, Δ is the maximum value among $\{de_n^s(t)\}$. Following this, the remaining unlicensed band is distributed evenly among operators. Lastly, the final bidding matrix is represented by the bandwidth allocation matrix. A fast-slow combination technique is proposed to identify the auction deal price efficiently. This technique dynamically adjusts the step size value. The mathematical description of the DAO is presented in Stage II of Algorithm 2. In cases where the complete unlicensed spectrum has not been fully demanded at the beginning of the DAO, P_A is set to $P_{base,s}$ for each operator. The feasibility of the proposed algorithm is demonstrated in the Appendix.

The computational complexity of proposed Algorithm 2 is described in two aspects. Based on Section V-A, the complexity of the matching game is $\mathcal{O}(\mathcal{M}^s \cdot \mathcal{N}^s)$ [35]. In Section V-B, since each operator needs to traverse the maximum acceptance price of the attached UAV-UEs each time, the complexity of DAO is $(K_2 \times \mathcal{O}(S \cdot \mathcal{N}^s))$, where K_2 is the convergence iterations of DAO [36].

VI. PERFORMANCE EVALUATION

In this section, we evaluate and compare the performances of our proposed approaches in both licensed and unlicensed spectrum under different system conditions and with other approaches.

A. Simulation Setup

In the simulations, we consider three different operators where each operator has 6 BSs (one MBS and 5 UAV-BSs),

Algorithm 2 Dynamic Spectrum Allocation and User Association in the Unlicensed Spectrum

```

1: Initialization:  $\mathcal{S}, \mathcal{N}^s, \mathcal{M}^s \setminus \{0\}, R_n^{l,s}, R_n^{Req}$ .
   Stage I: Matching Game
2: for each operator  $s \in \mathcal{S}$  do
3:   for each UAV-UE  $n \in \mathcal{N}^s$  do
4:     Calculate  $r_{mn}^{u,s}$  with the help of (10);
5:     Sort UAV-BSs according to  $r_{mn}^{u,s}$  in descending
   order;
6:     Match UAV-UE with the most preferred UAV-BS
   in the preference list.
7:   end for
8: end for
   Stage II: Dynamic Auction Operation (DAO)
9: for each operator  $s \in \mathcal{S}$  do
10:  for each UAV-UE  $n \in \mathcal{N}^s$  do
11:    Calculate  $de_n^s(t)$  by using (30),
12:    Submit the demand priority pair  $(a_n^s, de_n^s)$  to the
   operator  $s$ .
13:  end for
14:  Operator  $s$  computes the initial bidding value based
   on (33), and sent it to HAP-AC.
15: end for
16: Set iteration counter (i) equals 1;
17: while  $[\sum_{s=1}^S b_s(t) - B_{total}^U]_i \geq \Delta$  do
18:   if  $[\sum_{s=1}^S b_s(t) - B_{total}^U]_i \cdot [\sum_{s=1}^S b_s(t) - B_{total}^U]_{i-1} > 0$ 
   then
19:     Set  $P_A = P_A + \varepsilon$ ;
20:     Update  $B(t)$  and  $\mathcal{U}_s^S(t)$  based on (36).
21:   else
22:     Set  $\varepsilon = -0.5\varepsilon$ ;
23:     Set  $P_A = P_A + \varepsilon$ ;
24:     Update  $B(t)$  and  $\mathcal{U}_s^S(t)$  based on (36).
25:   end if
26:    $i = i + 1$ ;
27: end while
28:  $Q(t) = B(t)$ , and the HAP-AC allocates the unlicensed
   spectrum among the operators.
29: Output:  $\lambda^U, B^U$ 

```

and each operator has 20 MHz licensed bandwidth. In addition, a total of 20 MHz of unlicensed spectrum is shared between the operators. We consider a cube of 2 Km \times 2 Km \times 1 Km, in which both UAV-BSs and UAV-UEs are uniformly distributed within this area. The channel coefficients are generated from the Rayleigh fading channel model described in Section II, where $\rho^2 = 0.5$. Unless stated otherwise, parameter settings are presented in Table I.

Initially, we concentrate on the licensed spectrum before extending our analysis to the unlicensed spectrum. Specifically, we evaluate our proposed algorithm 1, which aims to maximize the per-operator sum rate in the licensed spectrum, compared with two established user association algorithms: the Max-SINR and the random algorithms. In the Max-SINR algorithm, UAV-UEs are associated with the BS, which provides the highest SINR. In contrast, in the random association

TABLE I
VALUE OF THE SIMULATION PARAMETERS

Parameter	Description	Value
\mathcal{S}	Number of operators	3
\mathcal{M}^s	Number of UAV-BSs per operator s	5
P_{MBS}^L	Macro BS PSD in licensed band	24 dBm/MHz
P_m^L	UAV-BS PSD in licensed band	22 dBm/MHz
P_m^U	UAV-BS PSD in unlicensed band	22 dBm/MHz
N_0	Noise PSD	-170 dBm/Hz
f_c^l	Carrier frequency of licensed band	2 GHz
f_c^u	Carrier frequency of unlicensed band	5 GHz
R_n^{Req}	UAV-UE average requested data rate	1 Mbps
B_s^L	Per operator s licensed bandwidth	20 MHz
B^U	Total unlicensed bandwidth	20 MHz

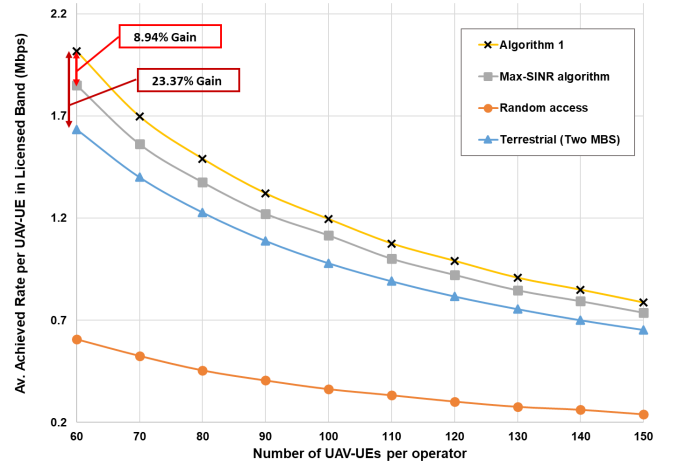


Fig. 2. The comparison of average achieved rate per user among UAV-UEs per operator.

scheme, UAV-UEs are associated with BSs randomly, without accounting for inter-cell interference [37]. Additionally, the performance of using a terrestrial network of two MBSs, without using UAV-BSs, has been examined in this comparison.

B. Algorithm 1 Results for Joint User Association and Power Control in the Licensed Band

Fig. 2 illustrates the average achievable data rate per UAV-UE for varying numbers of UAV-UEs per operator within the licensed spectrum. The data indicates that the proposed Algorithm 1 consistently outperforms other schemes, even under conditions of high UAV-UE density and significant inter-cell interference. Notably, when the number of UAV-UEs reaches 60, Algorithm 1 achieves an 8.94% improvement over the Max-SINR algorithm and approximately a 23% enhancement compared to the terrestrial network. This performance gain is attributed to the algorithm's consideration of BS load balancing during user association and its power control mechanisms for BS transmit power. Additionally, the figure demonstrates a decrease in the average data rate per UAV-UE as the number of UAV-UEs increases due to the inherent maximum limit of the total achievable sum rate per operator.

In Fig. 3, we represent the total achieved per-operator sum rate in the licensed spectrum for all the comparing algorithms. It shows that our proposed algorithm has better results than all the other algorithms. Specifically, our proposed algorithm

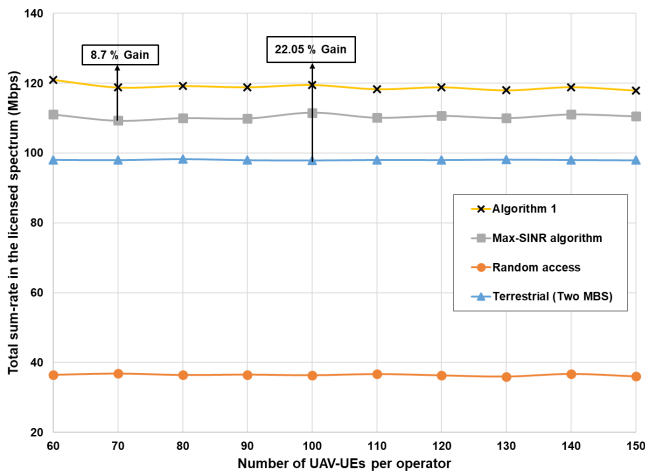


Fig. 3. The comparison of total sum rate among UAV-UEs per operator.

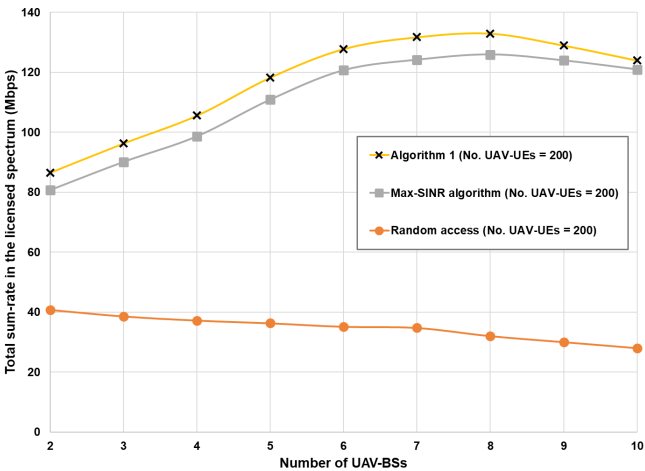


Fig. 4. Total sum rate vs. no. of UAV-BSs.

can achieve around 9 percent and 22 percent higher total sum rate per operator than the Max-SINR algorithm and the terrestrial network, respectively. The reason is that interference management through power control decreases inter-cell interference’s impact significantly when the number of BSs increases. In addition, considering the coupling issue when associating UAV-UEs with BSs prevents a BS from being more congested than other BSs.

Fig. 4 illustrates the effect of varying the number of UAV-BSs on the total achieved sum rate per operator in the licensed spectrum. It is evident that an increase in the number of UAV-BSs corresponds to an increase in the total achieved sum rate. Additionally, our algorithm consistently outperforms the Max-SINR algorithm. Conversely, the random association algorithm exhibits a decrease in sum rate with an increasing number of UAV-BSs, attributable to significant inter-cell interference. However, as the number of UAV-BSs continues to rise, the inter-UAV-BS distance diminishes, leading to heightened inter-cell interference and consequent degradation in the overall performance of all algorithms.

Fig. 5 shows that the convergence of the proposed Algorithm 1 is guaranteed in a limited number of iterations, which has been proven in Theorem 3.

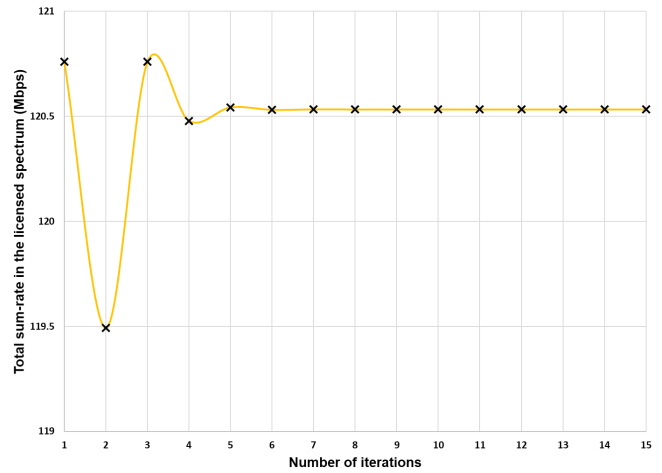


Fig. 5. Convergence of Algorithm 1.

Next, we compare the performance of the Algorithm 2 in the unlicensed spectrum with the existing spectrum management algorithms.

C. Algorithm 2 Results of User Association and Dynamic Spectrum Management in the Unlicensed Band

The output of Algorithm 1 is used as a baseline for the achieved data rate from the licensed spectrum before extending the service to the unlicensed band of all compared algorithms. We compare the proposed Algorithm 2 with two different spectrum management algorithms. The first algorithm is fixed assignment or uniform spectrum distribution, where all operators will be assigned the same amount of unlicensed spectrum without considering their load demand. The second algorithm is the game-theoretic approach developed in [22], where each operator sends a bandwidth request to a coordinator, who then distributes the unlicensed spectrum among the operators as a ratio based on their load demand. Afterwards, each operator allocates the assigned bandwidth over the users using the game theory.

We consider that each of the three operators owns 5 UAV-BSs that can extend the cellular service to the unlicensed band. We consider three scenarios while simulating the above algorithms in the unlicensed spectrum. The considered scenarios are as follows:

- In scenario 1, the number of UAV-UEs subscribing with operator one is 100, operator two is 200 and operator three is 300.
- In scenario 2, we consider a uniform distribution where each operator serves 250 UAV-UEs through their network.
- In scenario 3, the number of UAV-UEs served by operator one is 400, by operator two is 550, and by operator three is 700.

To measure the satisfaction level of UAV-UEs about their achieved data rate, we use the average proportion of satisfied UAV-UEs ($|\tilde{\mathcal{N}}_{Sat}^s|$) per operator over all the operators [22], which is represented as follows:

$$Rate\ Satisfaction = \frac{\sum_{s \in \mathcal{S}} \frac{|\tilde{\mathcal{N}}_{Sat}^s|}{|\mathcal{N}^s|}}{|\mathcal{S}|}. \quad (39)$$

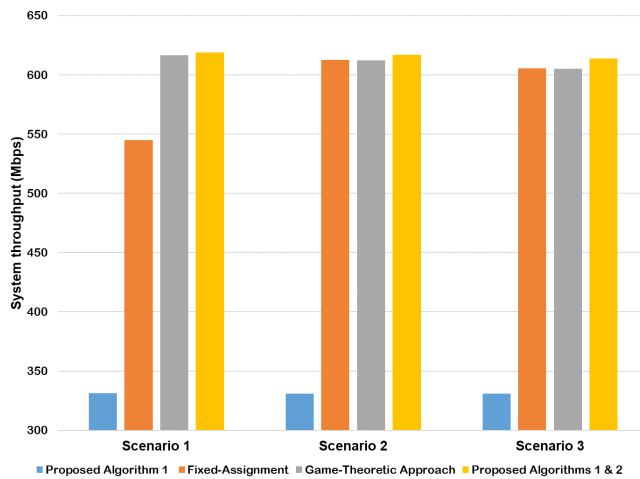


Fig. 6. System throughput vs. different scenarios.

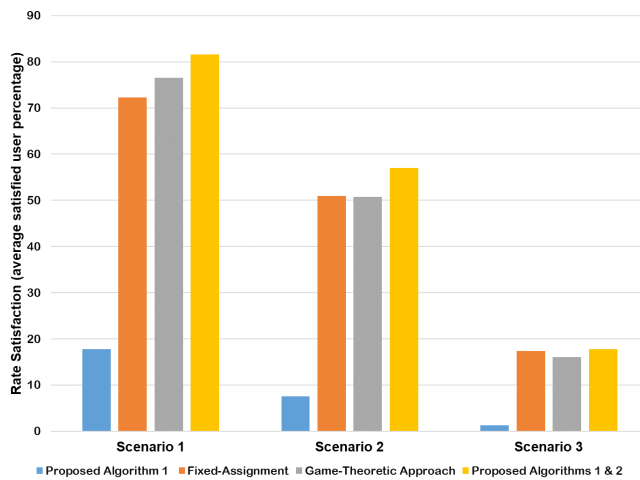
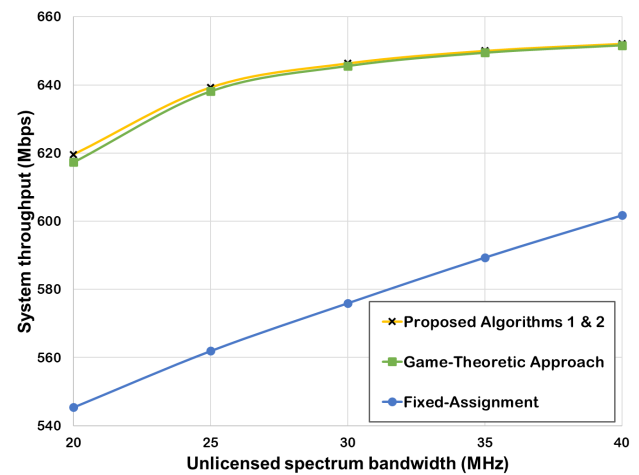


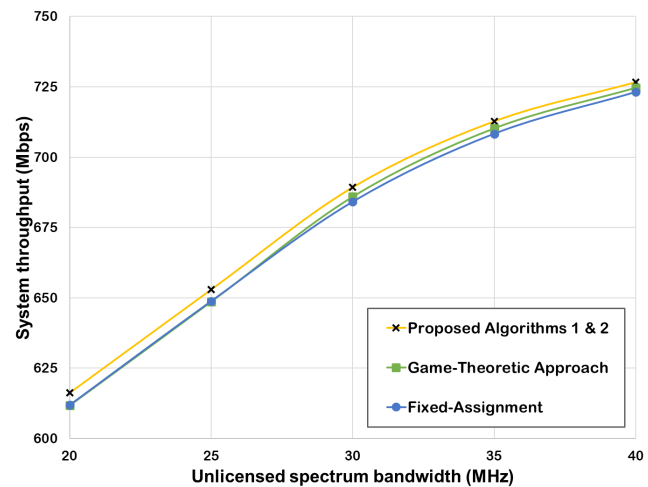
Fig. 7. Rate satisfaction vs. different scenarios.

Fig. 6 shows the total system throughput achieved for each algorithm under different scenarios. Our proposed system model can achieve about 87% gain in system throughput by extending the service to the unlicensed spectrum compared to using the licensed band only. Moreover, the proposed algorithm 2 achieves higher performance than the other two spectrum management schemes, especially in scenario 1, where it can be observed that the fixed assignment algorithm performs poorly when there is a load difference among operators. In addition, although the game-theoretic approach performs similarly to the proposed algorithm 2 in scenario 1, the actual performance could be much less. The reason is the lack of incentive for operators to inform about their actual load demand honestly. Therefore, in this case, if all the operators falsely demand the complete unlicensed spectrum, the game-theoretic approach will achieve a performance close to the fixed-assignment algorithm. In contrast, in proposed algorithm 2, if the operator requests higher unlicensed bandwidth than his actual demand, this would lead to a higher current auction price.

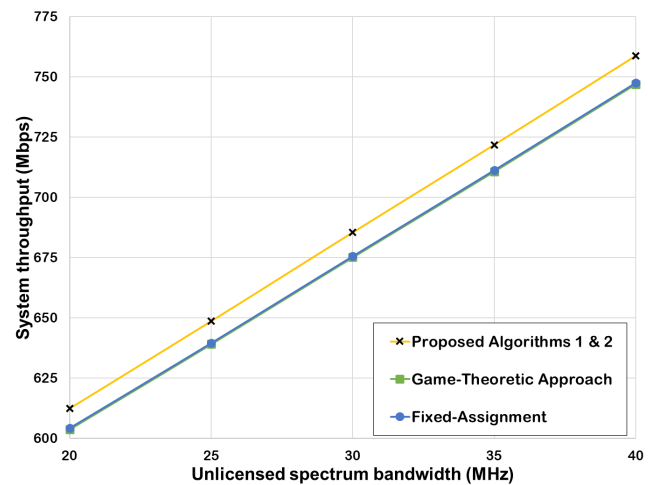
Fig. 7 shows the average percentage of satisfied users who achieved at least their minimum request data rate



(a) Scenario 1



(b) Scenario 2



(c) Scenario 3

Fig. 8. Total system throughput against different unlicensed spectrum bandwidth.

under different scenarios. As can be seen, the proposed algorithms 1 & 2 achieve an average percentage of rate satisfaction around four and six-fold the proposed algorithm 1 (the achieved sum-rate from licensed spectrum only) in scenarios 1 and 2, respectively. In addition, the proposed algorithm 2 achieves a higher data rate satisfaction percentage among

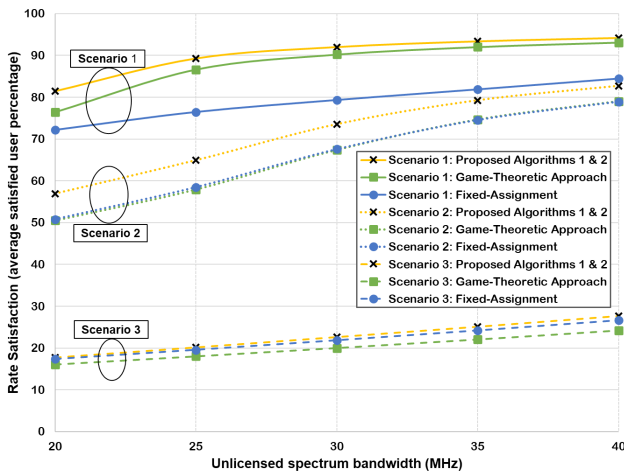


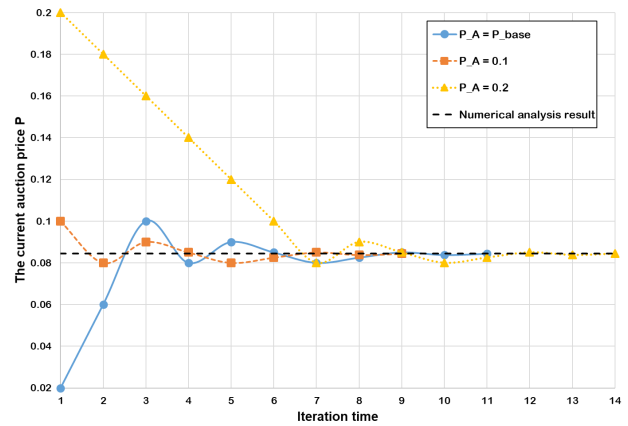
Fig. 9. Rate satisfaction vs. different unlicensed spectrum bandwidth.

UAV-UEs compared to the other two spectrum management schemes under all scenarios. Specifically, the proposed algorithm 2 has 9.3% and 7.1% more rate satisfaction compared to the fixed assignment algorithm and around 5.2% and 7.3% higher compared to the Game-theoretic approach in scenarios 1 and 2, respectively.

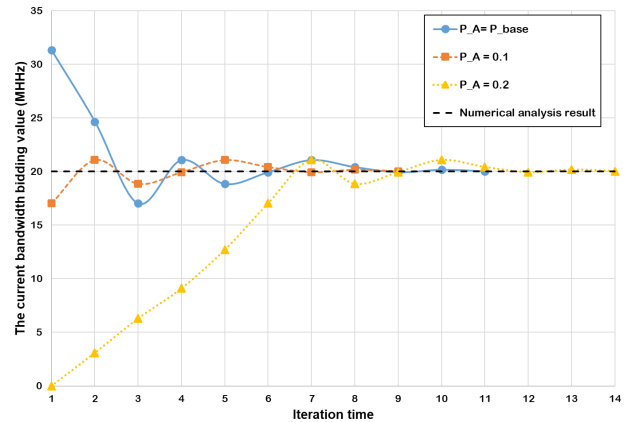
In Fig. 8, we show the total achieved system throughput against different unlicensed spectrum bandwidths. Fig. 8(a) shows that our proposed algorithm 2 achieves a significantly higher total system throughput than Fixed-assignment algorithms when there is a load difference between operators. Again, even though the game-theoretic approach has comparable performance to the proposed algorithm 2, the lack of incentive for operators to honestly demand unlicensed bandwidth would end up in a performance similar to the fixed-assignment algorithm. Fig. 8(b) shows that the fixed-assignment and game-theoretic approaches have the same performance under equal load distribution among operators. However, the proposed algorithm 2 still performs better than the other two schemes. Fig. 8(c) also shows that our proposed algorithm 2 works much better than the other schemes in cases where there is a severely crowded network scenario with different load distributions among operators.

Fig. 9 presents the rate satisfaction percentage across varying unlicensed spectrum bandwidths for all three scenarios. The data clearly indicates that the proposed algorithm significantly outperforms other algorithms in terms of user satisfaction across all scenarios. Specifically, in Scenario 2, the proposed Algorithm 2 achieves an average rate satisfaction percentage that is approximately 8% higher than that of the other two schemes, which exhibit comparable performance.

Fig. 10 depicts the convergence speed performance for various initial auction prices. In Figure 10 (a), it is evident that the current auction price stabilizes and converges to the final theoretical analysis price. Figure 10 (b) illustrates the variations in the total unlicensed bandwidth demand of the operators in response to the current auction price. Irrespective of the initial auction price, the dynamic auction mechanism rapidly converges to the theoretically optimal value, indicated by the black dashed line. Notably, when the auction price is set very low, the bandwidth demand exceeds the total available



(a) variation of auction price



(b) variation of total unlicensed bandwidth bidding

Fig. 10. Convergence of Algorithm 2.

bandwidth. Consequently, the auction controller incrementally increases the auction price, thereby reducing the unlicensed bandwidth demand until the optimal value is reached.

VII. CONCLUSION

In this work, we have proposed a novel integrated aerial-terrestrial multi-operator network considering inter-cell and inter-operator interference in licensed and unlicensed bands. The optimization problem, which aims to maximize the network sum rate while ensuring the UAV-UEs data rate requirements, has been divided into two sequential subproblems. First, a distributed iterative algorithm has been proposed to jointly optimize the transmit power of BSs and user association in the licensed band. Afterwards, we have proposed a three-layers auction process that dynamically allocates the spectrum among operators and a matching game to optimize user association in the unlicensed spectrum. Simulation results have shown that using power control in the multi-cell scenario has improved the network sum rate in the licensed spectrum compared to other schemes. In addition, the network has achieved an overall network throughput from licensed and unlicensed spectrum nearly double that from the licensed spectrum alone. For future work, the impact of wireless virtualization architecture on aerial network performance can be investigated using machine learning models.

APPENDIX

We prove the feasibility of dynamic auction operation using the duality theory of linear programming. Assuming $\alpha_n^s = q_n^s - de_n^s(t)$, the optimization problem (38) is mathematically rearrange and express as:

$$\begin{aligned} & \max_{\alpha_n^s} \sum_{s \in \mathcal{S}} \sum_{n \in \mathcal{N}^s} (a_n^s - P_A) \cdot \alpha_n^s, \\ & \text{s.t.}, \quad C_1: \alpha_n^s \geq 0, \forall s \in \mathcal{S}, \forall n \in \mathcal{N}^s, \\ & \quad C_2: \sum_{s \in \mathcal{S}} \sum_{n \in \mathcal{N}^s} \alpha_n^s \leq B_{total}^U - \sum_{s \in \mathcal{S}} \sum_{n \in \mathcal{N}^s} de_n^s(t). \quad (40) \end{aligned}$$

Using the duality theory, the dual form of the optimization problem (40) is expressed as:

$$\begin{aligned} & \min_{\Omega} [B_{total}^U - \sum_{s \in \mathcal{S}} \sum_{n \in \mathcal{N}^s} de_n^s(t)] \cdot \Omega, \\ & \text{s.t.}, \quad C_1: \Omega \geq a_n^s - P_A, \forall s \in \mathcal{S}, \forall n \in \mathcal{N}^s, \\ & \quad C_2: \Omega \geq 0. \quad (41) \end{aligned}$$

where Ω is the dual variable corresponding to the HAP-AC. Let Υ be a feasible assignment matrix for the primal problem. On the one hand, if the total bandwidth bidding is less than the entire unlicensed bandwidth spectrum at first, for each UAV-UE, we set $P_A = P_{base,s}$, where $a_n^s > P_{base,s}$ is guaranteed for each UAV-UE $n \in \mathcal{N}_{new}^s$ in the bidding procedures. On the other hand, if n is not assigned in Υ , the strategy should quit during the auction process, which means $a_n^s - P_A < 0$. Otherwise, n will be chosen by the HAP-AC with a positive bidding profit. Therefore, the proposed DAO solution has been proven to have a feasible solution.

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