This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2021.3138048, IEEE Access

IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

A Survey on Spectrum Management for Unmanned Aerial Vehicles (UAVs)

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ABSTRACT The operation of unmanned aerial vehicles (UAV) imposes various challenges on radio spectrum management to achieve safe operation, efficient spectrum utilization, and coexistence with legacy wireless networks. Current spectrum schemes have limitations when applied to UAV networks due to the dynamic nature of UAV networks that require adaptive spectrum decisions and robust schemes that provide seamless and reliable services. Existing surveys mostly focus on UAV applications, channel models, and security challenges, with a lack of studies on spectrum management in the context of UAV networks. Further, current spectrum efforts focus on terrestrial networks that feature fixed infrastructure and less dynamicity as compared to UAV networks. This motivates the need to revisit existing approaches and identify suitable schemes that allow for the rapid integration of UAVs with existing wireless technologies. Motivated by this observation, this article presents a comprehensive survey on spectrum management for UAV operations. It identifies suitable management schemes that align with UAV features and requirements to enable safe and efficient usage of the radio spectrum. The article assumes coexistence with prevalent wireless technologies that occupy the spectrum. It first presents the ruling from policymakers and regulators and discusses operation bands and radio interfaces. It then introduces deployment scenarios (applications and architectures) as standalone or heterogeneous networks. This is followed by a systematic structure for the management tools that employ deterministic, opportunistic, and competitive schemes. In addition, network monitoring, patrolling, and enforcement schemes are identified. The survey also specifies key tools that can be leveraged for spectrum management solutions such as optimization and blockchain. Finally, it recognizes open research directions and challenges that need to be tackled to advance UAV communications.

INDEX TERMS Auction mechanisms, decision making, resource allocation, spectrum enforcement, spectrum management, spectrum monitoring, spectrum sensing, spectrum sharing, spectrum patrolling, unmanned aerial vehicles, traffic management, radio interfaces.

I. INTRODUCTION

RADIO frequency (RF) spectrum is a key enabling factor for wireless technologies used by governmental and non-governmental agencies. This scarce resource has reached saturation levels due to the accelerating deployment of wireless networks and growth of user equipment. RF spectrum serves as the primary conduit over which big data is disseminated over radio channels. In order to facilitate the coexistence of various wireless networks, spectrum management pertains to the tool that achieves reliable, safe, and efficient use. It establishes policies and regulations for commercial, civil, and federal use at minimal interference levels, thus accordingly service providers develop spectrum access and sharing methods to highly utilize the assigned bandwidths with the optimum capacity and quality. For example, spectrum management is a vital tool for critical applications (e.g., military radios, aviation radars, and satellite) that requires a high level of reliability and security. For instance, spectrum allocation and channelization continuously play as the key motivation and cornerstone of cellular networks. Indeed, the five generations were developed based on the access scheme of the limited radio resource, which ranged from frequency-division multiple access (FDMA) in 1G to orthogonal frequency division multiple access (OFDMA) in 4G. Further, the frequency range (FR2) of the standalone standards relies on the full operations on millimeter wave (mmWave) bands. This follows the Federal Communications Commission (FCC) to auction these bands [1].

UAV communications have emerged as a promising wireless technology that allows fast, flexible, and agile scalability at low deployment and configuration cost in relevance to ground infrastructure. The dynamic on-demand nature of UAV networks allows users to utilize applications and services realization at reduced network overhead and intermediate entities that facilitate direct communications. Here a confluence of critical needs and technological advancements helped perceive UAV networks as a vital constituent in future communications systems that can revolutionize services, data processing, and transmission. Among these early needs included surveillance and radar, disaster recovery, wildlife monitoring, sensing, and imaging. This essential UAV role here mandated a UAV recognition by government and industry to seek further development and wide-scale adoption. This in turn allowed UAV networks to expand rapidly and achieve a projected growth in a market worth 17 billion US dollars in 2022 with a fleet of 2.4 million units, as reported by the as per Federal Aviation Authority (FAA) in [2].

Before the emergence of UAV networks, the RF spectrum was largely exclusive to ground networks (e.g., cellular, indoor, personal, etc) and few air networks (e.g., military drones, radar, satellite, etc). Now existing management tools and solutions such as spectrum pre-assignment (offline) are designed for ground networks of highly stationary network infrastructure depending on terrain, users dense areas, applications, and safety regulations. These management methods are less effective when applied to UAV communications. Foremost, the dynamics of the UAVs (e.g., flying base stations) such as velocity and lifetime entail dynamic cell shapes that vary rapidly, i.e., associated with different services, subscribers, and bandwidth demands. The wireless environment here changes faster, which dictates faster spectrum knowledge, online spectrum assignment and access, and decision making that assures seamless services without interruption and downtime. Hence, the expansion of air networks in the form of UAVs at low altitudes yields tremendous challenges and aspects that need new spectrum regulations and operation conditions. Along with this, an equitable spectrum management process is necessary for wireless networks that accommodate the future growth of UAV networks. Such a process needs to consider all relevant stakeholders necessary to create an environment that serves society, science, and the economy. These solutions need to facilitate widespread reliable connectivity with sufficient channelization capacity, thus entailing fairness among wireless providers and comparable bandwidths to ground operators. Further, the reduced infrastructure cost for UAV networks allows affordable management solutions without implementation barriers, albeit assuring safety and security. This survey is organized as follows. The first related work on existing surveys is presented in Section II, along with motivations and contributions. An overview of spectrum rulemaking is presented through the standards and regulations in Section III. Then the spectrum operation for the UAV network is elaborated by the operating bands in Section IV and radio interfaces in Section VII. This is followed by UAV deployment through use cases and applications in Section V and architectures in Section VI.

Then the spectrum management schemes are categorized into deterministic schemes, i.e., resource allocation and access technology in Section IX. Opportunistic schemes comprised of spectrum sharing XI, spectrum sensing, and decision making in Section XII. Competitive schemes are represented by auction mechanisms in Section XIII. This is followed by tools required for traffic management by introducing access control and scheduling in Section X and power control policies XIV. Spectrum surveillance is covered by spectrum monitoring in Section XVI, spectrum patrolling in Section XVII and spectrum enforcement in Section XVIII. Finally, mathematical tools are identified in Section XV, along with open research directions in Section XIX. Finally, conclusions are introduced in Section XX, along with a list of acronyms in XXI. See Figure 1 a detailed structure for this survey.

II. RELATED WORK, MOTIVATIONS AND CONTRIBUTIONS

A. RELATED WORK

Multiple surveys address UAV networks that range from applications [3], [4], [5], channel modeling [6], [7], [8], and deployment [9], [10] to resiliency [11], [12], topology [13], network management [14] and security [15], [16]. as per Figure 2. The work in [3] surveys civil applications from a communication viewpoint by covering four broad civil UAV applications including search and rescue, coverage (monitoring, surveillance), network coverage (UAVs as relays/base stations/data mule), delivery/transportation, and construction. These categories span aerial networks with different numbers of UAVs, mission distances, mission goals and requirements, and on-board sensors. This application categorization is followed by determining quantitative and qualitative communication demands for aerial networks such as quality of service (QoS) requirements, network-relevant mission parameters, data type requirements, and minimum transmitted rates for successful operation, along with challenging, constraints, and requirements related to connectivity, adaptability, safety, privacy, security, and scalability. A key limitation of this survey is it envisions a period over the period 2000-2015, which can be outdated in relevant to current breakthroughs in user demands and applications. Further, the work in [4] also surveys UAV civil application with an extended perspective. Namely, it presents a global UAV payload market value that covers equipment carried by UAVs (e.g., cameras, sensors, radars, etc). It proposes UAV classification based on endurance, maximum altitude, weight, payload, range, fuel type, operational complexity, coverage range, and

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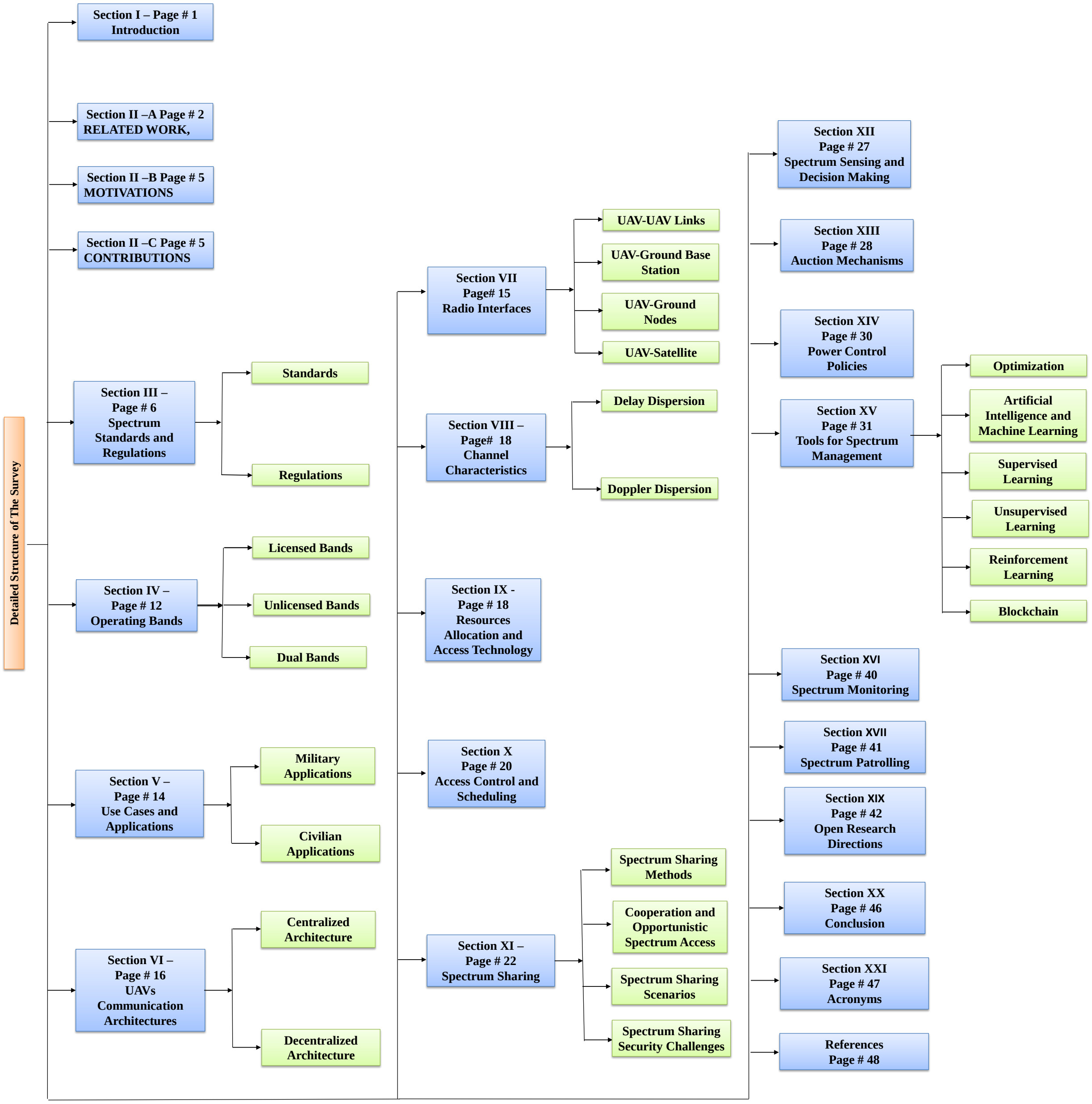

FIGURE 1: Detailed Structure of the UAVs Spectrum Management Survey.

application. Among the discussed applications include real-time monitoring of road traffic, remote sensing, delivery of goods, security and surveillance, precision agriculture, and civil infrastructure inspection. Then, research trends for UAV use and key challenges associated across different application domains, such as charging, collision avoidance and swarming, and networking and security challenges.

Another survey in [5] outlines UAV challenges as a potential entity for the delivery of IoT services. It envisions an architecture for this purpose and addresses related requirements, where UAVs are equipped with onboard sensors and cameras to collect and process data, i.e., enabling machine type communication (MTC). In addition, methods for collision avoidance, obstacle detection are investigated, and public safety concerns are discussed.

UAV communications feature distinctive channel characteristics as compared to conventional ground systems, e.g., spatial and temporal variations in non-stationary channels and air-frame shadowing for small size rotary UAVs. Therefore, a precise channel characterization is essential for the performance optimization and design of efficient UAV systems. Along with this, the work in [6] surveys measurement methods proposed for UAV channel modeling that uses low altitude platforms, along with review and suitability assess-

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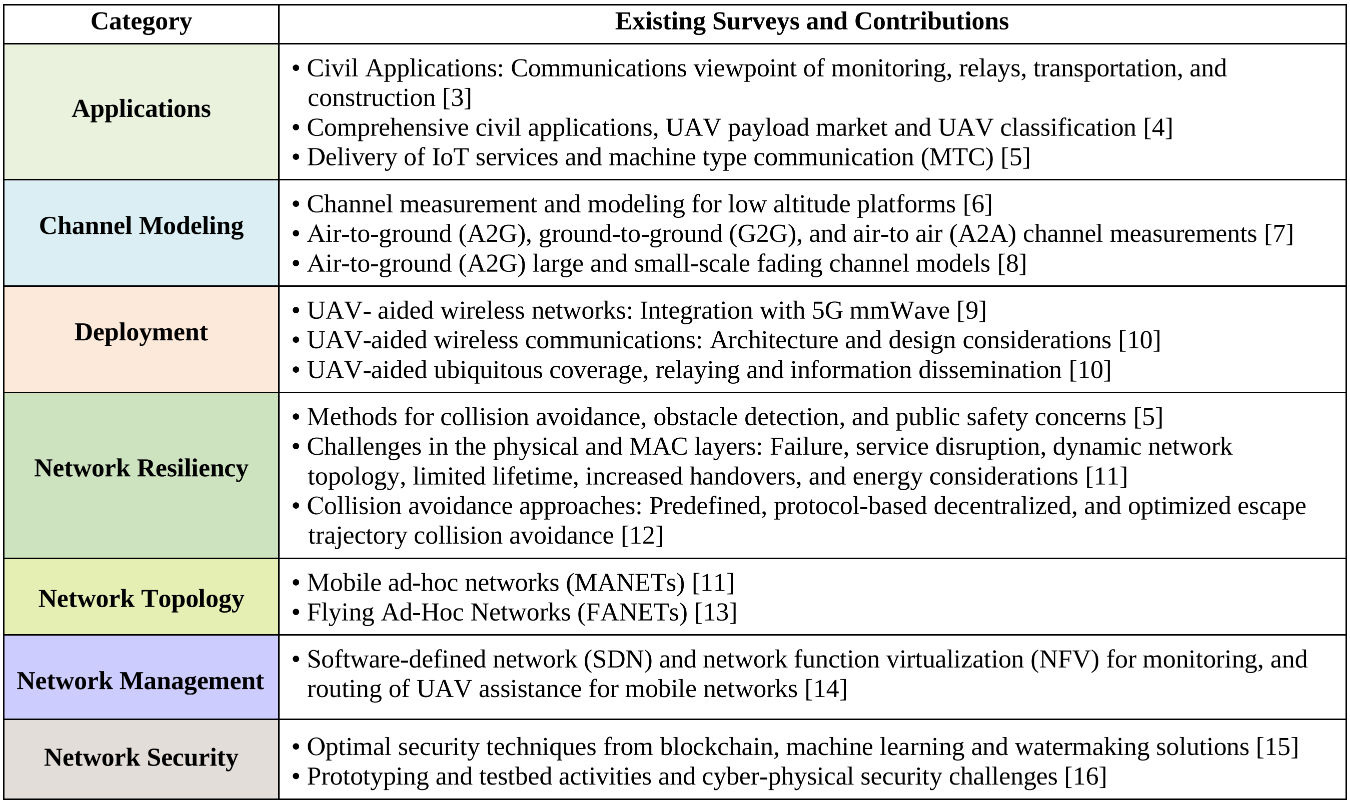

Category	Existing Surveys and Contributions
Applications	• Civil Applications: Communications viewpoint of monitoring, relays, transportation, and construction [3] • Comprehensive civil applications, UAV payload market and UAV classification [4] • Delivery of IoT services and machine type communication (MTC) [5]
Channel Modeling	• Channel measurement and modeling for low altitude platforms [6] • Air-to-ground (A2G), ground-to-ground (G2G), and air-to air (A2A) channel measurements [7] • Air-to-ground (A2G) large and small-scale fading channel models [8]
Deployment	• UAV- aided wireless networks: Integration with 5G mmWave [9] • UAV-aided wireless communications: Architecture and design considerations [10] • UAV-aided ubiquitous coverage, relaying and information dissemination [10]
Network Resiliency	• Methods for collision avoidance, obstacle detection, and public safety concerns [5] • Challenges in the physical and MAC layers: Failure, service disruption, dynamic network topology, limited lifetime, increased handovers, and energy considerations [11] • Collision avoidance approaches: Predefined, protocol-based decentralized, and optimized escape trajectory collision avoidance [12]
Network Topology	• Mobile ad-hoc networks (MANETs) [11] • Flying Ad-Hoc Networks (FANETs) [13]
Network Management	• Software-defined network (SDN) and network function virtualization (NFV) for monitoring, and routing of UAV assistance for mobile networks [14]
Network Security	• Optimal security techniques from blockchain, machine learning and watermaking solutions [15] • Prototyping and testbed activities and cyber-physical security challenges [16]

FIGURE 2: Existing surveys on UAV communications.

ment of existing UAV channel modeling approaches and outline research challenges in this domain. In [7], a survey on aeronautical channel modeling is presented in line with aeronautical characteristics and scenarios. It reviews the air-to-ground (A2G), ground-to-ground (G2G), and air-to-air (A2A) channel measurements and modeling for UAV communications and aeronautical communications under various scenarios. It then provides guidelines for link budget design by considering link losses, channel fading effects, diversity, and spatial multiplexing gain. The work is concluded by open challenges and directions in UAV channel modeling. A detailed survey is provided in [8] for A2G propagation channel models, i.e., large and small-scale fading channels, to be used in the design and evaluation of UAV communication links for control and payload data transmissions. It shows recent channel measurement campaigns and modeling efforts to characterize the AG channels for UAV networks. The survey emphasizes that available propagation channel models used for higher altitude aeronautical communications cannot be employed directly for low-altitude UAV communications due to differences in channel scattering environment. Also, small UAVs possess distinct structural and flight characteristics such as different airframe shadowing features.

Authors in [9] envision that UAV deployment is regarded as an alternative complement of existing cellular systems, to achieve higher transmission efficiency with enhanced coverage and capacity. However, spectrum congestion at microwave spectrum bands (sub-6 GHz) utilized by legacy wireless systems is insufficient to attain data rate enhancement for computation-intensive applications. Along with this, the available contiguous channelization at mmWave bands can serve as a pipeline for high throughput transmission. These bands here can be utilized for both ground and aerial UAV networks. Along with this, authors in [9] survey integration efforts of UAV with 5G mmWave communications (i.e., UAV-assisted wireless networks), present key technical challenges related to antenna systems, propagation channels, multiple access mechanisms, spatial configuration, power, and subcarrier allocation, and security solutions such as directional modulation.

Further, the article in [10] spans networking architecture, channel characteristics and design considerations for UAV-aided systems, along with performance techniques that consider UAV's mobility. Deployment scenarios in [10] include UAV-aided ubiquitous coverage (rapid service recovery and base station offloading), UAV-aided relaying for enhanced wireless connectivity, UAV-aided information dissemination and data collection in which UAVs are dispatched to disseminate delay-tolerant information to a large number of distributed wireless devices.

Despite the tremendous merits acquired from UAV communications, there are still key challenges in their design and realization. This motivated the work in [11] to survey prominent issues in the physical and medium access control (MAC) layers. Foremost, it outlines issues related to failure, service disruption, dynamic network topology, limited lifetime, increased handovers, energy considerations and intermittent links of varying quality. However, the analysis here is limited to UAV deployment in mobile ad-hoc networks (MANETs), thus it lacks co-existence in heterogeneous networks and related issues in simultaneous networks transmission. Authors in [12] present a comparative discussion of collision avoidance approaches for UAVs based on design factors such as active and passive sensing, maneuver realization dimension, and conflict detection. Among these approaches are the predefined (fixed), protocol-based decentralized, and optimized escape trajectory collision avoidance.

Other surveys categorized network typologies for UAV operations. For instance, the concept of MANET is applied to UAV and termed as Flying Ad-Hoc Networks (FANETs) in [13]. Here, the district characteristics between FANETs, MANETs and vehicle ad-hoc networks (VANETs) are clarified first such as node mobility and density, localization, power consumption and network lifetime. This is followed by the main FANET design challenges such as adaptability, scalability, and latency.

Motivated by the network management challenges, the work in [14] presents software-defined network (SDN) and network function virtualization (NFV) technologies to manage and improve the UAV assistance for mobile networks, i.e., monitoring, and routing. It outlines the main characteristics of SDN and NFV technologies, along with different classifications, use cases, and challenges related to UAV-assisted systems.

Another domain is security for UAV applications. Here a survey on optimal security techniques is provided in [15] that compares blockchain, machine learning (ML) and watermaking solutions. Each technique is presented with its advantages and suitably in securing UAV-based applications, e.g., surveillance, delivery of goods, Infrastructure and constructions inspections, and healthcare and medical systems. In [16], authors study types of available off-the-shelf UAVs for consumer use. It investigates interference issues addressed by standardization bodies for serving aerial users with existing terrestrial base stations. Moreover, it presents prototyping and testbed activities and cyber-physical security challenges.

B. MOTIVATIONS

The reliable and safe operation of the aforementioned applications and implementation in UAV networks is contingent upon effective spectrum management methods that achieve spectrum efficiency at minimal interference, and increased capacity, coverage, and QoS. Such methods that exhibit adaptivity and agility to cope with rapid fluctuations in the UAV environment. Versatile spectrum management techniques are required to cope with the rapid dynamics of UAV nodes, fast channel fluctuations, and changing topologies. The techniques here will highly impact physical and MAC such as network design and architecture, RF circuitry, node density and type, network volume and capacity, access control, communication range, cost, and revenue. Despite the several conducted surveys on UAV networks, there is a paucity for a comprehensive article that identifies the spectrum challenges and directions associated with UAV communications. Further, this work is motivated by the increased demands [17], [18] to propose spectrum solutions for this advancing technology, given its significant momentum and recent growing applications. Hence, UAV readiness for operations is contingent upon efficient spectrum assignment methods and regulations, in particular when considered as a primary constituent of 6G networks.

C. CONTRIBUTIONS

This article presents a comprehensive survey on radio spectrum management for UAV communications that consider the various operational challenges, use cases, and applications for UAVs, given the coexistence with prevalent legacy wireless networks that often dominate spectrum occupancy. The survey discusses the key relevant aspects that impact spectrum operations and decisions from the perspective of regulatory agencies, service providers, and users. A distinct attribute from existing surveys is the proposal of a management paradigm that spans the physical, MAC, and network layers, thus providing a hierarchical design analysis for underlying structures and technologies. The key contributions of the survey are as follows, as depicted in the taxonomy in Figure 3.

Spectrum Standards and Regulations: This section studies recent standards and regulations proposed by policymakers and government agencies that mandate the operation of UAV networks. Foremost, ruling and recommendations from the third-generation partnership project (3GPP) and FCC.

Operating Bands: This section outlines potential operational bands in the microwave and millimeter-wave (mmWave) for UAV communications, along with current assignments and challenges. This is elaborated for licensed, unlicensed, and dual bands.

Radio Interfaces: It outlines possible radio (control and data) interfaces for full UAV deployment scenarios including UAV interfaces with a ground base station (GBS), UAV, ground receivers, nodes in wireless local area networks (WLAN), and satellite stations.

Use Cases and Applications: It outlines primary applications based on the mission type. Namely, military such as surveillance, reconnaissance, electronics welfare, in addition to civil applications such as wireless communications, search and rescue, construction and infrastructure.

UAV Architectures: It classifies existing multi-UAV architectures in conjunction with underlying applications, i.e., based on the control structure (centralized and distributed), along with prominent deployment challenges.

Spectrum Sensing and Decision Making: It introduces sensing techniques to detect spectrum holes. It outlines UAV challenges attributed to the opportunistic transmission nature. Spectrum sensing demands adaptive and fast decision-making for spectrum access. Along with this, the section

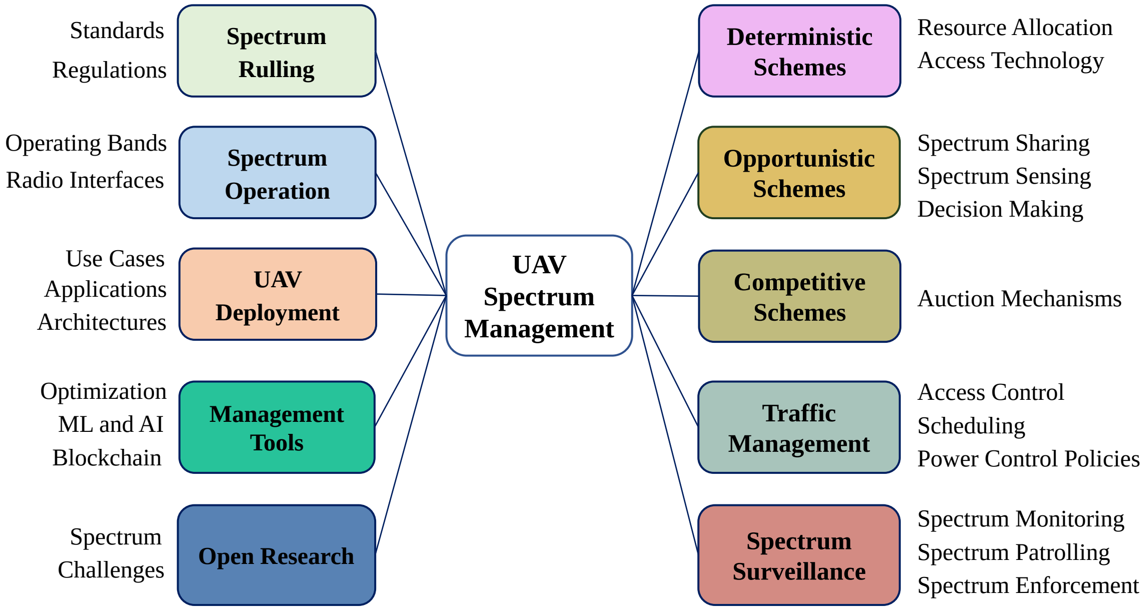

FIGURE 3: Taxonomy of the proposed spectrum management framework for UAV networks.

also outlines requirements for spectrum decision making that span decision model, cooperation, and reconfiguration over standalone and heterogeneous bands.

Auction Mechanisms: It presents prevalent auction mechanisms in the context of UAV networks, i.e., forward, combinatorial, homogeneous double, online, and collusion-resistant spectrum auction mechanisms. Here it discusses necessary features for auction mechanisms such as individual rationality truthfulness, budget balance, social welfare, collusion, and privacy preservation.

Power Control Policies: As a key tool in managing interference and impact on electromagnetic radiation, this section presents power control policies for UAV operations that enhance safety and minimize interference. It studies power ranges suitable for UAV nodes along with receiver sensitivity and signal detection.

Spectrum Monitoring: It identifies suitable monitoring entities for UAV operations in centralized and distributed platforms. This includes cloud- and fog-based, NFV and SDN, UAV-based, crowd-sourcing, and tomography schemes. It then illustrates the types of monitored signals and identifies key challenges associated with spectrum monitoring.

Spectrum Patrolling: This section discusses the need for patrolling to ensure legitimate spectrum activities, such as fair use and detection of unauthorized transmission (violations). It identifies the need for signal detection and studies crowdsourcing as a suitable tool for spectrum patrolling in UAV networks. It then identifies challenges associated with crowdsourcing such as UAV selection and fusion.

Spectrum Enforcement: The heterogeneous nature of spectrum occupancy by various entities entails enforcement policies for spectrum activities. Hence, this section elaborates on spectrum enforcement to achieve confidentiality, availability, authentication, nonrepudiation, compliance, and privacy. It first presents spectrum security and privacy threats. It then identifies enforcement measures to tackle these challenges, preventive and punitive measures. The first comprises tamper resistance and exclusion zones methods, whereas the latter comprises identification, localization, and punishment of rogue transmissions.

Tools Spectrum Management: Identified challenges in spectrum management require effective tools to achieve fast and adaptive spectrum solutions. Along with this, this section identifies mathematical tools that can be leveraged for UAV communication. This includes optimization, machine learning, along block-chain for UAV operation.

Open Research Directions: This section identifies open research opportunities in conjunction with the surveyed spectrum management schemes. In the context of UAV operations, it calls for future efforts to study RF planning, service disruption and downtime, licensing models, RF circuity, beamforming architectures, interference mitigation, network slicing, and spectrum isolation, spectrum aggregation, spectrum borrowing, spectrum partitioning, spectrum breathing, dual-polarization, and network access.

III. SPECTRUM STANDARDS AND REGULATIONS

Licensed and unlicensed bands offer promising potential for UAV operations. First, licensed spectrum presents an appealing tool to provide safe and robust UAV connectivity of sufficient channel capacities, which enables real-time applications of high computation requirements. The increasing popularity of UAVs is contingent upon effective spectrum regulations for authentication, monitoring, tracking, and coexistence with other networks. Hence, government agencies have mandated vital spectrum regulations for UAV connec-

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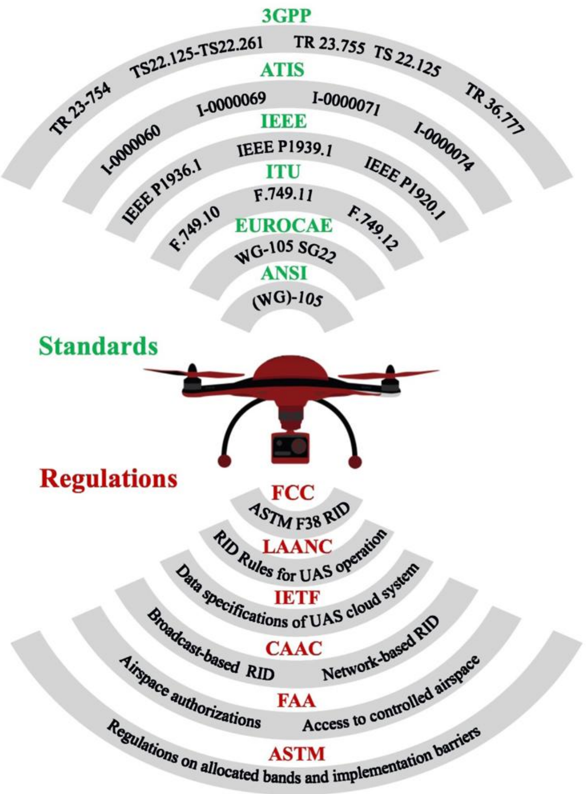

FIGURE 4: Standards and regulations for UAV networks.

tivity to ensure safe operation and air traffic management. On the other side, the unlicensed spectrum can be less suited for non-line of sight (NLoS) links in UAV connectivity. This is attributed to the limited coverage that rises from low permitted power levels and non-guaranteed QoS levels in the shared spectrum. Along with this, regulations in licensed bands constitute a major element in the growth of UAV networks, as part of the mobile networks infrastructure or operating as a separate network. Figure 4 depicts the major standards and regulations related to UAV operations, as detailed next.

A. STANDARDS

(1) 3GPP Standards

The third generation partnership project (3GPP) actively investigated architectures, related issues, and requirements for UAV networks, as per the proposed Releases 15-17.

Release 17-TR 23-754: This is the main release that relates UAV operation and coexistence with the 3GPP system. It proposes a reference architecture, and studies system aspects of command and control (C2) functions, UAV connectivity with unmanned aircraft systems (UAS) traffic management (UTM), identification, and tracking. This enables connectivity between UAVs in Los and NLoS settings and other traffic management factors [19].

Reference Architecture: 3GPP system enables UTM to associate the UAV and UAV controller (UAV-C) and identify them for both 3GPP and non-3GPP networked UAV-C. The architecture assumes that UAS is composed of one UAV-C and one UAV, and each UAS component is considered as an individual UE from the perspective of the 3GPP system.

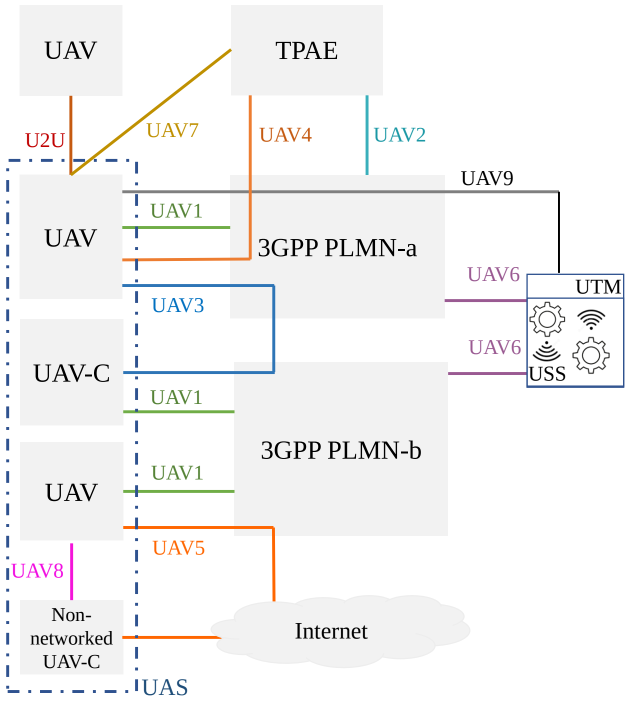

FIGURE 5: 3GPP reference architecture.

The latter enables the serving public land mobile network (PLMN) entities of the UAV(s) and the corresponding UAV-C to be different. Further, the 3GPP network is aware of the Civil Aviation Authority (CAA)-level UAV identity and it provides enablers to support geo-fencing (for in-flight UAV) and geocaching (for UAV on the ground intending to fly) functionality in UTM. Finally, UAV reports real-time flight information periodically to UAV Service Supplier (USS) and UAV Traffic Management (UTM) (USS/UTM) via the 3GPP network, where the reporting frequency depends on geography and regulations. Finally, the architecture considers a third-party authorized entity (TPAE), which is not part of the UTM functionality. Figure 5 depicts the 3GPP-based UAV architecture that defines the following interfaces [19].

- UAV1: Supports UAV and UAV-C authorization, authentication, and identification through the 3GPP network.
- UAV2: Enables remote identification and tracking for TPAE with the 3GPP system.
- UAV3: User plane connectivity with networked UAV-C for transporting C2 communication over 3GPP network.
- UAV4: It connects TPAE with a UAV over 3GPP network for UAV C2 communication, remote identification, and tracking.
- UAV5: User plane connectivity with a non-networked UAV-C (outside 3GPP) for transporting C2 communication.

- UAV6: Connects 3GPP system with external UTM for functionality support of UAV identification.
- UAV7: Used for remote identification information sent in broadcast (BRID), on a transport outside the 3GPP network.
- UAV8: Used for C2 communication over a transport outside the 3GPP network.
- UAV9: Supports connectivity between UAV or a networked UAVC and the USS/UTM for UAS management.
- U2U: Supports UAV-to-UAV communications for broadcast remote identification (RID).

Key Issues and Proposed Solutions: The TR 23-754 standard sets multiple key issues (KI) associated with the UAV operation in the reference architecture [19].

1) UAV Identification: The authorization, authentication, identification, and tracking of UAVs and UAV-Cs with various identities inside and outside the 3GPP system.

2) UAV authorization by UTM: Authorization mechanisms for UAV operation in the 3GPP system to enable tracking and identification once a UAV flight is authorized for by UTM.

3) UAV-C Identification: It includes the identification, authorization, and authentication mechanisms of UAV-C with UAVs such as UAV pilot.

4) UAV and UAV-C Tracking: The information required for the 3GPP system to track the UAV and the UAV-C.

5) UAV Authorization Revocation: It follows a UAV failed reauthorization and revocation of authorization by UTM.

6) UAV-C and UAV association: The association protocols between UAV-C and UAVs, i.e., to enable UTM flight mission authorization.

7) User Plane Connectivity for UAVs: The methods over which UAVs and a UAV-C establish connectivity in the 3GPP system with the UTM.

The standard then proposed multiple solutions [19], [20] to address the above KIs, as mapped in Table 1. Solutions include identifying interface correlation between UAV and 3GPP architectures, CAA authentication, geo-fencing, control-plane assisted UAV authentication, direct broadcast, and network publishing, etc.

Release 17-TS22.125-TS22.261: It addresses 5G connectivity enhancement for UAVs by setting various key performance indicators (KPI) and communication needs of the UAV with a 3GPP subscription. In particular, KPIs based on communication service, command and control traffic, onboard radio access node (UxNB), service restriction for UAV, and network exposure [21].

Release 17-TR 23.755: It studies use cases and requirements that relate to UAS identification and tracking and its potential impact on the application layer. In particular, application enabler functionalities for UTM and service interactions between UAS and the UTM (e.g., fly route authorization, location management, group communication support). The standard also develops KPIs that relate application layer support for UAS over 3GPP networks, corresponding architecture requirements, and solution recommendations. Moreover, the standard analyzes the re-use of functionalities, specifications, and solutions developed by the radio access network (RAN) working group (WG6) where applicable. It also provides application programming interfaces (API). [22].

Release 16-TS 22.125: The 3GPP system aspects group (SA1) studies requirements and use cases for remote identification and on the services to be offered based on remote identification of the unmanned aircraft system (UAS). [23].

Release 15-TR 36.777 This release investigates serving aerial UE by long-term evolution (LTE) networks. It identifies performance enhancements for UE- and network-based solutions, downlink interference mitigation, uplink interference mitigation, mobility performance, and aerial UE identification. It also enhances the measurement report triggering to address the issue of aerial UE interference to the base station (eNodeB). This includes two reporting events, H1 (above) and H2 (below) UE height thresholds, which assist eNodeB to view the UAV and resolve any potential interference [24].

(2) IEEE Standards

The institute of electrical and electronics engineers (IEEE) sets various standards for UAV networks. First, the IEEE P1936.1 standard [25] approved in 2018 supports application scenarios and required execution settings. This includes flight platform, flight control system, ground control station, payload, control link, and data link, takeoff, and landing system. It also mandates safety and management requirements related to airworthiness, qualification of operators, airspace, insurance, and confidentiality. Further, it sets operational methods, accuracy indicators, and technical requirements for the photogrammetry for light-small civil drone applications in power grid engineering surveys and design. For instance, fixed-wing or multi-rotor UAV, battery or fuel-based operations, weight without payload (0.25kg - 25kg), maximum active radius (15km), and maximum operational altitude (1km).

Moreover, the IEEE P1939.1 standard [26] approved in 2019 defines a UAV structure for traffic management at low altitudes. It comprises coding techniques, remote sensing and surface object extraction technologies, route planning, operation, and management that provides macro policies to support docking between the air route and UTM.

Finally, the IEEE P1920.1 standard [27] approved in 2020 sets protocols for air-to-air communications for self-organized ad-hoc aerial networks. This is applicable for unspecific communication standards (e.g., wireless, cellular, etc), small and large, and civil and commercial aircraft systems. It specifies service architecture, security framework, and data models. Overall, it enhances aerial networking and promotes situational awareness of aircraft to communicate in an ad-hoc aerial network.

(3) International Telecommunication Union (ITU)

The ITU recommends UAV standards as part of the non-telephone telecommunication services (F-series) reports [28].

ITU-F.749.10 (2019): It outlines requirements for communication services of civilian unmanned aerial vehicles (C-

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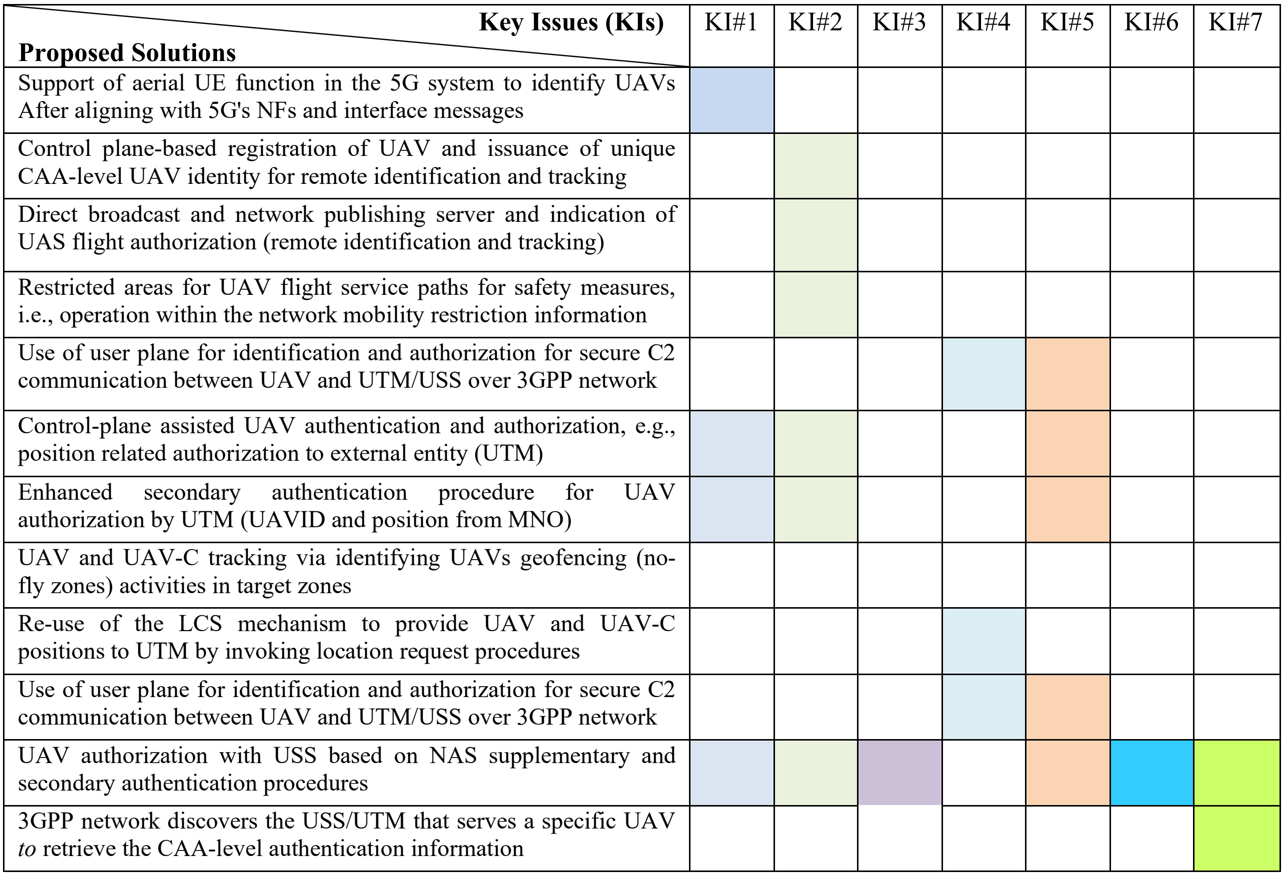

Key Issues (KIs) **Proposed Solutions**	KI#1	KI#2	KI#3	KI#4	KI#5	KI#6	KI#7
Support of aerial UE function in the 5G system to identify UAVs After aligning with 5G's NFs and interface messages	🟦						
Control plane-based registration of UAV and issuance of unique CAA-level UAV identity for remote identification and tracking		🟩					
Direct broadcast and network publishing server and indication of UAS flight authorization (remote identification and tracking)		🟩					
Restricted areas for UAV flight service paths for safety measures, i.e., operation within the network mobility restriction information		🟩					
Use of user plane for identification and authorization for secure C2 communication between UAV and UTM/USS over 3GPP network				🟦	🟧		
Control-plane assisted UAV authentication and authorization, e.g., position related authorization to external entity (UTM)	🟦	🟩			🟧		
Enhanced secondary authentication procedure for UAV authorization by UTM (UAVID and position from MNO)	🟦	🟩			🟧		
UAV and UAV-C tracking via identifying UAVs geofencing (no-fly zones) activities in target zones							
Re-use of the LCS mechanism to provide UAV and UAV-C positions to UTM by invoking location request procedures				🟦			
Use of user plane for identification and authorization for secure C2 communication between UAV and UTM/USS over 3GPP network				🟦	🟧		
UAV authorization with USS based on NAS supplementary and secondary authentication procedures	🟦	🟩	🟪		🟧	🟦	🟩
3GPP network discovers the USS/UTM that serves a specific UAV *to* retrieve the CAA-level authentication information							🟩

FIGURE 6: 3GPP standards: Challenges and solutions.

UAVs), as well as the use cases of C-UAV in industry and consumer application areas. it includes a general communication service framework, communication system requirements, requirements for flight control communication, and flight data transport. It also sets requirements for mission payload communication services (e.g., audio, video, images transport, and sensor data transport) [29].

ITU-F.749.11 (2019): It utilizes C-UAV as a mobile edge computing (MEC) platform to realize a flexible on-demand computing service that can be rapidly deployed according to the practical service needs of devices. Further, it describes the framework and requirements for a C-UAV MEC system, i.e., functional, service and security requirements [30].

ITU-F.749.12 (2020): It presents a general framework for communication application of C-UAV and its functional entities, reference points, etc. Addressed applications include industrial and consumer areas such as agriculture and plant protection, power line and petroleum pipeline inspection, police and traffic security surveillance, disaster monitoring, aerial photography and videography, express delivery, forestry, and forest fire monitoring, meteorological, resource, and scientific research, etc [31].

(4) Alliance for Telecommunications Industry Solutions (ATIS)

It identifies solutions for cellular-as-a-drone communication by providing field-testing data to characterize the ability to exist cellular networks to offer communications services to UAV [32], as per the following reports.

ATIS-I-0000060: It studies UAV utilization and adoption by mobile cellular networks through a synergistic combination. Here it specifies cellular service supported for UAVs and associated control, support of regulatory requirements and safe operation, location services, and technologies. It recommends UAV operating at low altitude (< 400) to leverage cellular networks due to the installed wide coverage, high reliability and managed QoS, robust security against eavesdropping and tampering with communications. Additional saliences include seamless mobility, high capacity with the ability to absorb the impact of a rapidly growing UAV population and integrated location technology [33].

The standard also sets requirements for cellular interface support for UAV control. This includes the reliable transmission of pilot commands to the UAV and return of telemetry data from the UAV to the pilot, low latency to support real-time piloting of the UAV, sufficient capacity to serve all UAVs within an area, sufficient coverage/range to communicate with the UAV throughout its flight, resistance to unintentional and malicious interference from natural and man-made sources, fail-safe operation in the event of failure of the original link.

ATIS-I-0000069: It highlights 3GPP standards and capabilities for UAV communications including objectives of LTE radio enhancements for UAV service in Rel.15, UAV identification in Rel.16, 3GPP enhanced UAV requirements and performance in Rel.17, along with UAV support in 5G new radio, and the support for high altitude platforms (HAP) in 5G [34].

ATIS-I-0000071: It details the planning and operations of UAVs usage for restoring communications in emergencies. For example, infrastructure damage due to disaster events, where UAVs are utilized to coordinate recovery operations. Aspects include spectrum and technical considerations (wireless services backhaul and fronthaul), regulatory implications and organizational aspects (decision making, lifecycle of UAV operations, access to airspace, and logistics) [35].

ATIS-I-0000074: It presents recommendations for 3GPP to use cellular communications for the support of UAV flight operations. This includes the C2 interface, UTM, UAV RID, and detect and avoid (DAA) features. Also, architecture is required to allow interaction between cellular networks and UAV flight operation systems. Hence, the report proposes high-level architectural approaches [36].

- Architectural approaches that use IP traffic over 3GPP networks.
- Architectural approaches based on direct communication over 3GPP interfaces between nodes in close physical proximity.
- Architectural approaches that require tighter integration of 3GPP and UAV technology, i.e., linking of identities between UAVs and 3GPP UEs.

(5) American National Standards Institute (ANSI)

ANSI proposes a roadmap for UAS systems through a set of gaps and recommendations, i.e., additional pre-standardization research requirements. Foremost, the task of the working group (WG)-105 investigates the safe integration of UAS into all classes of airspace. It defines six focus areas including DAA, UTM, design and airworthiness standards, enhanced automation for remotely piloted aircraft systems (RPAS), specific operation risk assessment (SORA), and command, control, communication, spectrum, and security [37].

The goal of the spectrum management area is to achieve alignment with regulatory directions and operational needs. The main technical deliverables (minimum aviation system performance standards-MASPS and minimum operational performance specification-MOPS) tactically address the needs of certified RPAS for spectrum management. Here the WG recommends the participation of various organizations to develop a comprehensive set of industry standards needed to cover the whole spectrum of UAS and their operations. Further, it considers a need for additional spectrum to communicate with public safety UAS.

Some key gaps that are related to spectrum management include Gap A4 [38] that identifies avionics and subsystems in UAS operations. Namely, reliability and cybersecurity of C2 data links, along with the use of the department of defense (DoD) spectrum (and non-aviation) on civil aircraft operations. Here it recommends creating a framework for UAS avionics spanning both airborne and terrestrial-based systems.

(6) European Organization for Civil Aviation Equipment (EUROCAE)

This is a pre-standardization effort that is still open to consultation, in particular, the WG-105 SG22 draft [39] that discusses minimum aviation system performance specification for the management of the C-band spectrum in support of RPAS C2 link services. Further, the WG-105 SG22 develops guidance on spectrum access for UAVs, use, and management for UAS and remotely piloted aircraft (RPA) for any non-payload purpose.

B. REGULATIONS

Multiple decision-making agencies have studies regulations for UAV operations. This includes the Federal communications commission (FCC), the Federal aviation administration (FAA), the low altitude authorization and notification capability (LAANC), the American society for testing and materials (ASTM), and others. Consider the details.

(1) Federal Communications Commission (FCC)

The Bureau of Engineering and Technology, Wireless Telecommunications within the FCC developed a report [18] that is consistent with Section 374 of the FAA Reauthorization Act of 2018 [40] (released on Aug. 2020). This report submitted to the House of Representatives (Commerce, Science, and Transportation and Energy and Commerce Committees) seeks regulations on allocated bands and implementation barriers. First, it seeks whether UAS systems operations should be permitted to operate on the spectrum that was recommended for allocation for aeronautical mobile service and control links [41] in 2007 (L-band, 960-1164 MHz) and 2012 (C-band, 5030-5091 MHz), on an unlicensed, shared, or exclusive basis. Further, the report addresses any technological, statutory, regulatory, and operational barriers to the use of such a spectrum. Moreover, it recommends alternative frequency bands if it was determined that the above spectrum frequencies are not suitable for beyond-visual-line-of-sight operations by UAS operations [42].

Overall, the FCC acknowledges the growth of UAS operations and hence supports spectrum allocation to accommodate this technology and its potential benefits. It demands addressing UAS spectrum requirements, enables command-and-control links, telemetry, payload, and other communications. It recommends the suitability of the unencumbered 5030-5091 MHz band and flexible-use spectrum bands, albeit some technical and regulatory issues that require further review before UAS operations may be permitted. Moreover, the FCC considers the encumbered 960-1164 MHz band with critical aeronautical navigation uses, thus making the deployment of UAS in this band challenging. It raises concerns regarding the possible impacts of such use to incumbents in the 960-1164 MHz band. Hence, it recommends that the Commission initiate a rulemaking proceeding to develop service and licensing rules enabling UAS use of the 5030-5091 MHz band.

(2) The Federal Aviation Administration (FAA)

The UAS identification and tracking aviation rulemaking committee (UAS-ID ARC) provides recommendations to the FAA regarding remote identification and tracking technologies for UAS. This formed the FAA rule on RID [20] and outlining viable tracking technologies. This includes automatic dependent surveillance-broadcast, low power direct RF, networked cellular, satellite, and flight notification with telemetry. Further, two methods are proposed for RID and tracking data, i.e., local direct broadcasting and network publishing information to an FAA-approved internet-based database (direct broadcasting). Note that direct broadcasting (uni-directional) requires no handshaking (network independent). This compels public safety officials to be equipped with appropriate receivers to obtain UAV transmitted information. Meanwhile in-network publishing, public safety officials can access data to obtain an ID and tracking information for UAS for which such data have been published [20].

The internet-based database approach requires only interoperability at the IP and application level, without the need for compatible technologies, where transmitters' hardware only needs to pass data to the internet-based service(s) and clients to be connected to the services. Hence, the FAA is required to leverage internet-based database infrastructure to integrate current recommendations. One method is provisioning remote ID and tracking services using private USS to provide services specific to UAS operations. This compels an exchange of information between operators, the USS and the FAA, thus making the USS act as the primary interface to the operator. In turn, this requires the FAA to collect telemetry information regarding various operations. These settings result in privacy concerns for held information and restrictions imposed on the USS on data usage and dissemination. Furthermore, the FAA and department of transportation (DoT) proposed rules for RID for UAS operation [43] that relate to owners, operators, designers, and developers, as presented next [43].

- ID Registration: UAVs with weight less than 0.55lb require no registration.
- RID Categories: ID information is broadcasted and unicasted to a USS through an internet connection (standard) or only unicasted to USS without broadcast (limited).
- ADS-B Use Approval: FAA prohibits its use without approval.
- Primary functions for USS: Real-time RID sharing, ID access security. It aims to meet contractually established parameters and inform UAS status to FAA, e.g., use of one-time session ID for communication with FAA.
- UAS Traffic Management (UTM): FAA envisions that third-party will supply UTM services, which does not exist currently.
- UAS Performance Requirements: Location, auto USS connection, time mark, self-testing and monitoring, tamper resistance, connectivity, error correction, message transmission.

(3) American Society for Testing and Materials (ASTM)

The ASTM aims to enhance the growing demands for the identification and tracking of UAS in airspace systems. This has been evolved by the ASTM F38 RID standard [44] that allows public and public safety officials to identify a UAV based on the assigned ID, without compromising the privacy, thus preserving identities information. The standard specifies mechanisms over which UAVs can transmit the assigned ID, location, speed, and direction, i.e., broadcasting over a wireless IP-based connection to a USS.

(4) The Low Altitude Authorization and Notification Capability (LAANC)

The LAANC advocates UAS integration into the airspace [45] through a collaboration between FA and industry. It supports UAV pilots with access to controlled airspace (below 400 ft.). Also, it provides awareness of fly and no-fly zones, provides air traffic professionals with regions visibility on UAV operations. It approves applications for airspace authorizations by checking multiple airspace data sources in the FAA UAS data exchange such as UAS facility maps, special use airspace data, airports, and airspace classes, temporary flight restrictions and notices to airmen [45].

(5) The Civil Aviation Administration of China (CAAC)

The CAAC published data specifications of UAS cloud system [46] that stipulates reporting requirements for UAVs flights. Namely, a period of real-time reporting to USS via mobile networks such as flight order ID, manufacture ID, UAS ID, timestamp, flight time, coordinates, speed, and path angle. The reporting frequency is set at once per second in dense areas, and once every 30 seconds in sparse areas. The high reporting frequency here mandates continuous maintenance for the data links used for reporting.

(6) Internet Engineering Task Force (IETF)

The IETF open standards organization proposes a drone remote ID protocol (DRIP) that supports UAS RID and tracking, along with related communications such as architectural building blocks and their interfaces. Two types of UAS RID are defined. First, broadcast for direct one-way transmissions from the UAV over Bluetooth or Wi-Fi, where connectivity is only needed for UAS registry information lookup by observers. The second type is network RID for data flow from UAS via unspecified means to a network RID service provider. The latter responds to queries from network RID observers specifying airspace volumes of interest. The standard also overviews USS interoperability as each UAS is registered to at least one USS. With network RID, there is direct communication between the UAS and its USS. Meanwhile, with broadcast-RID, the UAS operator has either pre-filed a 4D space volume for USS operational knowledge, and/or observers can be providing information about observed UA to a USS [47].

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2021.3138048, IEEE Access

IV. OPERATING BANDS

Drones communicate over a specific radio frequency (RF). The frequency band depends on drone applications since a different range of RF could provide better performance in comparison with others. A drone-based remote-controlled application uses the frequency band at 900 MHz for communication, where the video is not required to be transmitted back to the ground [6]. This range of frequency bands was originally assigned for industrial, scientific, and medical (ISM) devices. According to the FCC, 27MHz and 49 MHz were reserved for walkie-talkies, garage door openers, and remote-control toys which increase the risk of interference with early toy drones. The frequency band at 900 is known to penetrate obstacles and provide drones with the ability to transfer higher data rates. With the requirement for video streaming applications, drones manufacturer began to utilize higher frequency bands such as 2.4 GHz and 5.8 GHz in favor of the 900 MHz since the latest lack the opportunity to transmit video to ground stations [48], [49]. It is well known that the higher frequency used for communication, the higher the data rate but less communication range and less ability for the signal to penetrate obstacles. In addition, the 2.4 GHz and the 5.8 GHz frequencies are used by modern wireless communication systems such as Wi-Fi home networks. Therefore, drones pilot may experience interference when operating in residential areas. In general, they primarily operate at a range between 900 MH and 5.8 GHz [50].

Drones used for military applications utilize satellites for communication which allow drones to operate almost everywhere around the globe with no interference with public radio frequencies and less jamming. Still, there is a need for continuous studies regarding the operating band for drones. Up to date, adoptions of V2X to support drones are planned to appear in 3GPP R17 (Q2 2021) without further information on the frequency band to be used for broadcast.

A. LICENSED BANDS

The drones' market is growing tremendously, according to [51], in Europe alone there will be $400,000$ commercial and government UAVs by 2050. This continuous increase in air traffic will add more challenges to both air traffic management and aviation regulations if not resolved in near future. Therefore, the existing mobile spectrum is capable to support UAV operation where an embedded authenticated sim card can be used to safely control drone flight [52]. Qualcomm in a trail shows that at an altitude of 400 feet, the terrestrial mobile networks can be used to support UAVs connectivity [53]. Current mature mobile networks services around the world could take advantage of this initiative could open the door to regulators to permit licensed mobile spectrum to be used for UAV operation. MultiGP a global drone racing league for managing and controlling drone racing operates within the frequency range 5650 MHz to 5925 MHz within the USA. Any frequencies out of this range are illegal and a stiff penalty could be applied, see Figure 7 [54].

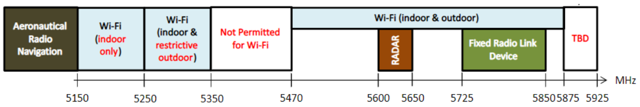

FIGURE 7: Aeronautical utilization of the RF spectrum.

B. UNLICENSED BANDS

The 3GPP developed a set of standards called 5G New Radio (5G NR). 3GPP in their release 13 specifications has announced the deployment of a new radio access technology named 5G new Radio unlicensed (NR-U). NR-U supports carrier aggregation, dual connectivity, and standalone mods to extend 5G NR to unlicensed bands [55]. Dual connectivity mode support user plane traffic of both upstream and downstream for the unlicensed band. There are low and high-frequency ranges planned for the operation of NR-U below 7GHz and at 60 GHz, respectively [56]. There is 2 GHz bellow 7GHz available for Omni-directional as unlicensed/shared spectrum over the ISM at 2.4 GHz, the Citizens Broadband Radio Service (CBRS) at 3.5 GHz, and the Unlicensed National Information Infrastructure (UNII) at 5 GHz and 6 GHz. In addition, there is also 14 GHz at the 60 GHz as unlicensed spectrum available for the directional communications [57]. Recently, the bands from 5.925 GHz to 7.125 GHz are proposed by the FCC to be used for unlicensed access according to their part 15 rules [2] [56], see Figure 8 [55]:

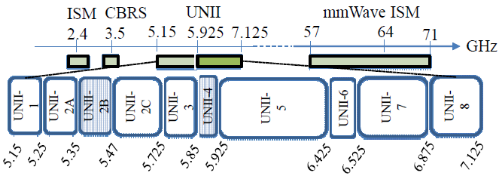

FIGURE 8: NR-U operation: Unlicensed/shared spectrum bands.

C. DUAL BANDS

In wireless communication, a Dual-band means the ability of a phone to support two different bands which are specified in advance. For example, in a global system for mobile communications (GSM) a phone supporting Europe dual-band will not work in the US. According to 3GPP in [58], intra-band contiguous is a convenient way for carrier aggregation which is using contiguous component carriers of the same operating bands as the case for LTE. Due to service provider allocation scenarios, this will not be always the case. In an inter-band allocation, different operating frequency bands are used for component carriers. The non-contiguous allocation same operating frequency band that can be used but with gaps in between. see Figure 9, [58]:

Dual band-based UAV to minimize total service where multiple pairs of transceivers are required to support UAVs communication using mmWave and microwave bands are presented in [59]. The authors in [60], design an antenna to support dual-band for UAV applications. A dual-band

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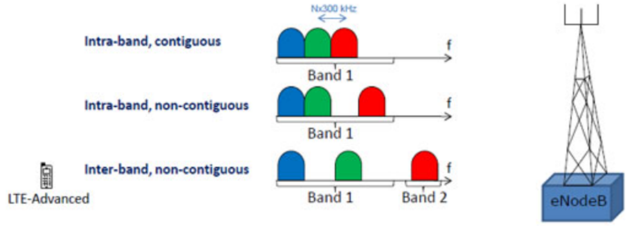


FIGURE 9: Carrier Aggregation; Intra and inter band aggregation.

sensor to achieve high-throughput to support cop-growth information for UAVs applications is studied in [61].

V. USE CASES AND APPLICATIONS

UAVs are becoming a topic of interest in the last few years due to their remarkable advancements and applicability in military [62], [63] and civilian [3], [64]–[66] applications. For more than 30 years, it has been widely employed in military applications, particularly in border and reconnaissance surveillance, strike, Maritime operations and electronic warfare. Recently, there has been a surge in interest in the use of UAVs in a variety of civilian applications, and their use is expected to rise quickly in the near future. UAVs usage can cover a wide range of civilian applications, such as public safety, search and rescue (SAR) missions [67], surveillance, IoT networks, wireless communications [68], [69], crowded events [70], [71], rail and transportation management [72], remote sensing [73], [74], scientific data collection [75], and industrial inspections, cargo delivery, agricultural [76]–[80]. Therefore, UAV applications can cover a wide range of military and civilian applications. UAVs can be equipped with different antennas, cameras, and sensors for doing various missions in challenging environments.

UAV's applications can be categorized based on the UAV mission type as a civilian or military application. This section presents the primary UAV civilian and military applications, communication, and spectrum challenges facing UAVs for each application. Moreover, future trends will be discussed. Figure 10 presents the main UAV applications for each category.

As mentioned earlier, a growing interest has existed in the use of UAVs in many applications. Hence, many studies have been conducted to integrate UAVs with these applications and improve the UAV deployment, communication, and spectrum sharing technologies for multi-UAV networks.

The National Telecommunications and Information Administration (NTIA) and the FCC regulate the rules of use and share the radio spectrum in the range of 300Hz - 300GHz in the United States. These spectrum ranges can be utilized and managed for both military and civilian applications. NTIA and FCC are responsible for coordinating the spectrum allocation and introducing technical specifications to avoid interference between different applications. Radio spectrum allocation is used to designates specific frequency ranges for particular applications or users, like public safety, wireless, terrestrial, and satellite communication. Moreover, radio frequency assignment happens when the radio spectrum was allocated for specific applications or users. The FCC allocates specific frequency ranges and grants licenses to civilian applications or users to use particular segments or specific frequency ranges. While, the NTIA gives specific frequency ranges to federal/government agencies and organizations, allowing them to operate in these radio spectra ranges [81].

Modern military applications such as UAVs, planes, underwater vehicles, satellites use the radio spectrum and spectrum management for communication and army missions control during military operations. In the united state, the DOD communication system uses the radio spectrum in the range of 3KHz to 300 GHz. They allocated various ranges from these radio spectrum for many applications starting from 3KHz-30KHz for maritime navigation signals, to 1.7 GHz to 1.85 GHz for tactical radio relay, precision-guided munitions, point-to-point microwave communication, software-defined radio, and 30GHz -300 GHz for radio astronomy and satellite communication. [81].

On the other hand, the third generation partnership project 3rd generation partnership project - long-term evolution (3GPP-LTE) broadband was adopting their standard to support voice and broadband video during public safety and search and rescue applications. The existing LTE-based architecture in 3GPP-LTE is upgraded to enable broadband public safety communication. The international telecommunication union (ITU) proposed to assign a broadband spectrum for public safety applications. They divided the world into three zones to efficiently manage the broadband spectrum among these regions [82].

VI. UAVS COMMUNICATION ARCHITECTURES

Multi-UAV communication framework architecture plays a crucial role in the intelligent control and autonomous coordination of multi-UAV systems [83]. Specifically, coordination and cooperation approaches play an essential function in the multi-UAVs network. Coordination is concerned with resource sharing, temporal and spatial coordination. While, UAV synchronization is considered in temporal coordination, and it is required in many ranges of UAV applications. Furthermore, spatial coordination of UAVs is concerned with the space sharing between all UAVs nodes in order to ensure that each UAV can perform safely and coherently with other UAVs missions as well as potential mobile and static obstacles. On the other hand, cooperation, defined by the designer's task sets as a multi-UAVs network represents cooperative behavior. The cooperation of independent UAVs requires integrating sensing, control, and resource planning in an adequate architecture [84].

Multi-UAVs network can be classified based on the control centralization structure as a centralized or decentralized system [83]–[85]. In the centralized multi-UAVs architecture, a single control unit communicates with and manages every UAV in the UAVs-network. Therefore, a centralized architecture requires significant cognitive resources for all nodes in the networks. On the other hand, decentralized

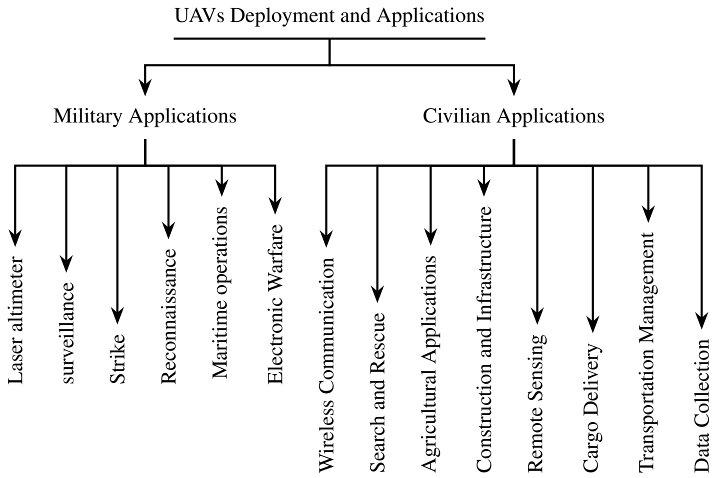


FIGURE 10: Classification of UAVs deployment and applications.

multi-UAVs architecture is a highly complex architecture, where the network lacks a centralized control station. This system can overcome the centralized architecture drawbacks such as large-scale information distribution among all UAVs and the high dynamic, mobility, and real-time challenges for centralized multi-UAV networks. In this architecture, the control station communicates with all node members through an Ad-hoc manner to manage a set of tasks for a group of autonomous UAVs [85], [86].

A. CENTRALIZED ARCHITECTURE

The centralized architecture in UAVs-network is extended from the conventional single-UAV architecture, where a ground control station is used to control and coordinate all UAVs in the swarm.

A centralized communication structure has been designed for a multi-UAV network. In this architecture, a single central ground control station is used to control and manage all UAVs in the network. Moreover, a direct connection is established between every UAV and the central ground control station to exchange control, commands, and data [83]. Figure 11 presents the centralized communication structure for a multi-UAV network.

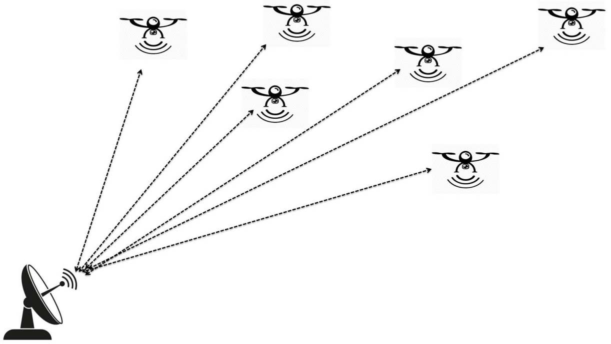


FIGURE 11: Centralized communication structure for multi-UAV network.

This architecture can be employed in many applications such as wireless coverage in crowded events [70], search and rescue operations [66], along with crowd monitoring and surveillance applications [87].

Although this architecture is simple, stable, and can use Ad-hoc and FANET routing algorithms, it is not scalable, unsuitable for a large coverage area, and can only be used for simple and small missions. Moreover, if the ground control station is disrupted or attacked, the overall network is then defective (faulty), a condition termed as the single point of failure (SPOF) [83]. To overcome the aforementioned challenges, researchers proposed a decentralized communication structure [83], [86], as presented next for multi-UAV networks.

B. DECENTRALIZED ARCHITECTURE

In decentralized systems, a single control station is required for multi-UAV networks. The control station needs to communicate with an automated mission to deliver required tasks for UAV-network node members autonomously [85]. Figure 12 presents the de-centralized communication structure for multi-UAV network. Although decentralized architecture in UAVs-network has a complex network structure, it reduces

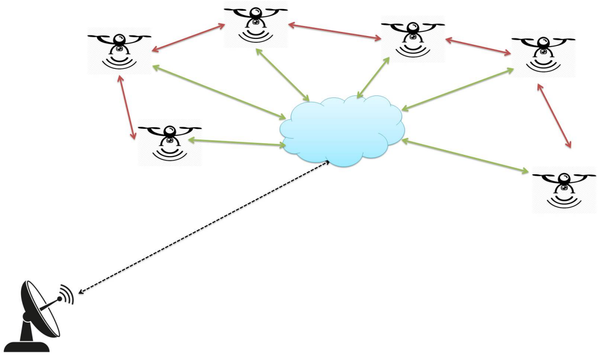


FIGURE 12: De-centralized communication structure for multi-UAV network.

the UAVs' dependence on the ground control station [83], [86].

Decentralized architectures are also referred to as intelligent swarm systems, where each UAV determines its flight control parameters independently. This allows companies (e.g., e-commerce) to utilize decentralized architectures in delivery applications [88].

VII. RADIO INTERFACES

The UAV-based network is characterized as a dynamic network with high mobility nodes and dynamic topology; these nodes change their locations randomly due to their continuous movement in 2D and 3D dimensions [11]. Therefore, the use of suitable communication technologies is an important issue for this network. Different technologies can be employed in the UAV-Base communication network for data and CNPC control links, such as Wi-Fi, cellular technology with LTE and 4G standards. Wi-Fi technology is considered one of the most widespread communication technologies, Which is based on the IEEE 802.11(a, b and b/g) standards and uses the unlicensed frequency band in the range of 2.4 and 5 GHz [89], [90]. The Wi-Fi technologies' main challenges are the short communication range and the line-of-sight (LoS) link connection requirement. On the other hand, cellular-connected UAVs with LTE and 4G can be used to overcome the Wi-Fi technology challenges, where the communication range is extended beyond LoS connections.

In the UAV-based network, UAV communication interfaces include these five-channel interfaces:

1) UAV - Ground base station.
2) UAV - UAV.
3) UAV - Ground receivers.
4) UAV - WiFi.
5) UAV - Satellite system.

Moreover, in this network and for each channel interface, there are two main communication links;

1) The data link connection.
2) The control link: Control and non-payload communications (CNPC).

Datalink is used to send and receive data in downlink and uplink transmission modes. The data can be sent over microwave or mmWave spectrum bands. ITU defines the frequency ranges of the microwave spectrum between 1 GHz to 6 GHz [91]. On the other hand, the mmWave provides high-speed wireless communications and high data rates; moreover, it can have frequencies ranging up to 300 GHz.

The Control/CNPC link provides a reliable connection for UAVs' safety operations, the control information is exchanged at a low data rate between UAVs and the ground control station and among UAVs, [10]. More specifically, the main characteristics of the CNPC in UAV-Base network: 1) Full-duplex communication, 2) High-reliability connections, 3) Low latency response, 4) Low data rates, and 5) Secure connections [92].

The loss of CNPC connection for UAVs may cause catastrophic results; therefore, the international civil aviation organization (ICAO) introduces that CNPC UAV's link should be working over a protected spectrum band. Accordingly, the ITU authorized certain parts of the L and C bands for UAV's CNPC connection; for L-band the frequencies span from 960 to 977 MHz, while the frequencies span from 5030 to 5091 MHz for C-band [7], [93], [94]. Moreover, CNPC must operate for LoS and NLoS connections, and this requires a spectrum of 34 MHz for LoS and 56 MHz for NLOS connections [95].

On the other hand, data links for UAV-based networks requires high data rates as compared to the control links requirements. For example, UAVs must provide high-resolution videos and images to the ground station in search and rescue missions. The data rate spans from a few Mbps to greater than 30 Mbps. Moreover, when UAV assisted as an aerial base station, the data rate may exceed tens of Gbps in downlink and back-haul links [93]. Figure 13 presents the basic networking architecture of wireless communications with UAVs.

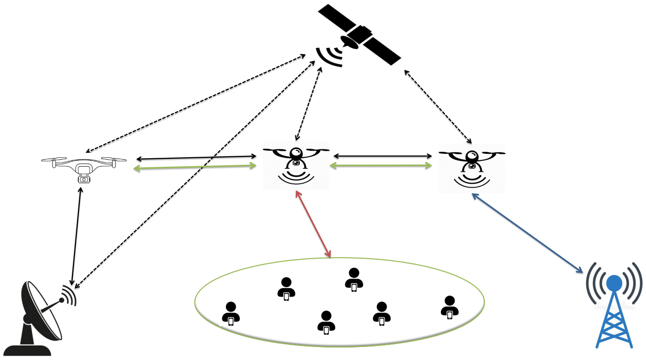


FIGURE 13: Basic networking architecture of wireless communications with UAVs.

A. UAV - UAV LINKS

The LoS channel component mainly dominates the UAV-UAV connection. The LoS UAV-UAV links can be efficiently utilized for the mmWave and 5G communications to obtain high-capacity backhaul links for UAV-UAV communication. Moreover, the UAV in a UAV-based network usually has continuous moving and mobility conditions [10]; therefore, UAVs can communicate with other UAVs directly or indirectly by constructing multi-hop communication paths with other UAVs [83].

Air-to-air (ATA) communication is a common channel model used in most UAVs networks to establish a backhaul link between UAVs, where multiple UAVs communicate with each other. Therefore, UAV-UAV links use ATA communication channels; Here, ATA is similar to free-space communication with the LoS component [8].

On the other hand, UAV as a relay node is one of the typical applications in UAV-UAV communication [7]. UAVs can communicate with each other using microwave and mmWave bands using frequencies spans from hundreds of MHz - a few GHz for 4G (700 MHz - 6 GHz) and LTE technologies to tens of GHz 5G (above 20 GHz) for 5G network.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2021.3138048, IEEE Access

B. UAV - GROUND BASE STATION

In Air to Ground ATG communication, proper technologies must be considered to enable seamless and reliable connections for both data and control links in various UAV applications. In [93], the authors present four different communication technologies, namely; 1) Direct link connections, 2) Cellular network, 3) Ad-hoc network, and 4) Satellite communication.

The direct link communication between the UAV and the ground station requires LoS connection, and usually, this communication operates over an unlicensed band such as the 2.4 GHz band. The main challenge that faces the operation for this connection in the urban and dense-urban regions is the blockage effects due to the building, trees, and other obstacles, which significantly hinder the reliability and data rate of the communication. Moreover, this link couldn't be used on a large-scale UAVs deployment in wide areas and for links with NLoS communications. Therefore, cellular network communication can be utilized to tackle these challenges. Cellular-enabled UAVs network is a promising solution especially employing the forthcoming 5G technology, where the expected data rate of this network is about 10 Gbits/sec with round-trip latency of less than 1 ms. This data rate can satisfy the requirements of the real-time UAVs application, such as high resolution and real-time videos [93]. 5G and mmWave provide new radio solutions and allow for intelligent spectrum management opportunities. Specifically, in a UAV-based network, 5G spectrum can help in time/frequency resource reservation over the cellular band. Therefore, the cellular network can provide the control and data link for UAVs. It can also provide everywhere control coverage for UAVs. [96].

UAV-based communication system utilizes two different streams. One for control the UAV that operates at a low rate but with high reliability and robust connections. The other for data streaming operates at a high rate. The response time of UAV's remote control is one of the essential requirements in UAV-based networks. Response time requires small frames and frequent direction changes across the half-duplex channel. The authors in [97], proposed a framework that used the chirp spread spectrum modulation [98] with a correlator-based de-modulator for the control link and a high data rate OFDM modulation for the data. The OFDM utilizes the same bandwidth as the spread spectrum modulation and uses its full bandwidth. More specifically, the system contains one uplink connection from the ground station to the UAV and two downlink connections one for control and the second for data. Datalink connection with high rate requirement uses OFDM, whilst the control uses spread-spectrum chirp modulation. The turn-around time of the frame is 10 ms as shown in Figure 14, and it consists of the following parts 1) 0.6 ms for the uplink control link. 2) 1 ms for propagation delay and for antenna to change their direction. 3) 3.7 ms for control chip downlink connection. 4) 3.7 ms for downlink data connection with OFDM. 5) 1 ms for antenna to change direction.

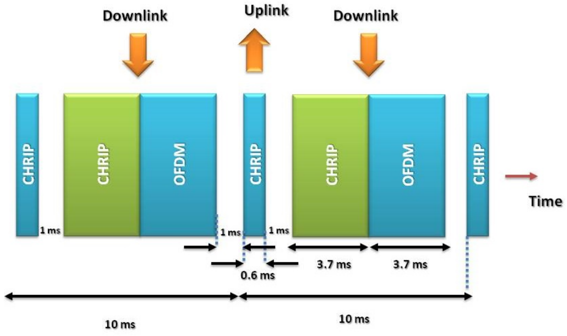


FIGURE 14: System timing frame [97].

C. UAV - GROUND NODES

UAV can be efficiently used in providing wireless coverage for ground users, especially during disaster situations or crowded events. Air to ground channel models can establish a connection between the aerial base station and ground users. Recently, several studies have been conducted using UAVs to develop an air to ground channel models. These models can be classified based on the communication technology and operating frequencies as 4G/LTE, 5G, and Wi-Fi. 4G/LTE operates over microwave frequency bands, 5G operates over mmWave bands, while Wi-Fi uses IEEE 802.11 standards [99].

In any communication system, the frequency band is considered one of the system's main parts. It is mainly responsible for determining the channel's propagation characteristics. It can be affected and significantly changed, depending on the frequency bands [8].

The authors in [100] proposed a statistical propagation air to ground model in low altitude platform (LAP) for different environment types; rural, urban, suburban, dense urban environments. The model operates in 4G over three various frequency bands 700, 2000, and 5800 MHz. Many researchers utilized this model to provide wireless coverage for ground users in different scenarios. Specifically, they use this model to provide wireless coverage using UAVs for disastrous situations, search and rescue missions, crowded events, and assist the ground station in providing wireless coverage for uses [68], [69], [71], [101]. FDMA is one of the popular channel access approaches used between the UAV and the ground users. Where the UAV divide the total channel bandwidth among users and all users receive equal bandwidth.

In [102], Q.Feng et. al. proposed another statistical propagation channel model. They developed an Air to ground channel model for urban areas where UAV acts as an aerial base station to provide wireless coverage for ground nodes. This model operates over frequencies band 200, 1000, 2000, 2500 and 5000 MHz.

The mmWave bands can provide very high bandwidths and very high data rate communication links; therefore, it is considered as one of the essential communication requirements for the 5G network. The UAV applications and civilian use cases can take advantage of the mmwave/5G communication network to support the high data rate requirements for real-time applications and HD video transmission. But for control and CNPC links, mmwave is an inappropriate option for this link due to the high attenuation, works over short distances, and requires strong LoS connections.

In mmWave frequency bands, many spectrum resources are available to satisfy the high rate demands and to be used in 5G communications [103]. Air to ground channel propagation models and channel characteristics for mmWave communication was studied by many researchers [8], [103]–[105].

The authors in [103], studied and analyzed the air to ground mmWave channel propagation characteristics for two different frequency bands 28 GHz licensed band and 60 GHz unlicensed band. They used ray-tracing software to conduct the analysis for rural, urban, sub-urban, and over-seas environments and to study the received signal strength (RSS) and root mean square delay spread (RMS-DS) of multipath components (MPCs) for the proposed communication system.

The Wi-Fi network equipped with directional or omnidirectional antennas and mounted over a UAV is a promising solution to provide air to ground coverage and real-time connections for users when the terrestrial network completely goes out of service during disastrous scenarios [90]. The commercial off–the–shelf 802.11 radios equipment can be integrated with UAV for developing an air-to-ground channel model and studying the propagation channel characteristics of this model [6].

The authors in [106] analyzed the characteristics of the IEEE 802.11a wireless link between UAV equipped with an antenna and off-the-shelf wireless radio, and the ground terminal. Then, they measured the path loss exponent for air to ground propagation channel. The IEEE 802.11a uses an interface that operates over a 5.24 GHz frequency band, and the used UAV height ranged from 20 m to 120 m.

D. UAV AND SATELLITE

The command and control CNPC link is very important for UAV safety, reliable communication, and exchange control information between the ground control station and the UAV either in presence of LoS or NLoS connections. Ground control station is used for LoS, while satellite communication links can be used for NLoS conditions. The two-channel components LoS and NLoS links mean different channel conditions and operating frequencies, with varying latency ranges; therefore, the control CNPC link faces a big challenge to satisfy the highly reliable and secure connections [107]. In remote and out-of-coverage regions, satellite communication is a promising solution to provide control and payload communication for NLOS links. Low earth orbiting (LEO) is the best choice to use for UAV CNPC links, LEO operates over narrow bands and has a low latency time compared to geosynchronous earth orbiting (GEO), Therefore, LEO can support the autonomous UAV functions for large coverage areas of hundreds of km through a one-hop connection between the ground station and UAV [107], [108].

In [107], The authors present the future frequency bands for satellite communications that can be allocated for NLOS CNPC links over L (850-2000 MHz), C (5-6 GHz), Ku (12 -18 GHz), and Ka (above 26 GHz) bands. Moreover, due to the continuous movement of UAV, antennas change their orientation, and this could cause attenuation of a CNPC signal. Therefore, the current physical layer configuration must be improved to fulfill the CNPC requirements. Specifically, the OFDM used in LTE is not a suitable choice in this link. Many other modulation schemes can be considered alternative solutions such as filter bank multicarrier (FBMC) and orthogonal chirp spread spectrum (OCSS) since these modulations are more compact and could be efficiently used for air-to-ground satellite communication NLOS links.

The limited studies and experiments conducted over the radio interfaces and the physical layer are considered one of the main challenges facing UAV-based networks' communication systems. Henceforth, a future research direction here is needed on radio interfaces, modulation schemes, and physical layers for UAV-based communication systems.

VIII. CHANNEL CHARACTERISTICS

A. DELAY DISPERSION

Delay dispersion plays an essential role in channel characteristics for any wireless communications system, including UAV networks. Dispersion here is mainly represented by the excess delay, the mean excess delay and root mean squared (RMS) delay spread measurements from the power delay profile (PDF). These variables are essential for channel characterization and spectrum allocation. Along this, various measurements have been conducted to gauge the delay dispersion parameters, in particular for air-to-ground (A2G) networks. One observation in [109] is that the RMS delay spread generally decreases with the increase in the elevation angle attributed to the probability of higher scattered NLoS components for small elevation angles. The results in [110] show that the RMS delay spread depends on the UAV altitude or elevation angle with respect to the ground station. Results in [111] and [112] shows that a delay spread resolution in the micro-seconds (µs) range for suburban environments. The work in [6] illustrates dispersion levels at different environments, where likewise µs levels were observed. First, the median RMS delay spread was approximately 0.06 µs for mountainous desert scenario in [113]. Meanwhile for residential area, the measured median RMS delay spread was approximately 0.03 µs. Overall, the attained RMS levels in desert terrain was larger attributed to the rough mountainous scatters along the flight path as compared to the residential area. Along this, the RMS delay spread in [113] was modeled as lognormal distribution. The mean excess delay, RMS delay spread, and coherence bandwidth for open and sub-urban areas are measured in [114] using channel sounding at various scenarios. Namely, a terrestrial receiver is placed

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2021.3138048, IEEE Access

at a height of 1.5 m from the ground, while considering the effect of foliage in Scenario 1 and eliminating its effect in Scenario 2. For the two areas, recorded results show that the mean excess delay and RMS delay spread are the highest for scenario 1, and lowest for scenario 2, where the delay levels are in the ns range. Further, the coherence bandwidth is found to be at least 100 MHz. Furthermore, the channel gain and delay dispersion in [115] are studied at three different UAV heights for an open area, a tree-lined environment, and an enclosed area. Here Rician distribution is modeled for the received signal strength, whereas the mean excess delay and RMS delay spread for the open and tree-lined environments follow a Weibull distribution, whereas the enclosed area tests follow lognormally distribution.

B. DOPPLER DISPERSION

Doppler frequency shift (DFS) can degrade the link performance of UAV-aided networks in high mobility scenarios. Along this, authors in [116] propose a data-aided approach for mmWave spectrum to optimize the DFS estimation process using historical results, in efforts to achieve a fast and accurate DFS compensation. A cost function is developed to evaluate the performance of the DFS estimation algorithm based on frame structure and Cramer–Rao lower bound in terms of the mean-squared error (MSE) and SNR. Furthermore, an adaptive frequency domain DFS compensation algorithm is designed by leveraging DFS estimation results to enhance the quality of communication link for UAV-aided 5G system, achieving an optimal tradeoff between accuracy and complexity.

In efforts to enhance the operation of UAVs in public airspace, a reliable CNPC link connecting the ground control station to the UAV is needed. Here CNPC design need to cope with time- and frequency-selectivity (double selectivity) of the wireless channel, i.e., attributed to the low altitude operation and flight dynamics of the UAV. Along this, the work in [117] focuses on the operation of transmission of continuous phase modulated (CPM) signals for UAV CNPC links that operate over doubly selective channels. The work leverages Laurent representation for CPM signals to design receiver structures that equalize doubly selective channels in UAV networks based on frequency shift versions of two proposed equalizers. The first is a linear time-varying (LTV) equalizer that is synthesized under either the zero-forcing (ZF) or minimum mean-square error (MMSE) criterion. The second recovers the transmitted symbols from the pseudo-symbols of the Laurent representation in a recursive manner.

In a delay-Doppler spectrum sharing operation, an assistive slots (AS) technique is deployed in [118] to recover the desired signal at the receivers in UAV and terrestrial networks, i.e.., free from delay and Doppler shifts effects. The insertion of AS in the frames yields in various possibilities of signals that are sampled at AS and non-AS points. This is followed by differentiating the UAV/terrestrial signal samples from the compound signals, i.e., by focusing on the energy gap among the samples. The work takes into account multipath and mobility parameters and shows that despite AS allows signal recovery, signal transmission efficiency degrades. Hence, the work investigates the optimal AS ratio that achieves a tradeoff between delay-Doppler parameter extraction accuracy and transmission efficiency. Here the SINR of the spectrum sharing system plays a key role under Rician/Rayleigh distributed terrestrial fading channels, i.e., for an optimal AS ratio.

IX. RESOURCES ALLOCATION AND ACCESS TECHNOLOGY

Wideband communications using orthogonal frequency division multiplexing (OFDM) can be a good technique for transmitting payload data from a drone to a ground station in an unmanned aerial system (UAS). However, the Doppler spread causes inter-channel interference in OFDM systems. Furthermore, due to the high speed of drones, the Doppler spread can be large. It is critical to provide an acceptable air-to-ground channel model that correctly models the Doppler and multipath properties of the wideband channel from the drone to the ground station in order to build a proper OFDM system for a UAS. The authors in [119] propose six different channel models based on different scenarios of the drone's altitude (very low, low, and high) and the type of environment they fly over (low-density suburban areas and high-density urban areas). The parameters of narrowband aeronautical channel models are combined with downlink channel models of wideband terrestrial networks, such as HiperLAN, LTE, and IEEE 802.16 systems, to construct these models. The efficiency of an OFDM for drone-to-ground communications was evaluated using these channel models. According to simulation results, the number of sub-channels in an OFDM for high-speed UAVs should be kept to a minimum in order to ensure reliable communications. If OFDM is to be used for UAS communications, effective ICI cancelation schemes with low complexity should be investigated.

The combination of non-orthogonal frequency division multiple access (NOMA) and drone is a very new field with a lot number of unexplored research directions [120]. The efficient spectrum utilization of NOMA and flexible mobility of drones enable NOMA drones to become a prospective approach for future wireless networks [121]. Drone and NOMA have also been considered in 3GPP standards for 5G networks due to their importance. As a result, drones and NOMA can be combined to achieve the benefits of high mobility and performance, which will be important in future 6G cellular networks [122]. However, some open research issues in the context of implementing NOMA-enabled drone networks remain [123]: (1) A Unified Spatial Model for NOMA-Aided drone Networks: The single-drone case, multiple-drone case, uplink, downlink, cooperative communications scenarios, and so on are all possible communication scenarios for NOMA-aided drone networks. It is desirable to provide a unified spatial analytical framework for NOMA-assisted drone networks that can be easily switched to suit various realistic application scenarios. (2) Data-Driven

NOMA-Aided drone Networks Design: The majority of current research in the area of NOMA-assisted drone networks is focused on data produced at random, which may vary from real scenarios. Data from social networks can be utilized for collecting the locations of users. As a further advance, data mining and stochastic modeling can be used to analyze historical data and provide more precise predictions in terms of NOMA users' mobility. By doing so, the drones are able to adjust their placements more accurately to further enhance the system performance. (3) MIMO-NOMA Design in drone Networks: NOMA is expected to coexist with multiple-input multiple-output (MIMO) techniques in order to improve spectral efficiency and supporting the massive connectivity of drone networks. However, using multiple antenna techniques in NOMA necessitates meticulous channel ordering planning. Furthermore, beamforming-based or cluster-based MIMO-NOMA design becomes more challenging due to the 3D characteristics of drone networks. As a result, further research is needed to determine how to order channels in MIMO-NOMA systems while taking into account the characteristics of drone networks. (4) Low-Latency Design for NOMA-Aided drone Networks: If the number of NOMA users is large, the SIC decoding characteristics of NOMA will inevitably cause significant delays at receivers. Hybrid multiple access, which divides a large number of NOMA users into various orthogonal groups, is one possible solution. A limited number of users in each group use NOMA to reduce the delay caused by SIC.

Carrier Aggregation is a technology that improves network performance by increasing data capacity, throughput, and rates in the uplink, downlink, or both [124]. Combining two or more carriers in the same or separate frequency bands into a single aggregated channel, it enables efficient spectrum usage [125]. It allows for the aggregation of FDD and TDD carrier spectrums, as well as licensed and unlicensed carrier spectrums. It is important in giving operators the flexibility they needed to make the greatest use of the available spectrum. There are 44 frequency bands available with a theoretical range of 700 MHz to 2.7 GHz that can be aggregated, however commercial solutions can use up to three component carriers with a downlink speed of up to 450Mbps. Carrier aggregation technology is important for allowing 4G and 5G to coexist because it allows operators to combine different 4G carriers with other 4G or 5G carriers. According to the LTE-A standard, each component carrier is limited to 20 MHz of bandwidth, and aggregation of up to five allows for a total signal bandwidth of 100 MHz, resulting in a fivefold increase in channel capacity and data speed [126]. The authors in [92] present a capacity-deployment method for designing the backhaul network for drone-assisted networks and evaluating the backhaul network's performance in a realistic situation in Ghent, Belgium. This tool allocates resources to both ground users and the backhaul network, taking into account backhaul capacity and power constraints. They look at three distinct types of drones and analyze three distinct backhaul situations using a 3.5 GHz link, 3.5 GHz with carrier aggregation, and the 60 GHz spectrum. The capacity results clarified that a practical solution could be reached by using simultaneous access and backhaul resource allocation, servicing up to 17.3%, 72.4%, and 68.1% of users for a 3.5 GHz link, 3.5 GHz with carrier aggregation, and 60 GHz network configuration, respectively.

The impact of drone antenna configuration on their connectivity to ground stations is one of the main problems that has not been properly studied in the current state of the art [127]. Given the vast range of drone applications and the increasing number of drones on the market, various antenna configurations of different complexity and efficiency levels are anticipated in the network. Along this, the network performance will be drastically affected by antenna design, which will govern how network operators handle the problem of providing wireless connectivity to drones. In [127], the authors study the performance of a dedicated ground station network for omnidirectional, fixed directional, and steerable directional drone antennas. One of their contributions is a stochastic geometry model that is general enough to represent the impact of these antenna types on performance. They can demonstrate the exact impact that drone antenna directionality combined with intelligent beam alignment can have on network performance by comparing network behavior for different drone antenna types. They also compare the numerical results of their model to simulations of drone service from terrestrial base station networks, as envisioned in state-of-the-art. This comparison allows the benefits of dedicated ground station networks for drone service to be quantified against the existing terrestrial base station networks. The numerical results also show how the drone antenna configuration and height above ground will be a crucial factor in determining whether an operator needs to use dedicated drone infrastructure or can rely on the current terrestrial base station network.

Drones must communicate with peer UAVs in every direction of three-dimensional space in the next wave of swarm-based applications. Various antenna placements and orientations are feasible on a single UAV and across several UAVs. If the transmitting and receiving antennas are cross polarized, large levels of signal loss are expected in free space. Increasing the reflective and scattering objects in the channel between a transmitter and receiver, on the other hand, might lead the received polarization to become fully independent of the transmitted polarization, making antenna cross-polarization insignificant. Normally, these effects are examined in the context of cellular and terrestrial networks, but they have not been investigated when the objects are the actual bodies of communicating UAVs that can travel in various directions or at different elevations. The authors show in [128] that the UAV's body can change received power over a range of antenna orientations and positions, acting as a local scatterer that increases channel depolarization and reduces cross-polarization discrimination. They explore these impacts and conduct testing ranging from a controlled environment of an anechoic chamber with and without UAV bodies to in-field environments with UAV-mounted antennas in various orientations and relative positions, with the following results: 1) The direction of the UAV can have a big impact on the cross-polarization discrimination results. 2) When it comes to 3D link performance, elevation angle is a critical factor. 3) For co-located cross-polarized antennas, the antenna spacing requirements change. 4) Cross-polarized antenna setups more than double spectral efficiency. These results can be used to model and simulate drone networks and swarms more precisely.

Frequency Hopping Spread Spectrum (FHSS) and Time Hopping Spread Spectrum (THSS) are often used in wireless drone communications [129]. The data signal is modulated onto a carrier signal in FHSS communication systems, and the carrier signal's frequency is rapidly switched between multiple channels. A pseudo-random sequence generator sends a sequence to a frequency table, which chooses the carrier wave's frequency. This frequency is then carried to a frequency synthesizer, which generates the carrier wave at the specified frequency, allowing the carrier wave to be switched more easily. This pseudo-random sequence generator is known to both the transmitter and the receiver. As a result, interference in a single frequency segment impacts the total transmission for a very brief time as the carrier wave frequency switches. The input signal is not transmitted continuously in THSS. Instead, it's divided up and sent in pulses, with 2^k distinct pulses serving as carrier signals to send k bits per pulse. The signal is sent in one of the n segments of a transmission window with a duration of x seconds. Interference resistance is achieved by adjusting the carrier pulse period and duty cycle pseudo-randomly to alter the transmission time. Time hopping does not introduce any spread spectrum features. Hence, it is generally utilized in the hybrid spread spectrum with FHSS.

The authors in [130] study the duplexing modes that are used in drone wireless networks. In reciprocity-based MIMO systems, TDD is often more efficient [131], [132]. The number of samples needed for channel state information (CSI) acquisition is the limiting factor in FDD mode. TDD requires that the number of uplink pilot symbols per coherence interval be at least equal to the number of UAVs. In FDD, however, it must be at least equal to the total number of ground station antennas plus the number of UAVs. However, because UAV communication scenarios have fewer multipath components, beam tracking may be possible, reducing the need for CSI acquisition. Different duplexing modes must be thoroughly examined in various environments and applications. Because of the scarcity of spectrum, inband Full-Duplex communication has gained popularity because it boosts throughput and capacity when compared to Half-Duplex communication by sending and receiving data in the same frequency band and at the same time [133]–[136]. The most difficult challenge in achieving the benefits of Full-Duplex communication is canceling self-interference [137]. Recent studies in self-interference Cancellation techniques show that self-interference is reduced by more than 110dB [138]–[140], therefore for the next generations of UAV wireless networks, full-duplex communication should be considered. Authors in [141]–[143] use Half-Duplex transmission in drones, while authors in [144] study the problem of 3D UAV base station location with Full-Duplex communication in heterogeneous networks. To boost network throughput, the authors utilized Full-Duplex UAVs in coexistence with the ground base station. The authors considered that UAV base stations had different frequency spectra, therefore there is no interference between UAVs.

X. ACCESS CONTROL AND SCHEDULING

Access technologies play an important role in wireless communication where they are used to increase channel capacity and allow users to access the system simultaneously. There are two types of access technologies used in wireless communication: i) multi-user access schemes and ii) single-user access schemes. There are different types of access schemes for multi-user have been extensively discussed in literature such FDMA, TDMA, Code-division multiple access (CDMA), OFDMA, Spatial division multiple access (SDMA) , and NOMA while other technologies adopt single user access over one channel such as TDD, FDD, Full duplex.

In telecom history, each generation can be defined by certain key technologies. For multi-user as an example, the first generation of telecom (1G) uses FDMA which provides only the service of analog voice while the second generation of telecom (2G) adopts TDMA where digital voice and low data-rata services are included. CDMA was the access scheme for the third generation (3G) which is known by multimedia services with peak data rates from 2 Mbps to tens Mbps. OFDM can support various services of mobile broadband (MBB) with a peak data rate from 100 Mbps to 1Gbps which is used for the fourth generation (4G) system. NOMA as a promising candidate has been proposed to solve the challenges of the fifth-generation (5G) [145]. The technology behind NOMA is to use different levels of power for multiple users using the same resource block i.e time, frequency, and space compared to the previous generation of telecom technologies where the frequency is used.

The single-user access has also been presented in various studies such as [146]. The authors compared various two-ways wireless communication mode systems operating in half-duplex (HD), full-duplex (FD), time-division duplex (TDD), and frequency-division duplex (FDD) modes in terms of energy efficiency (EE). The result shows that with a large distance between transceivers, FD achieves the best EE performance. The work in [147] discussed the communication and networking for UAVs. Multi-user access technologies such as Orthogonal Multiple Access (OMA), TDMA, Beam Division Multiple Access (BDMA), and NOMA have attracted researchers toward UAV communication. NOMA, as an example, has received significant attention from the researcher as a promising access technique for UAVs in both academia and industry. Various studies [123], [148]–[156], have considered NOMA to solve the challenges of UAVs communication such as High Line of Sight Interference, High Altitude, Measurement Reporting Mechanism, and High Mobility. Another candidate to handle interference in a UAV communication system is the Full dimension multiple-input and multiple-output (FDMIMO) [157]. This access technology has the potential to produce a very high and stable data rate since antennas are placed in two dimensional (2D) arrays and the number of antennas is increased compared to traditional communication systems with less number and linear one-dimensional (1D) antennas.

Scheduling is used in wireless communication to ensure the most efficient use of the channel when users have data to transmit and need to coordinate with each other, which have been investigated in various studies. In [158], authors developed an algorithm that requires no prior knowledge of each UAV state. Their algorithm focusses on tasks scheduling problem exist in UAV swarm network through proposing distributed optimal scheduling algorithm while keeping in mind the power constraint on each one to limit. Their algorithm utilizes stochastic network optimization and distributes correlated scheduling. Through designing a UAV trajectory path, the authors in [159], investigate an energy-efficient UAV communication where both energy and throughput are considered. A binary decision variable is used to schedule UAV to user communication. The UAV is kept flying at a fixed altitude to avoid tall obstacles. Channel model communication based on line of sight and non-line of sight are derived for UAV-to-user considering transmit power, optimize the trajectory, the speed of UAV, UAV-to-user scheduling to maximize throughput. Spectrum trading problem based on contract theory is presented in [160] to enable mobile base station manager to maximize its revenue by trading spectrum with UAVs operators. Since each contract contains a different set of bandwidths this allows each UAV operator to choose the most profitable bandwidth price. The authors in [161] consider the case of UAV-to-UAV (U2U) communication where the transmit-receive pairs coexist with uplink (UL) of cellular ground users (GUEs) in cellular network deployment. The article compares two spectrum sharing techniques; i) splitting the available time-frequency resources into orthogonal portions for U2U and GUE communications and ii) sharing the same resource by both links which result in mutual interference. To identify the best spectrum sharing techniques, they evaluate the coverage probability and rate for all links. The study shows that for a large number of UAV pairs, adopting the second option seems to be the most suitable approach to guarantee a minimum rate for UAVs and better GUE UL performance. The article in [162], present a distributed mechanism for spectrum sharing among a group of connected UAVs and licensed terrestrial networks where UAVs may require to use external spectrum when the spectrum is congested or when changing its operational frequency in case of security threats. The authors investigated the scenario where the UAV network act as remote sensing. In their model, UAVs are classified into two clusters relaying and sensing where the relay UAVs are used to provide services for the rest of sensing UAVs to obtain spectrum access in a licensed network. A distributed mechanism based on a reinforcement learning algorithm is developed to help UAVs decide whether they need to serve in relaying or sensing considering communication among them may not be reliable or feasible.

Due to the increasing useability of UAVs in different applications such as surveillance, delivery using line-of-sight links, video streaming, and the requirement for large RF transmission footprint from UAV to ground nodes, UAV connectivity may deteriorate the performance of links to cochannel ground communication. In [163], authors investigate the need for researchers to design efficient spectrum-sharing policies for UAV communications in order to enhance spectral efficiency (SE) and control interference-to-ground communications. The challenges, fundamentals, and applications of spatial spectrum sensing (SSS) for UAV spectrum access and other open research problems are also studied by the same authors.

Up to date, the researchers in the UAV communication area have developed a variety of interesting techniques in the domain of access control and scheduling and have obtained some results. Nevertheless, they have faced some challenges and opportunities since the adoption of UAVs in cellular networks such 5G and Beyond is still in the preliminary and research stages. Therefore, intense research is required to tackle such challenges.

XI. SPECTRUM SHARING

Spectrum sharing is a powerful technique to improve spectrum utilization and efficiency for network operators at increased capacity/coverage and reduced network infrastructure, thus increasing revenue and reducing operational costs. Various schemes have been proposed for UAV networks based on deep learning, machine learning, cooperative learning. Sharing methods are deployed to enhance channel capacity, enhance secrecy and security, and enable relay nodes for traffic offloading and disaster recovery. These methods whether overlay, underlay or interweave are applied on different network topologies and architectures, e.g., sharing between aerial and terrestrial (UAV-ground), air (UAV-UAV), aerial and wireless local area networks, underwater UAV networks, or solely between aerial networks, see Figure 15.

A. SPECTRUM SHARING METHODS

Dynamic spectrum sharing applies to UAV networks akin to conventional cellular and indoor networks, where traditional sharing schemes in time and space can still be applied to UAV networks in various applications and architectures. This still requires adjustments to the transceiver designs, link budgets, channel uncertainty, and propagation characteristics. Prominent sharing methods include the following [164].

Underlay Spectrum Sharing: Here spectrum is concurrently shared by a second user with the primary licensee in time and space domains. The second user knows the channel strengths and thereby controls power levels and ambient noise and

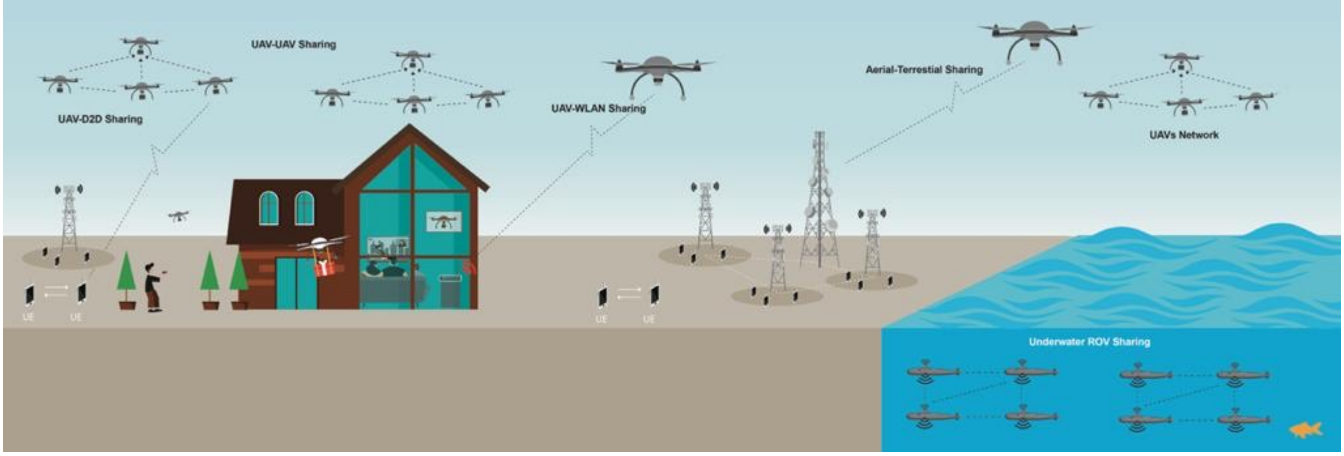
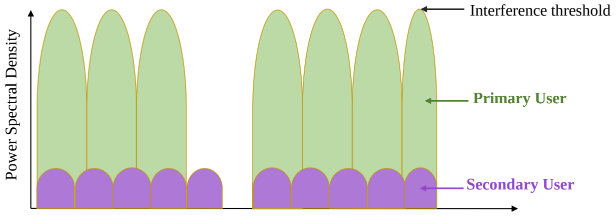
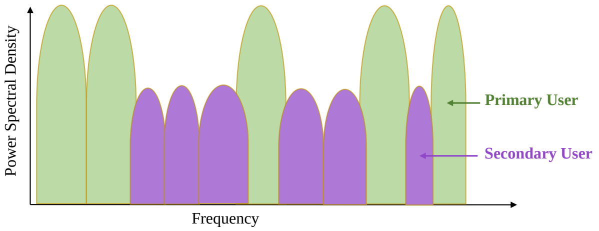


FIGURE 15: Spectrum sharing scenarios.

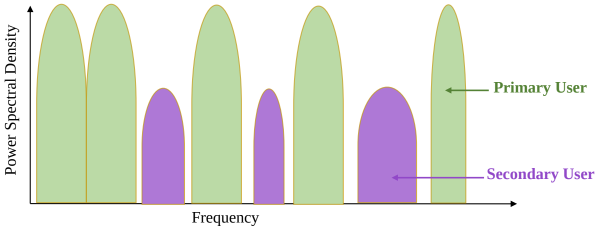
maintains minimum interference under a predefined threshold (interference temperature threshold).
Overlay Spectrum Sharing: Explicit spectrum sharing is performed in opportunistic or cooperative spectrum access. First, opportunistic sharing is used when the licensee does not use it, which yields low overhead and fast access times at the detriment of higher failure rates. Meanwhile, in cooperative sharing, bands are allocated centrally based on real-time negotiation with the licensee, where both the primary (licensee) and secondary users simultaneously transmit over the same band, and interference is offset by exchange control signals. The latter provides maximum spectral efficiency and reduced false alarm probability, albeit communication overhead, extended control time, and power consumption. ***Interweave spectrum sharing:*** This opportunistic sharing approach allows secondary users to periodically monitor the spectrum, analyzes primary user occupancy rates and patterns over time, space, and frequency, i.e., developing spectrum awareness. Thereafter, it accesses fragmented spectrum holes (voids) with minimal interference.



a) Underlay Sharing: Concurrent parallel sharing over underused bands



b) Overlay Sharing: Explicit opportunistic or cooperative sharing across unused bands



c) Interweave Sharing: Explicit use of fragment bands

FIGURE 16: Spectrum sharing methods.

B. COOPERATIVE AND OPPORTUNISTIC SPECTRUM ACCESS

Authors in [165] propose a superposition coding-based NOMA downlink scheme for UAV communications in effort, termed as network-coded multiple access (NCMA). It allocates equal power to the superposed signals of different downlink users in the absence of channel information. To achieve high NOMA throughput under such equal power allocation, the scheme introduces a phase offset between users' superposed signal to optimize the joint use of physical-layer network coding (PNC) and multiuser decoding (MUD). Authors conduct real-time implementation for the scheme based on software-defined radio, where results show that robustness against varying channel conditions, along with an enhanced throughput in a practical system setting. The NCMA method here enhanced the spectrum efficiency as compared to TDMA by allowing downlink transmission from multiple users. Furthermore, the method provides improved fairness and throughput as compared to conventional NOMA schemes such as successive interference cancellation-based superposition coding (SIC-SC), thus boosting boost throughput in UAV networks.

In general, CR allows secondary users (SUs) to share a portion of the spectrum with licensed or unlicensed primary users (PUs). One opportunistic access approach is orthogonal CR that allows SUs to transmit orthogonally on the resources of the PU (space, time, or frequency). This requires a multidimensional spectrum sensing to detect the resources of the PU. To reduce the complexity of the sensing requirements here, a cooperation mechanism between the primary and secondary systems can be applied, such as employing a two-phase protocol that spans over OFDM symbols as proposed in [166] and [167], i.e., to allow SU to help the PU avoid outage as well as transmitting its own data using disjoint subsets of subcarriers. However, this cooperative approach may also face difficulties in terms of resource allocation, along with increased system complexity attributed to the increase in the number of subcarriers. On the other hand, non-orthogonal CR (NOCR) intuitively mandates non-orthogonal spectrum sharing between the two users. For instance, the SU shares the PU resources while maintaining low interference temperatures. Also, encoding and decoding techniques can be leveraged to reduce the mutual interference between the PU and SU transmissions. Lastly, interference alignment methods can be applied to relax the threshold on the SU transmission powers. Here it can be critical to precisely determine the interference level a secondary transmitter causes to a primary receiver in the first approach [168]. Meanwhile, encoding techniques can be sophisticated to achieve noticeable reduced interference levels. For example, dirty paper coding (DPC) [169] require a priori knowledge of the PU's transmitted data and information about how the encoded mechanism is applied to the sequence. Further, a global CSI is required for the interference alignment in the last additive superposition solution.

Along this, authors in [170] present a dynamic spectrum-sharing paradigm for single-carrier CR networks, where a SU maintains the performance of a PU transmission, while also obtaining a low-data rate channel for its own communication. It allows the SU to transmit concurrently with the same time-frequency slot of the PU to enhance the ergodic channel capacity, where the SU earns an unlicensed channel access with low transmission rates, which allows to reduce its average delay per symbol. Along this, when the SU detects the signal transmitted from the PU, it can superimpose its transmission on the PU signal by simple multiplicative precoding, without requiring any cooperation between the primary and secondary systems. The SU employs a cooperative strategy termed as amplify-and-forward (AF) relaying when the PU is active. Specifically, the PU signal received by the SU is multiplied by the information symbols of the SU and retransmitted thereafter. Further, authors in [168] extend this concept to a multicarrier CR network to increase the ergodic capacities of the SU and PU. Specifically, the SU superimposes precoded block symbols in parallel over the OFDM subcarriers on the PU received signal in a time-domain convolution (convolutive superposition).

In another spectrum cooperative approach, the capacity limits of mobile UAV-based multiuser communication is investigated. For example, the work in [171] characterizes the capacity regions over a given flight duration. It adopts a flying UAV at a constant altitude that sends independent information over two-user broadcast channels (BC) at different fixed ground locations. The work jointly optimizes the UAV's trajectory and transmit power rate allocations over time, subject to the maximum speed and maximum transmit power of the UAV. At a high UAV flight duration and speed, it is shown here that a simple hover-fly-hover (HFH) UAV trajectory with TDMA-based orthogonal multiuser transmission is capacity-achieving. Results imply that UAV movement is less effective for capacity enhancement as SNR increases. Further, the optimal UAV trajectory continuous to follow the HFH structure, likewise to the capacity-achieving case with superposition coding (SC)-based nonorthogonal transmission, albeit differences in the hovering locations as compared to the TDMA case. Lastly, the work shows that the capacity gain achieved by the optimal SC over the suboptimal TDMA decreases as the UAV maximum speed and/or flight duration increases.

C. SPECTRUM SHARING SCENARIOS

(1) Spectrum Sharing between Aerial and Terrestrial Networks

Air-ground integrated networks (AGIN) introduce a new dimension for the growth of wireless communications, albeit a bottleneck in the spectrum. Hence spectrum sharing techniques have been proposed.

UAV networks can require an external spectrum due to congestion or variation in operational frequency due to security threats. Hence, authors in [162] develop a distributed mechanism for spectrum sharing among UAVs and licensed terrestrial networks through a licensed primary user that shares part of its spectrum in exchange for receiving a cooperative relaying service. Namely, the UAV network performs a remote sensing mission, where UAVs are categorized as either relaying or sensing clusters. The relay UAVs provide a relaying service for a licensed network to obtain spectrum access for the rest of the UAVs that perform the sensing task. Here the UAVs locally decide on the participation in the relaying or sensing process, where optimal task allocation is developed using a distributed reinforcement learning algorithm. Authors in [172] propose a collaborative 3D sharing approach by leveraging the location flexibility of flying UAV spectrum, along with false alarm and detection probabilities. A joint spatial-temporal spectrum sensing technique is developed that features a temporal fusion window and a spatial fusion sphere to address the composite spatial-temporal data fusion, termed as 3D spatial-temporal sensing (3DSTS). Moreover, the sensing space is divided into black, grey, and white layers, which represent different spatial spectrum access opportunities. Finally, the authors propose multiple sensing schemes to improve the 3D sensing framework, i.e., double fusion, temporal and global spatial sensing to enhance detection performance under various spectrum environments, taking into account primary user sensed range, working probability, UAV density, and NLoS channel.

Capacity improvement is another motivation for spectrum sharing. For example, authors in [173] investigate the spectrum sharing between the air-to-air (2D and 3D) UAVs mesh deployment and ground networks to enhance the capacity of air-to-air communications. The coverage performance of the UAV network is analyzed by applying stochastic geometry and directional antennas are employed to improve coverage performance versus omnidirectional modes. Furthermore, the maximum transmission capacity and the optimal altitude of UAVs are obtained using optimization theory. Likewise, the work in [174] investigates spectrum sharing between air-to-air UAV mesh networks and ground networks to improve the capacity of the UAV networks, i.e., communications among UAVs share the spectrum of the ground networks while assigning different spectrum to the air-to-ground communications. The distribution of UAVs is modeled as a 3D homogeneous Poisson point process (PPP), where stochastic geometry is applied to analyze the coverage probability of UAVs and ground network users. Findings show that the optimal height of UAVs can be computed with the constraint of the coverage probability of ground network users.

The work in [175] leverages UAVs as mobile relays for secure communications composed of four-channel setups, i.e., source, destination, buffer-aided mobile relay, and eavesdropper that are all equipped with a single antenna in NLoS settings. Also, the mobile relay here operates in a frequency division duplex (FDD) with equal bandwidth for information reception and transmission. The work aims at maximizing the secrecy rate by optimizing the transmit power of the source and the UAV relay to the destination as compared to static relaying methods. Likewise, the work in [176] proposes a UAV-aided mobile relaying system composed of the same four entities and information-causality constraints, in efforts to jointly optimize the relay trajectory and the source/relay power allocations for maximizing the secrecy rate, while satisfying the practical mobility and information-causality constraints. The mobility constraints here include the relay's initial and final location and speed. The work here exploits the alternating optimization (AO) method with a given trajectory, i.e., the power allocation problem.

Furthermore, sharing schemes are deployed to enhance secrecy and confidentiality. A cooperative jamming approach is developed in [177], where one UAV transmits confidential information to a ground station and another UAV generates artificial noise (AN) to jam a suspicious eavesdropper on the ground. The UAV trajectories are jointly optimized with the communicating/jamming power allocations over time, i.e., using alternating optimization and successive convex approximation methods. However, the location estimation of the eavesdropper and the ground station is a key challenge here. Also, the cooperative jamming approach in [178] deploys spectrum sharing between two UAVs and a ground station to combat ground eavesdropper overhearing effects, thus inherently acting as cooperative jammers (i.e., mutual interference) for each other. To realize this, authors implement an iterative algorithm to jointly optimize the flying (horizontal and vertical) trajectory and transmit power of both UAVs, while maximizing secrecy rate gains.

Spectrum sharing for mission-critical services such as disaster recovery and public safety is proposed in [179], where UAVs serve as relays (flying BS) to provide extended network coverage for the affected area. A macro BS serves PUs located in the primary network (safety area). When a disaster occurs, then flying UAV BS is deployed to form a small cell serving SU in the disaster area. The UAV here shares spectrum with cellular networks via cognitive radio to restore services. The spectrum allocation problem is formulated as a mixed-integer optimization model that maximizes the network throughput of primary and secondary networks under the constraint of maximum tolerable interference impinged on the primary users. Further, a deep neural network (DNN) model is used to reduce the execution time of the optimization framework. Finally, authors in [180] propose a robust spectrum sharing framework that deals with state uncertainties and security threats in AGIN by integrating controls and communications. The framework is comprised of spectrum utilizing networks, spectrum monitoring networks, and spectrum clouds.

Despite the proposed sharing schemes, there are key challenges that need to be addressed in UAV-ground spectrum sharing that enhances the spectrum efficiency and UAV mobility. This includes spatial isolation, parametric configuration, and pattern control that require prior information such as user locations and instantaneous CSI. Further, the LoS link between the ground base station and UAV makes it vulnerable to security threats such as jamming, eavesdropping, and spoofing [180].

(2) Spectrum Sharing between ROV Networks

Authors in [181] utilize NOMA to increase the efficiency of underwater UAV (UUAV) networks, known as a remotely operated underwater vehicle (ROV), where each one is allocated several sub-carriers occupying partial spectrum, i.e., the combination constitutes the overall channel bandwidth. The use of NOMA for UUAV results in a multi-user interference problem that is modeled as a non-cooperative game, and resort to the multi-agent reinforcement learning to approach the Nash Equilibrium. However, the resulting sub-carriers still suffer from non-linear patterns attributed to the interference residue, which implicates efficient resource utilization. Hence, authors utilize reinforcement learning to model this non-linearity as an optimization problem, where each UUAV maintains a Q-learning process, and then Nash Equilibrium (NE) is approached through a stochastic learning process between learning agents.

(3) Spectrum Sharing between UAV and UAV Networks

The work in [182] utilizes spectrum interaction of flight formations in a layered UAV structure that assigns spectrum for UAVs with the highest priority, where the latter acts as the temporary command decision center. The dynamic channel model exchanges information between two UAVs, where the time slot is divided into current state evaluation, action selection (UAV number to perform the information sharing), data transmission, and policy update at the end of the round. In the same time slot, two UAVs share one channel to complete information sharing. Different types of

UAV formation methods are evaluated (e.g., time slot sharing between UAVs) based on the QoE metric using deep reinforcement learning and the long-short-term memory (LSTM) network for faster convergence. Here it is important to address communication modes in the dynamic channel and slot allocation (e.g., single or broadcast), and propose designs for the dynamic slot model that assigns different UAVs priorities that occupy time slots for information sharing. Authors in [163] develop a robust spectrum sharing technique using path optimization, where a transmitting UAV and receiving UAV are flying at constant altitude (100 m) exchange information while sharing the same spectrum band with five terrestrial communication pairs of estimated locations. The aim is to maximize the sum throughput via optimizing UAV paths to exploit the heterogeneous spatial spectrum. Namely, the non-convex sum throughput maximization problem is converted into a semidefinite programming problem, then a successive convex approximation algorithm is applied. Note that the location inaccuracy of the terrestrial transmitters yields in path uncertainty problem, which reduced the sum rate and degrades network performance.

(4) Spectrum Sharing between UAV and D2D Networks

Spectrum sharing between UAV and D2D networks is applied to enhance spectral efficiency, capacity, throughput, physical layer security, along with interference mitigation, and link reliability. Consider the details.

First, the work in [183] proposes an opportunistic 3D spatial spectrum sharing for UAVs to access the licensed channels occupied by D2D links of ground users, in efforts to maximize the area spectral efficiency (ASE) of UAV networks while guaranteeing the required minimum ASE of D2D networks. The work computes the probabilities of spatial false alarm and missed detection at the UAV using machine learning to characterize the density of active UAVs. Further, the coverage probability of D2D and UAV communications is formulated based on the Neyman-Pearson criterion. The outcome is a decrease in the spatial spectrum sensing radius of UAVs, which reduces the coverage probability of UAV communications, albeit improving the ASE of UAV networks. In [184], a spectrum sharing problem for a full-duplex UAV and underlaid D2D communications is studied, where a mobile UAV assists the communications between separated nodes without a direct link. The source and destination nodes here have one antenna, whereas the UAV is equipped with transmitting and receiving antennas that operate in full-duplex mode. It is important to investigate self-interference cancellation technologies to combat interference that arise from the transmit antenna. The design aims to maximize the sum throughput under the transmit power budget, while guaranteeing the coexistence with terrestrial D2D pairs, satisfying the information causality and UAV's trajectory constraints.

The work in [185] investigates physical layer security (secrecy) performance in D2D-based UAV (DUAVs) by applying spectrum sharing in two scenarios, i.e., UAVs serve as flying BSs and aerial UEs. The sharing strategy exploits interference incurred by spectrum reuse. Namely, it combines cooperative jamming technique and underlay pattern, where idle D2D UEs serve as friendly jammers to generate artificial noise to protect these UEs reusing the same spectrum with them. Moreover, the sharing strategy allows D2D UEs to underlay cooperative jamming patterns to reuse the spectrum of cellular UEs/overlay D2D UEs to provide a security solution. Here the total spectrum of the cellular system is divided into two portions based on a spectrum partitioning factor that is orthogonally and equally assigned to each cellular UE, whereas the remaining spectrum portion is likewise assigned to each overlay D2D UE.

Another application of spectrum sharing is throughput enhancement. Authors in [186] leverage spectrum sharing between 3D drone small cells (DSCs) underlaid with 2D conventional cellular networks to develop aerial base stations deployment of varying densities. The tractability of the PPP is leveraged to develop DSCs coverage probability and achievable downlink throughput with and without cellular networks. Further, the optimal density of DSCs aerial base stations is gauged to enhance throughput, considering the efficiency constraint of the cellular network. Note here that the adopted channel model is rather simplistic to facilitate closed-form derivations, thus extended channel models are further needed to account for mobility, blockage, increased heights.

In [187], static and mobile UAVs are deployed to enhance downlink throughput for an underlaid D2D network. Thus acting as a flying BS, where the UAVs and D2D users have the same spectrum access priority. In the static deployment, the coverage probability and the sum rate for the users are derived as a function of the UAV altitude and the number of D2D users. Meanwhile, the disk covering problem is applied in the mobile deployment to compute the number of required stop points that the UAV needs to visit for complete area coverage. Moreover, the overall outage probability of the D2D users is also developed to consider the case of multiple retransmissions between the UAV and users. Findings show that the optimal settings for the UAV altitude depend on the density of D2D users, which directly impacts the sum rate and coverage probability. Results also show that the total transmit power of UAVs can be minimized by adaptively moving UAVs over a finite target area.

Furthermore, the work in [188] focuses on the interference problem in spectrum sharing between connected UAV and D2D users that simultaneously operate in an underlying NOMA network. A closed-form for the outage probability is derived and a power control method is developed to achieve a good QoS for UAV connected users without causing interference to D2D users, where the power control problem is formulated as a non-convex optimization problem that aims to maximize the power and QoS for each D2D user operated by a UAV. Then a convex linear program is leveraged to simplify the complexity of the problem by setting a limit on the interference that can be encountered by a D2D user (enabling gradual sub-optimal solution).

Authors in [189] concentrate on the degradation of link reliability due to spectrum sharing over multi-bands between UAV-connected uplink users and D2D users. For instance, the performance of uplink transmissions to UAV BS can degrade due to malfunctions of the ground BS, and uplink cellular users share multiple bands with other D2D users to provide a reliable disaster recovery approach. The work here derives the successful transmission probability, average sum-rate, and energy efficiency while considering D2D user density, uplink user density, UAV altitude, and outage signal to interference plus noise ratio (SINR) thresholds. A stochastic geometrical arrangement is developed (Johnson circles) at which a single flying UAV BS hovers the central point of intersection of three cells to serve users who are involved in either cellular uplink or D2D communications. One key limitation here is the consideration of a single UAV without considering mutual interference between multiple UAVs of various flight heights. Hence, the development of multiple UAV networks for disaster recovery along with interference and outage models is required.

(5) Sharing between UAV and WLAN Networks

Spectrum sharing is also introduced between UAV and WLANs for offloading and capacity improvement via concurrent transmissions. Authors in [190] propose a user association method for a single UAV BS (operating on LTE bands) coexisting with a WLAN access point (AP) operating on microwave unlicensed spectrum, where certain users served by the UAV BS are offloaded to the AP via the LTE-WLAN aggregation (LWA) protocol. Further, the UAV BS can gain access to the unlicensed spectrum via the LTE-unlicensed (LTE-U) standard. The objective here is to minimize the average queuing (M/M/1) delay of users served by the single UAV BS, while maintaining the delay of the WLAN users less than a certain threshold, via jointly optimizing the spectrum allocation, the set of offloaded users, and their offloaded traffic rates. The authors propose a sub-optimal solution via the block coordinate descent method to solve the nonconvex optimization problem. Scalability presents a key challenge in the presence of multiple UAV BSs competing on the available unlicensed spectrum, where interference issues arise on the unlicensed spectrum.

In [180], concurrent transmissions are facilitated via overlapped spectrum sharing between WLAN and UAV networks to maximize throughput under ultra-dense deployment. This is achieved by coding redundancy in which current coding schemes can tolerate extra errors. Consequently, the dispersion of the partial channel interference can be extended over the entire channel, with the ability to restore corrupted bit information. Here the physical layer structure is leveraged by measuring the subcarrier superposition effect under partial-channel interference on a GNU radio testbed. Various bit error rate (BER) levels are obtained with different degrees of overlap.

D. SPECTRUM SHARING SECURITY CHALLENGES

Despite the tremendous benefits for network operators and users from spectrum sharing, there exist many challenges that can impede its efficient and secure utilization. One key factor that attributes to the security threat is the high altitude of flying UAVs, which enhances the LoS transmission probability and exacerbates the network to security attacks. Consider the following challenges.

Malicious Spoofing Attacks: The inherent broadcast nature of the spectrum sharing approaches can result in spoofing attacks on legitimate users and network operations. Here malicious adversaries transmit forged signals of high power levels to suppress the signal of legitimate users. Consequently, the illegal signals are assumed to be authorized, thereafter adversaries perform a series of false instructions. Thus resulting in security threats that need to be addressed [185], [180]. Further, transmitted information in the network can be concealed via artificial noise, thus various artificial signals need to be examined and compared for secure spectrum sharing in UAV communications.

Eavesdropping: Unauthorized access to the shared medium can also occur by eavesdroppers that demodulate the legitimate signals using stealthily receivers. Despite the enhanced communication that results from encryption algorithms, they still fail to mitigate jamming threats as jammers deteriorate the SINR of legitimate links. Note that these security threats can result in higher abominable consequences in AGIN as compared to terrestrial links, e.g., UAVs may be induced to collide by jamming their control signals or spoofing them. However, one advantage of UAV is the mobility that can be utilized to accommodate security threats, such that a UAV can be employed as a cooperative jammer against eavesdroppers [180].

Jamming: Malicious attacks transmit jamming signals to legitimate communication links over the same spectrum band used in UAV terrestrial or aerial networks. This deteriorates the SINR levels of legitimate links, thus degrading the channel quality and causing link failures [180]. Lightweight Link resiliency and redundancy along with restoration schemes for UAV networks present a key research area here.

State Uncertainty: The UAV mobility results in location uncertainty that impacts the channel condition and quality, as well as uncertainty in path flight planning between multiple UAVs and ground stations. Also, the propagation environment such as wind speed and air density [191] influences the energy consumption levels. Hence deterministic parameters (e.g., UAV weight) need to be extended to include new parameters such as UAV propulsion [180], which adds complications in the link budget design.

XII. SPECTRUM SENSING AND DECISION MAKING

The UAV must be aware of the spectrum's occupancy, which can be accomplished by spectrum sensing. Spectrum sensing is used in wireless networks to define vacant spectrum bands (spectrum holes) [192]. The presence or absence of wireless devices can also be determined using spectrum sensing [193],

[194]. The sensing control involves how quickly the UAV detects the spectrum hole with high accuracy while minimizing wireless system interference. The UAV must make decisions in real-time about when to sense the spectrum, how long to utilize it, and which frequency band to use. The authors of [195]–[197] discuss a variety of current spectrum sensing schemes for tracking vacant channels.

Since there is no dedicated spectrum for UAV communications, opportunistic transmission has been thought to be a realistic option for supporting UAV communications. To prevent interference, effective spectrum sensing and allocation are important for UAV communications when sharing the same spectrum with other users such as mobile base stations and satellites. Since UAVs may travel to different 3D placements with different spectrum environments, spectrum decisions can become invalid in a short period, necessitating quick spectrum sensing. Furthermore, a UAV must anticipate potential spectrum holes in both time and space. As a result, the UAVs are expected to communicate through opportunistic transmissions, such as accessing a spectrum hole or sharing the spectrum with other users. UAV communications do not interfere with licensed communications, such as satellite-ground, civilian airplane-ground, or airplane-satellite communications. As a result, the sensing of primary signals must be as precise as possible, or the risk of missing them must be low enough [198].

The limited-time cost of spectrum sensing is a more relevant concern since UAVs fly through various wireless environments in a short period of time. The complexity of the used sensing technique determines the time cost, with a trade-off between complexity and sensing accuracy. That is, meeting the requirements of quick and accurate sensing at the same time is difficult. As a result, spectrum prediction is used to reduce the complexity of the sensing technique while also increasing the sensing accuracy [198]. In this way, instead of sensing all or random frequency bands, only the expected potential holes are sensed [199]. However, since terrestrial users with low speeds will not regularly alter wireless environments, the prediction methods for terrestrial communications could not be explicitly applied to UAV communications. The spectrum prediction for terrestrial users only needs historical information in the temporal dimension. The prediction of UAVs necessitates both time and space historical information [198].

While opportunistic transmission has been used in scenarios such as mobile and satellite communications, it still poses some challenges when used for UAV communications. These challenges are presented as follows [198]:

(1) Fast algorithms for spectrum prediction and sensing: The UAVs can travel into new environments in a matter of seconds, meaning that spectrum prediction and sense must be completed in a short amount of time. The time needed for spectrum prediction could simply be Δt, while the time required for sense could be much less than Δt because communication would take up the majority of Δt. If Δt is a couple of seconds, for example, the sensing time could be set in milliseconds. It can vary from the situation in terrestrial communications, where processing time is measured in more than a couple of seconds [198]. Since the algorithms must be highly accurate at low SNRs, this problem can be difficult to deal with [200]. Even though some reports claim that the sensing time is on the order of microseconds, the SNR must be greater than -5 dB [201]. In [198] a fast spectrum sensing technique for UAVs was proposed. They presented a novel approach to improving energy detection efficiency using linear programming-based optimization, which significantly reduced the expected noise variance error without requiring high additional computation. Based on the simulated results, the optimized noise estimation-based energy detection consistently provided good performance for various degrees of noise estimation errors, suggesting that their proposed approach might not be very sensitive to noise uncertainty. Furthermore, the constantly missed detection rate-based decision rule ensures primary signal detection accuracy. While the proposed technique was tested using a terrestrial base station scenario, it can also be used for UAVs in other scenarios, such as UAV-HAP scenarios.

(2) Spectrum prediction based on temporal-spatial information: The UAV communications require to predict possible holes in the next space location and next time. As compared to terrestrial prediction, which predicts potential holes in the future but at the same place, the theory and algorithms for UAV prediction become much more complicated because the problem appears to be of high dimensions [198]. Another scenario for unlicensed sub-6GHz UAVs is that, despite finding a suitable hole, a licensed user begins to access the hole shortly after the UAV begins to communicate. The reason for this is that the sub-6GHz bands are maturely developed, with a large number of users and high spectrum usage [198]. To prevent a conflict, the spectrum idle time should be expected (or spectrum occupancy) [202]. First, some holes with enough idle time for UAV communication are chosen for the next spectrum sensing from among the possible holes expected. That is, the expected holes should have an idle time of approximately Δt. The prediction of spectrum idle time is, of course, also based on spatial-temporal information [198]. Another important topic is how to create a database of spatial-temporal information. It will be a complicated and massive task to save information for each point in the dimensions of latitude, longitude, latitude, and time (similar to the terrestrial database of information for each time slot). To reduce the prediction complexity, this problem can be approximated to some simple boundary issues, such as homotopy dependent models [198].

(3) Constant missed detection rate based spectrum sensing: Many studies have found that spectrum sensing is based on the constant false alarm rate detection principle, which involves detecting signals using a threshold determined by a pre-defined false alarm probability. The constant false alarm rate-based detection is used in many applications such as radar where the false alarm probability should be fixed. The missed rate, on the other hand, might be more important

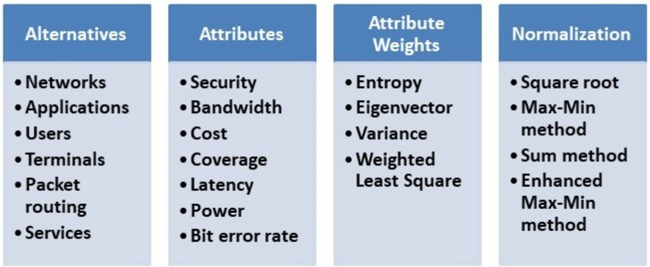


FIGURE 17: Spectrum decision technical aspects.

for some UAV communications. The cost of sensing another hole could be much less than the cost of interfering licensed users with a missed detection in this case, so the false alarm probability is unimportant. As a result, a new topic of constantly missed rate-dependent spectrum sensing may provide a solution, meaning that the threshold is set by a predetermined missed rate or detection probability [198].

The selection of the appropriate channel from the available options is part of the spectrum decision [192]. The UAV must decide whether or not to use the available channel [203]. Spectrum characterization, channel selection, reconfiguration, and routing protocol are all important aspects of spectrum decision [193]. Path loss, received signal strength level, how many wireless devices are accessing the spectrum, and channel interference are the parameters used to characterize a spectrum hole [203]. Since there are so many different channels and routes between the transmitter and receiver in distributed UAV networks, channel selection becomes more difficult. The suitability of these combinations for data transmission must be determined. To make a spectrum decision, the protocol used for routing and the parameters relevant to data transmission must be reconfigured [192]. The authors of [204] investigate an application and events-based spectrum decision technique. For real-time services and future applications, this technique ensures maximum capacity and minimum variance. The spectrum decision in [205] is based on QoS requirements and variation in the availability of spectrum. As shown in Figure 17, various technical factors used for spectrum decision making are classified into four major subcategories [192].

Unlike existing wireless networks, the handover does not only execute due to movement of UAVs but also due to the presence of licensed wireless devices. Typically, UAVs are considered as visitors to available spectrum bands in various networks. As a result, UAVs must seamlessly switch between available vacant channels. It is termed as spectrum mobility [192]. Spectrum handover and link management are two key operations [193], [206]. Handover parameters collection, handover initiation, and handover execution are all part of the spectrum handover process [207]. Various handover techniques for spectrum mobility are discussed in [208], [209]. For a seamless handover, there must be no interruptions in connectivity. The handover and link management in distributed UAV networks become more complicated due to the lack of a centralized controlling entity [210].

Several challenges remain to be overcome in the implementation of the spectrum decision function [211]:

(1) Decision model: In UAV networks, estimating spectrum capacity using the SNR is insufficient to characterize the spectrum band. Moreover, various applications have different QoS requirements. As a result, the development of spectrum-adaptive decision models is still an open issue.

(2) Cooperation with reconfiguration: Transmission parameters can be reconfigured for optimum operation in a specific spectrum band using spectrum management techniques. By using adaptive modulation instead of spectrum decision, bit rate and bit error rate can be preserved even if SNR is changed.

(3) Spectrum decision over heterogeneous spectrum bands: Certain spectrum bands are currently allocated to various uses, while others remain unlicensed. As a result, spectrum decision operations on both licensed and unlicensed bands should be supported by a UAV network.

XIII. AUCTION MECHANISMS

Spectrum auctions are thought to be a cost-effective way of redistributing spectrum and gaining dynamic spectrum access. The growing demand for wireless broadband services is putting a strain on the limited spectrum resources available. Meanwhile, the spectrum shortage is exacerbated by the underutilization of licensed wireless devices, which obtain a long-term static right to use spectrum by conventional regulatory allocation policies. Researchers have proposed dynamic spectrum access, which is facilitated by various auction mechanisms that feature fairness and allocation efficiency, to alleviate the scarcity problem and increase spectrum efficiency. Bidders' geo-location information is utilized to achieve spatial reusability, and spectrum auction mechanisms are designed to encourage bidders from bidding their true valuations on the spectrum [212].

By bidding on products or services, buyers and sellers may trade goods or services. Bidders (e.g., sellers and buyers) and an auctioneer participates in the auction. If there is only one seller/buyer, the seller/buyer will be the auctioneer. The auctioneer selects winners and payments based on bids obtained from bidders in a spectrum auction process [212]. Auctions are classified into three categories: 1) Forward auction, which contains numerous buyers and a seller (the auctioneer). 2) Reverse auction, which involves numerous sellers and a buyer (the auctioneer). 3) Double auction, which contains numerous sellers and buyers and a third-party auctioneer [212].

The spectrum channels are interference-constrained spatially reusable, unlike conventional goods that can only be used once. That is, a single channel can only be assigned to multiple buyers if it is free of interference. An undirected interference graph $A = (B, C)$ can be used to represent buyer interference relationships, where B represents buyers, and C represents interference edges. If two buyers in set B

interfere with each other, then they share an edge in set B. The interference graph is generated based on the buyers' geo-location information and the spectrum channels' propagation ranges. Since the path loss varies by frequency band, the buyers' interference relationships vary by spectrum channel. Theoretically, the interference relationship is tight on the low-frequency spectrum and loose on the high-frequency spectrum [212].

The aim of a spectrum auction is to achieve spectrum reuse while also achieving desirable characteristics like social welfare maximization and economic robustness. Auction participants are believed to be greedy and rational individuals who will select the best auction strategy to maximize their own benefit, according to microeconomic theory. As a result, policymakers must carefully design auction mechanisms to enable auction participants to act as desired. One of the main goals of auction mechanism design is to achieve economic robustness, which is described as individual rationality, honesty, and budget balance [212]. The auction mechanism should guarantee the following properties:

(1) Individual Rationality: A rational bidder would only take part in a spectrum auction if it will increase their usefulness. Individually rationality is accomplished in a spectrum auction scheme when all bidders achieve non-negative utility, which ensures that every seller earns more than their bid and every buyer pays less than their bid [212].

(2) Truthfulness or Strategy-Proofness: Bidders are susceptible to manipulating bid prices in order to increase their profit margins. The truthfulness or strategy-proofness of a bidder means that their true value for the spectrum channel is equal to their bid value. A truthful spectrum auction scheme means that a bidder will have no reason to be untruthful because they will not be able to make a higher profit by lying about their true value [212].

(3) Budget Balance: By maintaining a non-negative budget, the auctioneer maintains a budget balance. The auctioneer, in fact, earns more money from the winning buyers than the winning sellers. Keeping the budget balance is enough to encourage policymakers to host spectrum auctions. The auctioneer, on the other hand, will seek to maximize their own revenue because they are profit-oriented [212].

(4) Social Welfare: The cumulative utility of all auction participants is used to quantify social welfare, which is an important economic measure of auctions. The social welfare equals the difference between the total bid of all winning buyers and the total bid of all winning sellers in a truthful auction when bidders reveal their true valuations [212].

(5) Spectrum Efficiency: The average reusability of all spectrum channels or the average number of buyers who share the same channel in the final allocation, is known as spectrum efficiency. Since the spectrum channel is a limited resource, it is desirable for the auction to achieve high spectrum efficiency [212].

(6) Seller/buyer happiness: The ratio of winning sellers (buyers) to the total number of sellers (buyers) is generally used to assess how happy sellers and buyers are [212].

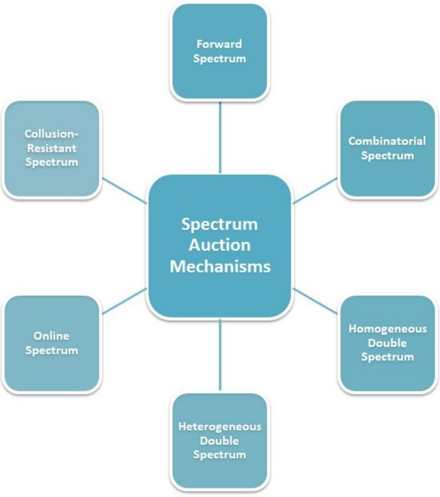


FIGURE 18: Spectrum auction mechanisms.

(7) Collusions: Participants can band together to exploit the spectrum auction to their own advantage, resulting in increased utility. For example, by inserting dummy bids, the seller/buyer can collude with the auctioneer to obtain higher payments [212].

(8) Privacy Preservation: Other parties, especially the untrustworthy auctioneer and rival bidders, should be kept out of sellers' and buyers' private and sensitive information [212].

Existing mainstream spectrum auction mechanisms are shown in Figure 18 and can be classified into [212]:

(1) Forward Spectrum Auction: In a forward spectrum auction, a single seller acts as an auctioneer, redistributing N channels to several buyers, each of whom can claim $C_i \geq 1$ channels. According to the non-ascending order of buyers' bids, winners will be specified by sequentially checking whether the buyer has a lower demand C_i than the number of available channels $N - e_i$, where e_i denotes the number of channels already allocated to this buyer's interfering neighbors [213].

(2) Combinatorial Spectrum Auction: Combinatorial spectrum auctions allow buyers to bid on several channels at once, allowing them to show a preference for contiguous spectrum over the non-contiguous spectrum. A channel that is concurrently included in the requested packages of non-interfering buyers will be converted into a virtual channel to achieve spatial reuse. The buyers are ranked in a non-increasing order by the ratio of their bids to the bundles' sizes, transforming a combinatorial spectrum auction into a traditional combinatorial auction. The auctioneer selects winners by sequentially testing each bidder, as long as their requested combinations do not include any previously allocated channels [214].

(3) Homogeneous Double Spectrum Auction: Multiple buyers and sellers engage in a homogeneous double spectrum auction, each of whom demands or owns one channel. Non-interfering buyers are grouped together by the auctioneer, resulting in diverse groups of all buyers. The group's minimum bid and group size are both needed to determine each group bid. The auctioneer then runs the McAfee auction mechanism between the buyer groups and sellers to assign spectrum and decide payments [215].

(4) Heterogeneous Double Spectrum Auction: There are two main differences between heterogeneous and homogeneous spectrum double auctions. First, each buyer has different channel valuations, so a single bid vector is submitted for all channels. Second, heterogeneity leads to more complicated interference relationships, which are expressed in the interference radius. For example, a channel with a longer transmission range may cause interference on a pair of buyers, while a channel with a shorter transmission range may not. Thus, in heterogeneous spectrum double auctions, non-interfering buyers are grouped against each channel [216], [217].

(5) Online Spectrum Auction: The requested time slots of buyers must be processed in the online spectrum auction, taking into account the temporal dynamics of spectrum demand and supply. At each time slot, the auctioneer collects bids from newly arrived buyers and reviews sellers' available channels. After the current buyers have been confirmed, the auctioneer will perform a sifting process to exclude buyers who bid less than the expected future value of the channel. The spectrum allocation is then determined among the remaining buyers using the double spectrum auction mechanism [218].

(6) Collusion-Resistant Spectrum Auction: The auctioneer decides the relevant price to break the consensus among a group of possibly colluding bidders to prevent collusion among bidders. The smart contract on the blockchain can act as a collusion-resistant spectrum auction in a decentralized manner [219]. It is clear that due to the high mobility of UAVs, the appropriate spectrum auction mechanism for UAV wireless networks is the online spectrum auction.

The authors in [220] propose a decentralized competitive open market approach-based model of exploring a new dimension to spectrum sharing. The proposed model is focused on UAVs sharing spectrum with various mobile network operators, resulting in new revenue opportunities. The proposed algorithm's key concept is to consider an approach that benefits both the UAV base station and the mobile network operators. The proposed spectrum sharing algorithm is based on each UAV's logarithmic utility function and willingness to pay, resulting in a decentralized spectrum sharing approach. They present a case study to evaluate the algorithm's usefulness and show a flow diagram of the proposed algorithm. To illustrate the variation in revenue generation based on the demands, a trade-off study between the price provided by a mobile network operator and the spectrum shared by the agent UAV is presented. The proposed open market model can be extended to a drone cluster-based network, in which the drones work together to provide services to users. The authors assumed the case of high-altitude UAVs and considered that a line of sight channels exists between the users and the UAVs. The research work can be extended to low-altitude UAVs where physical obstacles can obstruct the line of sight transmissions. Another promising area for future research may be to investigate the use of blockchain to ensure a secure network environment. The blockchain-based network will ensure UAV registration while also allowing for trust-based smart contracts between UAVs and mobile network operators.

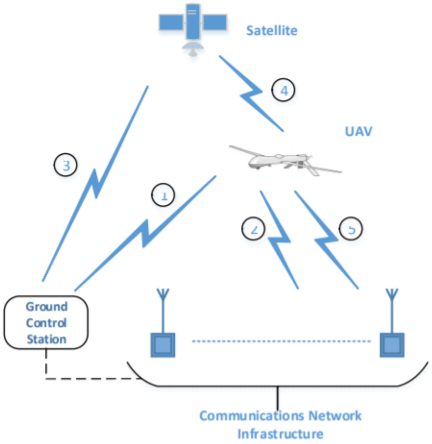


FIGURE 19: UAS architecture.

XIV. POWER CONTROL POLICIES

One of the issues concern in spectrum management for small UAS is power range to mitigate the safety concern mentioned in part 107 rules of the FAA. For example, in 107 rules for the small UAS to operate outside the rules, the FAA will consider any technologies for safety enhancement as its waiver such as utilizing Automatic Dependent Surveillance-Broadcast (ADS-B) system. The ADS-B system allows an aircraft to locate its location using satellites then broadcast its position, identification, direction, and altitude to the air traffic control using the ground station of ADS-B system. Since the ADS-B system considers to be the function of Next Generation and required for all aircraft within the controlled airspace in the US, its standards specify a transmission power over 7 Watts [221]. This power range would not be possible for small-size UAS systems due to the amount of interference this might cause with other small UAS in flight and general power constraints. Small power requirements for such a system would be more feasible since allowing drones to be detected few miles away [222]. The UAS system Architecture is shown in Figure 19:

Links 1 and 2 are the primary connection to link ground control station (GCS) to UAV through the service provider that managing the terrestrial communications network. Link 3 and 4 are the secondary links using satellite networks. Link 5 shows the requirement for data relay channels for transmitting needed data required by the UAS separated from the control and command messages for flight operating in UAS.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2021.3138048, IEEE Access

XV. TOOLS FOR SPECTRUM MANAGEMENT

The tools used for Radio Frequency Spectrum Management are very important for UAVs. Such tools play an important role in the procedure, analytical, and policy approaches to manage and plane the use of electromagnetic spectrum. Optimization, Artificial intelligence (AI) and machine learning (ML), and blockchain are discussed in the following subsection.

A. OPTIMIZATION

Optimization tool for efficient use of spectrum in UAVs is widely studied. The article in [223] provides a comprehensive survey on UAV-assisted wireless networks resource management from an optimization perspective covering the classification, benefits, and applications of UAV- assisted wireless networks. Detailed descriptions on resource management with metrics such as data offloading, spectrum, charging, path planning, backhaul, UAV trajectory, and placement of UAVs are provided in the same article. In terrestrial cellular networks, the long distance from mobile terminals (MTs) to the service ground base station (GBS) causes a performance bottleneck. The authors in [224] utilize UAVs as an aerial mobile base station to offload data traffic for cell-edge MTs for maximizing the minimum throughput of all MTs. In their study, the total bandwidth is shared between UAV and GBS where mutual interference is avoided. The article in [225] investigates the optimization of energy-efficient (EE) and spectrum-efficient (SE) for cognitive UAV networks based on location information. Therefore, one spectrum band which is available in one location may not be available in another due to the high mobility of cognitive radio (CR) based UAVs that operate on a frequency band that varies in time and location. A hybrid model is developed where the UAV's transmit power and the sensing performance can be adjusted to meet the primary user's constraint using the location information of both the UAV and the primary transmitter.

The analyzes and optimization of UAV to ground mmWave was proposed in [226] using the downlink energy and uplink information transfer process between the ground internet of things (IoT) and the UAV base stations. Furthermore, the authors in [122] utilize subchannel assignment and power allocation to improve energy efficiency for UAV wireless networks through NOMA integration. The work in [227] considers UAV relaying systems consist of several hops where they maximize the end-to-end average throughput to improve spectrum efficiency through jointly optimizing, the transmit power, the bandwidth allocated to each hop, and trajectories of the UAVs. Another work that deals with multiple UAVs in terms of joint optimal resource allocation is provided in [228] for both front haul and backhaul through convex optimization theory.

The article in [229] integrates non-orthogonal multiple access for high spectra efficiency and to increase connectivity in downlink transmission of UAV backhaul networks where they maximize the achievable rate of the worst ground user by UAV's power allocation, placement, and optimizing bandwidth allocation.

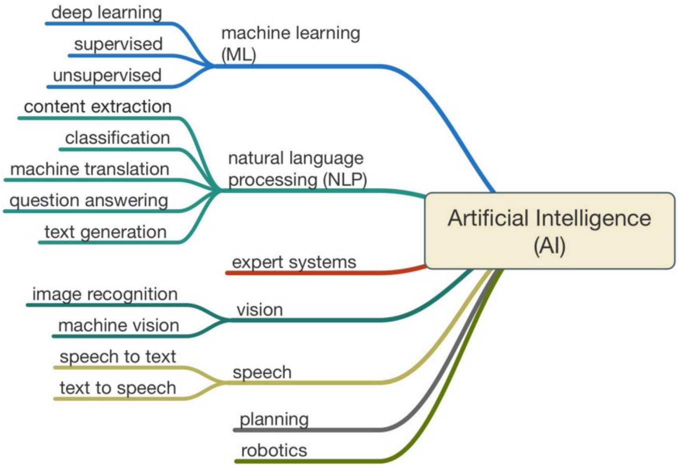


FIGURE 20: Artificial intelligence (AI) tools and uses.

B. ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING

Artificial intelligence (AI) is the process of integrating human intelligence into machines. This process can be defined based on the good old-fashioned (GOFAI) concept and extended to current technologies such as deep learning. It is a set of intelligent behavior accepted when a machine process (solves) a task using a defined algorithm. In general, AI can be classified based on type (weak or narrow) or based on functionality (reactive machine, limited memory, theory of Mind, and Self-awareness). ML is the process of enabling machines to learn by themselves for accurate prediction using provided data. Figure 20, shows different applications of AI, [230].

The intelligence of AI made it possible for significant researchers to integrate it through applying AI algorithms with the core of UAVs networks to solve challenges related to drones. The most recent work in [231] provides a comprehensive study on potential AI applications that could be integrated into UAV. They report the previous supervised and unsupervised ML, reinforcement learning (RL), and federated learning (FL) works designed for UAV networks and highlighted future directions for more possible applications of AI-based UAV. UAV can be equipped with a camera to capture images related to controller interest. The operator can control the image resolution by flying at a lower altitude. However, in order to interpret high-resolution images, ML algorithms are needed [232]. The scope, importance, and future prospect of ML-based UAV is provided in [233]. Another interesting work in [234] discussed different AI techniques such as expert system, ML, distributed AI, and automatic planning-based UAVs applications.

Overall, UAV-based networks can leverage various schemes in optimization theory. Foremost, heuristics, and meta-heuristics provide fast convergence to suboptimal solutions, which suits the requirements for UAV networks.

Among these schemes include Nelder-Mead, Luus-Jaakola, pattern search, divide and conquer, where the problem formulation can be formulated based on a few variables, and solutions are developed in a gradient-free structure. Meanwhile, for multiple variables, integer linear programming (ILP) and mixed integer linear programming (MILP) can be applied as mentioned earlier, however, it is important here to reduce the computational complexity associated with these schemes to better fit UAV network needs.

Machine learning has been applied for intelligent cooperation of UAV swarms in [235] in efforts to relax its complex and coherent characteristics. It starts by developing a digital twin (DT)-based model to reflect the physical entity (i.e., UAV swarm) with high-fidelity and monitors its whole life cycle. Thereafter, the decision model that integrates machine learning is constructed to explore the global optimal solution and controls the behaviors of UAV swarm.

This combination results in various challenges attributed to the high complexity and heterogeneity of these networks. Along this, the work in [236] identifies the suitable categories of machine learning algorithms for the design of U-RANs, in particular supervised and reinforcement learning strategies.

The work in [237] investigates wireless connectivity and security challenges in various UAV use cases, i.e., UAV-based delivery systems, UAV-based real-time multimedia streaming, and UAV-enabled intelligent transportation systems. It leverages artificial neural networks (ANN) to introduce adaptive operation that exploits the wireless resources while achieving a secure operation in real-time. The proposed solutions enable UAVs to predict future network changes, thereby adaptively optimizing their actions to efficiently manage their resources while securing a safe operation.

C. SUPERVISED LEARNING

Generally, supervised learning is one of the main branches of machine learning which aims to find a good function that maps an input to an output based upon a preceding acknowledged sample of input-output pairs. Namely, it deduces a function from labeled training data composes of a set of training samples. Here each sample/example represents a pair consisting of an input object (i.e., vector) and a desired output value (i.e., supervisory signal). Overall, a supervised learning algorithm analyzes the training data and results in an inferred function that can be used for mapping posterior new samples. Consequently, this yields an optimal situation that permits the algorithm to precisely determine the class labels for unseen instances, while this in return mandates the learning algorithm to generalize from the training data to unseen situations in a plausible manner. In the UAV context, spectrum solutions can leverage supervised learning techniques such as regression models and Bayesian learning. Consider the following.

1) REGRESSION MODELS, KNN AND SVM

The set of statistical processes in regression analysis techniques can be leveraged for estimating, modeling and analyzing the relationships among several vital parameters in the UAV systems. This arises when such parameters can be classified into dependent and independent categories. Hence, the goal of these models is to estimate the precise values of one or multiple continuous-response estimation targets, conditioned by the knowledge of input variables in a specific D-dimensional vector space. Note that the estimation target here is a function of the independent variables [238]. Regression models facilitate the behavior the dependent variables fluctuations when any of the independent variables is varied, while the other independent variables are fixed.

Various regression techniques can be adopted here for UAV spectrum management such as the parametric models including linear, ordinary least-squares and predictive logistic schemes. In addition to the nonparametric regression models that allow the regression function to be expressed and constricted by a specific set of functions rather than a predetermined form estimation, i.e., infinite-dimensional [238]. However, nonparametric regression here mandate extended sample sizes as compared to regression derived from parametric models' counterpart since data here need to provide the model structure in addition to the model estimates.

Furthermore, additional notable algorithms that can be explored include support vector machine (SVM) and K-nearest neighbor (KNN). First, KNN method classifies an object into a specific category by a majority vote of the object's neighbors, with the object being assigned to the class that is most common among its k-nearest neighbors. The output can be comprised by a specific property of the object, e.g., average of the values of its k-nearest neighbors. Meanwhile, the SVM algorithm depends on nonlinear mapping, i.e., transforming the original training data into a higher dimension where it becomes separable. Thereafter, it explores the optimal linear separating hyper-plane that is capable of separating one class from another, iteratively in this higher dimension. Overall, these algorithms correspond to non-linear classification methods depending on the category of kernel methods. It is important here to investigate the functionality of nonlinear mapping to a sufficiently high dimension, and study the hyper-plane data separation potential from different classes.

In MIMO-based UAV networks, channel dimensionally and spectrum assignment yield in various challenges such as channel estimation and spectrum bandwidth. Along this, regression models can be leveraged to estimate the channel parameters from a limited number of measurements from the high-dimensional search-problem. This extends to reduction of sparse high-dimensional structures using compressive sensing solutions such as the orthogonal matching pursuit and basis pursuit. Also, the co-existence of UAVs with other networks in urban environment imposes several challenges during handovers. Here UAV handover schemes can leverage KNN and SVM schemes to find the optimal solutions, i.e., achieving near-instantaneous rates with minimized latency levels at the control- and data-planes. Furthermore, these models can be applied to learn the UAV mobility and spectrum usage in diverse spatial-temporal settings. Thereafter, this can also be leveraged to forecast the location interface configurations of the UAVs using spatio-temporal, which enhances the energy and spectrum efficiency.

2) BAYESIAN LEARNING

Mixture Bayesian inference learning models can also be considered such as the Gaussian mixture model, expectation maximization, and hidden Markov models. First, the probabilistic Gaussian model assumes that the data points are constructed from a mixture of a finite number of Gaussian distributions with unknown parameters, where the models here incorporates information regarding the covariance structure of the data in addition to the centers of the latent Gaussians. Moreover, the expectation-maximization (EM) method evaluates the maximum-likelihood estimates for model parameters when the given dataset is incomplete or features unobserved (hidden) latent variables as compared to the conventional maximum likelihood estimation (MLE). It approximates the maximum likelihood function by two key procedures, i.e., the estimation procedure that selects a function that represents the lower bound of the likelihood and the maximization procedure that evaluates the parameters maximizing the chosen function.

Bayesian learning models can be employed for spectral characteristic learning and estimation in UAV networks. For example, it can be deployed to estimate pilot contaminations in massive MIMO UAV networks to enhance the spectral efficiency. Bayesian algorithms such as (expectation–maximization) can be utilized to gauge pilot contamination in massive MIMO based UAV networks. This allows to learn the channel parameters such as the weighted sum of the distributions of the received signals of the desired links in a target UAV coverage cell, as well as the interfering links in the adjacent UAV cells. Furthermore, EM algorithms can be deployed for spectrum sensing in cognitive radio UAV operations, i.e., cooperative wideband spectrum sensing schemes for the detection of primary users. This includes the investigation of the likelihood function of the unknown spectrum occupancy, along with the channel information and noise in the expectation procedure. Thereafter, the likelihood function can be maximized to infer the unknown information during the maximization procedure. This can be accomplished by jointly detecting the PU signal as well as estimating the channel's unknown frequency response and the noise variance of multiple sub-bands. Other estimation variables include the inactive states of PUs, signal strength levels, and channel availability for single and multiple transmissions in single and multi-path situations.

D. UNSUPERVISED LEARNING

In general, unsupervised learning techniques construct function inferences from datasets consisting of input data without labeled responses that describe the structure of unclassified (unlabeled) data. Developed models need to achieve accurate structure outputs in the presence of the unlabeled datasets, i.e., in contrast to the supervised and reinforcement machine learning methods. Here various clustering algorithms can be utilized for an enhanced UAV system performance such as k-means, mixture models, hierarchical clustering. In addition to neural network schemes, e.g., such as autoencoders, deep belief networks, Hebbian learning and self-organizing map algorithms.

Among main applications of unsupervised learning for UAV networks is clustering. As discussed earlier, UAV networks will coexist with various wireless networks that use conventional microwave and mmWave bands, thus resulting in overlays of various cell sizes. These dynamic cells need to be clustered to avoid interference, along with clustering requirements for the UAVs and the available spectrum bands, along with clustering requirements for ground users. Along this, clustering algorithm (e.g., k-means) can be leveraged to optimize network performance, The clustering here helps to reduce redundant traffic operating and decision making across the various overlaid networks. Moreover, the principal component analysis (PCA) method can be used for sparse channel estimation in massive MIMO UAV deployment. It achieved dimensional reduction that facilitate spectrum usage patterns and decisions.

Furthermore, independent component analysis (ICA) algorithm can be used as robust statistical signal processing techniques designed to resolve statistically independent signals from their linear mixtures such as the classification of the intended UAVs behavior. Thus ICA can resolve and separate the statistical properties of signals of different UAVs with distinct beam vectors.

E. REINFORCEMENT LEARNING

Reinforcement learning algorithms enable machines and software agents to effectively determine the ideal behavior within a specific context based upon specific feedback, i.e., in efforts to enhance and maximize systems performance. Namely, the agent determines the optimum action to choose based upon current state, where the iterative procedure here forms Markov decision process, as well as information from the reinforcement signal reward feedback. One major saliency in reinforcement learning is the focus on system performance, rather than input/output pairs (as in conventional supervised learning). This can yield in a balance between exploration and exploitation. Among the notable techniques that can be leveraged for UAV networks include multi-armed bandit and finite Markov decision processes (MDPs), partially observable Markov decision process (POMDP), and Q-Leaning algorithms. These algorithms can be leveraged for frequency selection and association in small cells, channel sensing, and network access. Moreover, MDP/POMDP algorithms can be utilized for UAV spectrum management. For instance, the limited spectrum and the time-variant channels are represented as the environment, whereas channel selection or spectrum utilization for multi-UAV can be classified as the actions. Efficient assignment models are required that consider available licensed or unlicensed bands, channel state, and channel access mode.

Furthermore, Q-learning algorithms can be used with the objective of policy learning, which can lead an agent to determine the type of action taken under specific circumstances. Q-learning algorithms here can be leveraged to develop self-configured and self-optimized UAV networks, i.e., taking into consideration resource allocation and interference coordination challenges. For example, developing schemes that maintain spectrum allocation awareness that allocate the available unoccupied spectrum chunks for the provision of opportunistic access. Then, choosing suitable sub-channels from the available spectrum pool and configuring the ground users supported by the UAV small cells. Further, Q-learning can be applied to study the spectrum usage state, i.e., composed of UAVs, resources blocks allocations, and channel state information and quality, where actions represent the transmitted power and channel bandwidth, whereas the reward is gauged by the signal-to-interference-plus-noise ratio (SINR) rates.

Finally, multi-armed bandits (MAB) schemes can be applied to model resource allocation (e. g., spectrum auction and opportunities access) under various UAV constraints. Resources are proportioned among competing projects whose properties are only partially known at the time of resource allocation, which may become known as time elapses. It is essential here to achieve a balance between exploitation and exploration at each instance. Namely, exploitation of the specific machine that has the highest expected payoff and the exploration required to extract additional information about the expected rewards of the other machines. Furthermore, the MAB scheme can be extended into a multi-player, multi-armed bandit game (MP-MAB), where the reward extracted by any player relies on the specific decisions of other players. Overall, this enables each user to predict upcoming actions of opponents based upon public knowledge; hence this knowledge can be exploited to determine best responses to the predicted joint action profile using bandit techniques. Overall, MAB and MP-MAB models can be leveraged for adaptive spectrum decision making in multi-UAV (multi-player) configurations, while knowing the channel conditions.

F. BLOCKCHAIN

Blockchain is a decentralized public ledger technology that allows transactions in a distributed peer-to-peer manner. It is composed of multiple chains managed by distributed nodes, where each chain consists of blocks that maintain an aggregated list of records, where a block features a body and header. The header contains the hash of the previous block. Likewise, the subsequent block header contains information on the header of the current block. This results in a chained block that resembles a continuous linked list, as per Figure 21 that depicts a common block in the blockchain. The block body contains a timestamp that records the time over which a block was created, a 32-bit random number (nonce) added by miners to achieve certain patterns in the block-hash, a Merkle root that stores transactions within a specific period via a hash binary tree mechanism and a 256-bit hash of the previous block. When the first block of a chain is created, a nonce generates the cryptographic hash, after which data in the block are considered signed and is permanently tied to the nonce and hash unless it is mined.

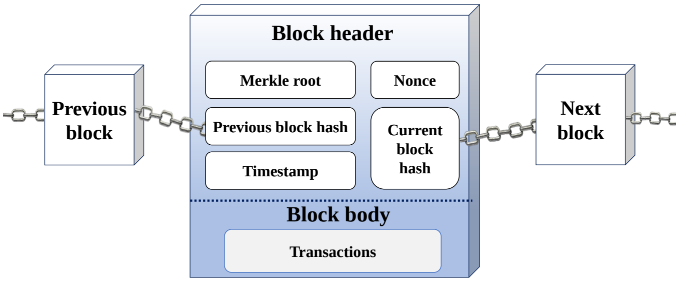


FIGURE 21: Structure of a block.

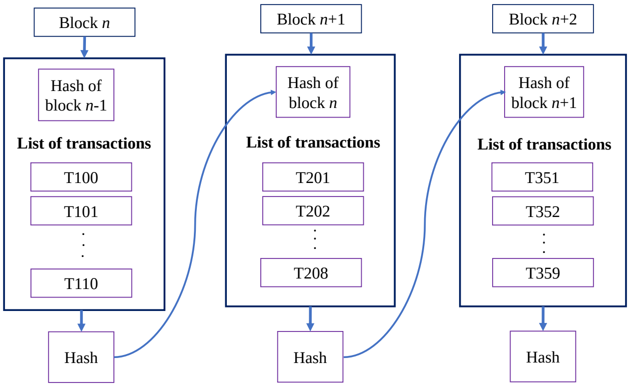


FIGURE 22: Interconnected transactions within a chain.

(1) Blockchain Features

Further, blockchain features key characteristics and goals [239], [240].

Replicated Ledger: Transactions are distributed and replicated among all participating nodes that package them into blocks. Thereafter, blocks are appended with immutable past. Each Now each block in the chain contains multiple transactions, where a block in the chain can be generated from any miner, while preserving the structure of the hash of the previous to the current block, as shown in Figure 22. When creating a block, the miner picks up the hash of the last block in the chain, combines it with its own set of messages and creates a hash for its newly created block. This newly created block now becomes the new end for the chain and thus the chain keeps on growing as more and more blocks are added to it by the miners. Note that introducing changes to any block earlier in the chain requires re-mining not just the block with the change, albeit all precedent blocks. Therefore, if a third party aims to tamper the contents of a block, then its hash will be invalid, since each transaction is time-stamped to secure tampering its chronological order without affecting the hash value of the block.

Peer-to-Peer Network: Participating nodes feature equal privileges that share the public ledger work synchronously to verify transactions using digital signatures. Namely, upon the creation of one transaction, it is then broadcasted to neighboring nodes for verification, followed by the verification that is exchanged among nodes, whereas it is discarded in the case of rejection. Transactions here are authenticated using an asymmetric cryptography mechanism based on the digital signature [241] that has verification and signing phases.

Consensus: Prior to the insertion of new blocks into the chain, all participating nodes in the network reach a consensus on the validity and the order of transactions within the blocks, thus eliminating the need for a centralized entity. Prominent consensus mechanisms include Delegated Proof of Stake (DPoS) [242], Proof of Work (PoW) [243], and Proof of Stake (PoS) [244]. Other consensus algorithms include Tendermint [245], Ripple [246], Stellar [247], Proof of Bandwidth (PoB) [248], Proof of Reliability (PoR) [249] and Practical Byzantine Fault Tolerance (PBFT) [250]. For further studies on these protocols, see the studies in [241], [251], [252].

(2) Blockchain Types

Blockchain systems have been broadly classified into three categories based on the ownership and the allowed participants in the verification and addition process [253], [254].

Public Blockchain: All the records are visible to the public, and everyone is allowed to participate in the consensus process, i.e., a permissionless consensus process. Public blockchains have the highest immutability attributed to the high number of participating nodes [253]. However, it has the lowest efficiency as compared to the other two categories.

Private Blockchain: Specific nodes from a certain organization are only allowed to join the network and the participate in the consensus process, i.e., a permission-based consensus process. It is regarded as a centralized network as it fully controlled by one organization. Private blockchain networks feature high efficiency, however the small number of nodes can make the network more vulnerable to tampering as compared to the robust public blockchain.

***Consortium blockchain**:* Only a few select organizations can participate in this category on a permission-based consensus process. Therefore, it is regarded as partially decentralized system of high efficiency, at the detriment of higher tampering vulnerability when compared to the public counterpart [253].

(3) Blockchain Benefits

Securing UAV Information: In general, blockchain can be applied to UAV networks to enhance the network security. For example, if an intruder UAV aims to modify data stored in blocks, then this requires recalculating the hash of all blocks in the chain, which requires huge processing power that is infeasible for an on-board UAV. Further, security is enhanced by the unique fingerprints and addressing mechanism of every block.

Securing UAV Infrastructure: Blockchain can secure ground and aerial UAV infrastructure against multiple threats such as spoofing, denial-of-service (DoS), man-in-the-middle, eavesdropping, and data tampering attacks. For example, the work in [255] shows that blockchain-based security model possesses higher performance as compared to other security solutions in terms of communication latency and cost. It designates one UAVs for block creation (termed as a forger node), while all other UAVs participate in block validation and verification using the PoS consensus protocol. A utility function based on game theory is used to select the forger node.

Data and Entity authentication: The nature of digital signatures in blockchain allows UAVs to communicate with each other through common channels without exposing data to hacking by third parties who can get access to the channel. Here UAVs can uniquely sign the collected data using their private key and broadcast it to the whole network. This enables data source and entity authentication between UAVs and third-party agents, i.e., allowing to trace the origin of data. This saliency is essential UAV swarm applications such disaster recovery [256].

Collision-Free Mobility: UAV networks require a high level of coordination to achieve collision-free operations to provide optimum performance levels. Blockchain here can be leveraged to store the spatial coordinates of all the UAVs in its database, thus by the stored database UAVs can decide optimal routes without any collision and with minimum interference. The work in [257] leverages blockchain to investigate the positioning accuracy and incurred delays for placement and distribution of cooperative UAVs.

Load Balancing: In inter-service operations, it is important to ensure uniform distribution of services between different vendors who lack trust among each other. Here the transparent electronic ledger nature in blockchain can be leveraged to alleviate this trust challenge, where UAVs can be assigned to their regions of operation based on load information of different regions, thus enhancing the uniform distribution. Another approach here is the set assignment of randomly generated non- overlapping coordinates which can be used when the load is dynamic [258].

Cooperation and Synchronization: Blockchain creates a common communication channel among participating UAVs that can initiate assistance requests from other UAVs in case of emergency, e.g., low battery, failure, malfunction, etc. Also, UAVs can adopt a distributed decision-making criterion that relates to traffic capacity, mobility, handover, relaying, backup, etc. Further, new UAVs can access the decisions stored in the ledger for use during synchronization instead of coarse training, which can save time and power. This can be suitable in a multi-terrain environment, where NLoS becomes more dominant and the number of visible UAVs becomes less, which yields in higher failure probability in UAVs. Moreover, Blockchain can maintain cooperation among different UAV networks that operate in the same environment, where they can securely share common communication channels [259].

(4) Challenges of Blockchain for UAV Networks

Despite the tremendous challenges that blockchain offers to UAV networks, there are still significant challenges that can impede a mature implementation of blockchain. This includes the following.

Limited Resources: Miners require a significant amount of processing power to execute blockchain consensus algorithms on UAVs. This further adds complexity and additionally carried payloads, which yield a computation burden on the batteries and storage units. This in turn can impact the flying mechanisms and service periods. Therefore, power-efficient blockchain algorithms are required for UAV networks to meet the limited available energy at the UAVs.

Latency: The information dissemination over blockchain-based UAV networks requires an aggregate number of links for data exchange between the UAVs. This can yield in exceed delay with the growth of the participating nodes. As a result, blockchain networks face challenges to support ultra-low latency for mission-critical and time-sensitive applications, despite the reliable transmission radio medium between UAVs. The delay here can provide adversaries with an ample amount of time to perform some attacks. Other challenges in blockchain-based UAV networks include network congestion, block size, and synchronization mechanisms.

XVI. SPECTRUM MONITORING

Spectrum Monitoring is an essential network entity that facilitates the spectrum management domains, such as sharing, sensing, auctioning, and access control. It controls the frequency assignment, reuse, determines frequency availability, interference control, security (e.g., spoofing attack) and privacy assurance, service quality, active and dormant cells, analyzes transmission patterns to detect any abnormal transmit power, characterizes emissions, and detects illicit transmissions, as well as coverage and capacity analysis, power usage and cost. Hence, spectrum management has a significant impact on network operations, spectral efficiency, QoS, and QoE. It also enhances the system robustness by actively tracking the network state such as actual usage state, occupancy state, transmit power, and location. It detects UAV abnormal behaviors. Spectrum monitoring requires active UAV nodes to continuously collect and report information such as spectrum usage and activity through data links (i.e., consoles) to other UAVs or network managers (e.g., aerial or ground base station). This allows the network to dynamically adjust spectrum decisions on sharing, access, scheduling, auctioning strategies based on the observed information, which further enhances network state, security, capacity, and quality. Moreover, it enables network operators to comply with real-time spectrum regulations through the series of monitoring, feedback, control, storing, processing, and decisions, i.e., thus forming a dynamic closed-loop control system. Based on the monitoring outcomes, the network demand UAVs to configure their spectrum usage in the uplink and/or downlink, adjust power emissions, antenna tilting, operating bands, and access mechanism.

A. SPECTRUM MONITORING NETWORKS

Spectrum monitoring networks can be either centralized using dedicated (specialized) equipment or distributed platforms via virtualization technology based on the pre-existing ground or air infrastructure. These solutions include the following.

(1) Cloud-based Spectrum Monitoring

Spectrum cloud servers support real-time monitoring to provide robust management for network entities, configuration information for UAV terminal nodes, thus acting as the spectrum core unit in the network that clusters all resources information and provides a sufficient database for dynamic decision making. Cloud servers enable dynamic monitoring for the time-variant wireless channels and calibrate the transmission of UAV devices and ground stations to cope with the network's abrupt changes such as failure and mobility. Spectrum clouds can be categories as either centralized or decentralized. In the first, all UAVs report their spectrum usage and activities to the closest station, which in turn report spectrum activities to be stored in a massive cloud-based datacenter, thus acting as a resource pool for all stations in the network. This adds scalable, flexible, and reliable shared computing services in case one of the reporting nodes fails. In the decentralized setting, each UAV node independently acts as a data center that forms a spectrum cloud. This results in local spectrum-related decisions based on reported information in neighboring clusters without global knowledge about the network's entire state. However, spectrum cloud can limit the network performance attributed to the aggregated transmission and propagation delays, where the large separation to the cloud core can yield a delayed spectrum state and lack of synchronization. Hence fog computing can be leveraged to alleviate the network delay.

Along with the local monitoring mechanisms, a global cloud-based spectrum monitoring approach in [260] aims to reduce communication overhead in a time-varying environment and supervise the behavior of transmitting stations by enabling sensor nodes to directly transmit monitoring data to the cloud domain. The approach aims to allow multi-dimensional data processing in the global network, without limitations to small-scale data. The work in [261] presents a cloud-based system-of-systems for spectrum monitoring in response to the notice of inquiry from the U.S. national telecommunications and information agency [262] regarding the spectrum monitoring pilot program. Spectrum management and monitoring are supported based on ontology descriptions that support the use of semantic techniques such as queries, responses, and reasoning. Further, authors in [263] also propose cloud-based information system architecture to realize an intelligent monitoring and spectrum management approach in the borderlands of China. This comes in efforts to overcome traditional monitoring schemes such as man-machine communication systems that are based on radio monitoring transfer protocol (RMTP), which are unable to detect and process the radio interference automatically.

(2) Fog-based Spectrum Monitoring

Fog computing proposed in [264] extends the cloud services to the edge of the network, thus providing storage and computing resources at reduced link delays. This allows

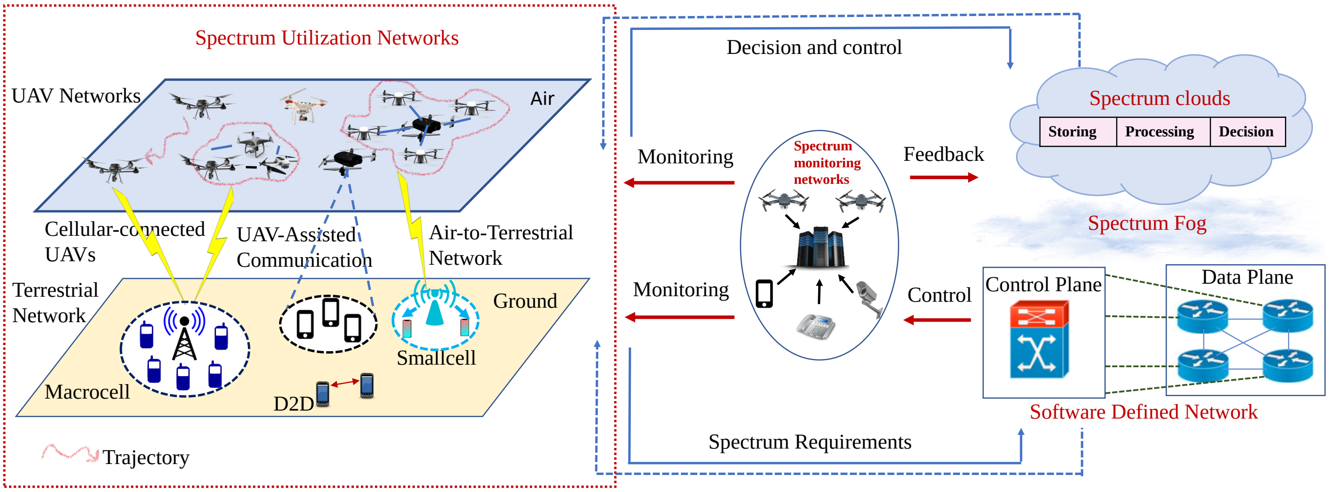


FIGURE 23: Spectrum monitoring networks.

in more recent spectrum state with access to synchronized database, which enables fast spectrum decisions and UAV usage adaptation. In centralized networks, spectrum fogs are highly dispersed and possess less processing capabilities versus the spectrum cloud solutions. Hence, at higher traffic densities and excess traffic, the control links can saturate fog servers and yield congestion at the network monitoring servers. Support and confidence-based (SCB) approach is proposed in [265] that optimizes the resource usage in monitoring services. A fog-based emulator with synthetic data examines real-time traffic use cases that show reduced resources consumption required for the monitoring services.

(3) NFV-based Spectrum Monitoring:

NFV deals with the delivery of network functions (NF) run over general-purpose equipment. As opposed to the general approach that deploys specific functions only over dedicated network equipment. This enables distributed network entities to locally monitor and configure the spectrum run as a virtual network function (VNF). This seamless and lightweight monitoring deployment supports the UAV's high mobility and rapid spectrum state, where authorized entities in proximity to the UAVs participate in the spectrum monitoring through network slicing after migrating the VNFs needed for monitoring. As opposed to conventional architectures that route spectrum state to the specific-hardware monitoring, NFV allows for dynamic on-demand monitoring by migrating related VNFs over the commodity hardware in the locations of interest (e.g., high density) or varied network topologies. Along with this, a modular programmable architecture is proposed in [266] based on SDN and NFV implemented over UAV infrastructure to allow dynamic deployment and migration of modular context-specific processing functionality. It supports high mobility and situational-awareness to pilots and payload operators during UAV missions, increases service continuity for vulnerable backbone networks, reduces latency of telemetry monitoring and applications related to situational awareness such as anomaly detection.

(4) SDN-based Spectrum Monitoring

In general, network operation is composed of a control plane that manages operations and controls traffic and a data plane that transmits throughput to UAV users based on the outcomes of the control plane. This requires the network to comprise two planes run by two separate entities. SDN decouples the control from the data plane in the network, which permits service abstraction and virtualization. This enables the direct operation over network elements of the data plane (such as routers, and switches) through a well-defined API. Instead, SDN proposes a three-plane communication interface, i.e., application, control, and data planes. The decoupling allows fast provisioning of required NFs over the network devices to be logically controlled by a centralized unit. This yields an inflexible network that adopts based on the demanded applications and environment state, i.e., adaptive with the underlying physical hardware.

Few studies have leveraged SDN for UAV networks. For instance, an SDN architecture is proposed in [267] for robust end-to-end connectivity such that UAVs are equipped with multiple interfaces (indoor and cellular), where the controller utilizes these interfaces for a multipath disjoint routing protocol, i.e., for failure resiliency. Further, the work in [268] presents an SDN-based flying UAV ad-hoc network (FANET) for rural zone monitoring, thus providing video monitoring as a service platform.

Despite the key saliences associated with SDN-based UAV networks such as reconfiguration and programmability, spectrum monitoring in UAV networks imposes design challenges that relate to dynamic variations in UAV locations, link failures, and on-board computing and power constraints [269]. This yields in demands for resilient, reconfigurable, and power-efficient monitoring networks in the SDN-based centralized UAV networks. For example, extended mobility results in prolonged propagation delay to the centralized control unit and requirements to increase the radiated power, which impacts battery life and interference. In [270], an SDN-based monitoring platform is proposed to monitor and collect link switching and routing information in UAV-ground backbone networks to develop a load balancing algorithm that maintains network service. The algorithm considers the power limit of UAVs and the global and local dynamic status in the network.

SDN-based monitoring introduces computing and communication overhead that results from the excess control signaling exchanged between the UAVs and SDN controller, this requires a large spectrum chunk dedicated for the control plane, thus reducing spectrum efficiency. Hence, the location of the controller highly impacts the monitoring process and network performance, e.g., the design of dynamic controller location that adapts and configures to the network topology. The optimum placement of the controller location here needs to guarantee optimum coverage and capacity, without limiting UAV mobility patterns or degrading their channel quality.

(5) UAV-based Spectrum Monitoring

The network manager can deploy one dedicated UAV with the sole function of spectrum monitoring. This allows mobility-based monitoring that is adaptive to the UAV user patterns and it also allows the detection of interferes in 3D maps [271]. Further, UAVs can monitor challenging areas that are difficult to detect with existing spectrum monitoring equipment such as an inter-mountainous base station, EIRP measurement, and canyon intrusion detection. Authors in [272]- [272] present two methods for UAV-based monitoring, i.e., wired UAV places in a vehicle and wireless UAV with mounted-antenna. The first is suitable for long-duration flights, with a low failure risk and low installation and maintenance cost, albeit limited and terrains. The wireless UAV allows wide-area coverage, flights in a short time, and a wider range of periodic measurements and detection capabilities. However, it suffers from short flight durations, higher failure, and collision risk. Overall, the UAV monitoring solution allows adaptive control that is close to the users, which yields reduced network latency. Here the battery lifetime compels a UAV monitoring downtime period during which the spectrum can suffer from gaps without monitoring until replacement in the UAV occurs. This yields security challenges during this transmission downtime period.

(6) Crowdsourcing Spectrum Monitoring

Crowdsourcing is a distrusted process that enrolls scattered users such as sensors, mobile stations, and UAVs to perform a specific task in the network operation. Here UAVs (crowd) work collectively to monitor and sense the spectrum. The disturbed monitoring nature allows for redundant monitoring nodes that are robust against node failures and allows fast reporting and decision making with challenges related to UAV authentication, risk of data manipulation, and increased control traffic.

A distributed monitoring approach (termed as Electrosense) in [273] adopts a crowdsourcing paradigm among sensors to collaboratively collect and decode spectrum data. The approach supports wide deployment areas, software modules for low- and high-end sensors, flexible architecture tuned for spectrum data management, and secure sensor deployment.

Likewise, crowdsourcing is also leveraged in [274] for white space spectrum monitoring. It aims to overcome limited deployment of spectrum observations and to eliminate the traditional sequential spectrum approach, improve monitoring efficiency and reduce energy consumption. It first categorizes users into incumbent primary users and secondary users that opportunistically access the idle spectrum white space conditioned interference-free emission to the primary users. The secondary devices concurrently use and monitor the spectrum with the coordination of a central controller, i.e., to reduce cost and achieve wide-scale monitoring. Further, an adaptive scheduling algorithm is developed that records past spectrum datasets to extract past spectrum access patterns and implicate future spectrum access. Here machine learning-based monitoring algorithms can be leveraged to learn spectrum access patterns.

Early mobile crowdsensing techniques for spectrum monitoring can be classified into two categories [274]. The first is hardware implementation [275], [276] that builds prototypes using commodity mobile devices, with a lack of assessment on monitoring performance. The second is a dedicated and fixed sensors approach [277], [278], where each sensor sequentially scans the spectrum. The work in [279] presents incentive schemes to attract mobile users to participate in the crowdsensing campaign, e.g., reward in terms of time and energy. This includes incentive schemes for collecting certain number of data samples through adjusting the reward [280], [281], schemes based on quality [282], [283] , and schemes that consider the QoI and credibility of the collected data [284], [285].

Crowdsourcing imposes various challenges on spectrum monitoring coverage due to the limited energy at mobile users and dynamics in the crowd distribution, e.g., the number of users within one area varies with time due to mobility and battery lifetime. The number of devices within an area that can be used to monitor the spectrum varies at different times and may lead to temporary insufficiency in local device numbers. Hence, the work in [274] proposed crowdsourcing-based spectrum monitoring for the large geographical area that leverages the power of masses of portable mobile devices and their occupancy patterns. The system predicts future spectrum utilization, after which it schedules spectrum monitoring tasks among mobile secondary users, thus saving energy of mobile devices and increases the monitored spectrum activities. A large-scale spectrum monitoring platform (SpecSense) for efficient querying of spectrum occupancy is proposed in [286]. It operates on low-cost and low-power commodity SDR/embedded platforms and provides data analytics in a central spectrum server. First, spatial interpolation techniques of RF signals in time-variant environments are developed to enhance spectrum occupancy queries. Further, the authors address the sensor selection problem to select the minimum number of spectrum sensors that can best estimate the spectrum at the requested locations with low overhead.

(7) Tomography-based Monitoring

Network tomography (NT) is a recent monitoring approach that predicts network performance and QoS parameters based on traffic measurements collected from a limited subset of network entities, e.g., link-level parameter prediction and traffic volumes estimation. It has emerged as a lean monitoring approach of lower complexity and traffic overhead, as opposed to the high monitoring overhead and resource consumption associated with conventional monitoring (e.g., IP-based) schemes. The decentralized monitoring mechanism here infers successive intermediate link metrics via in-network parameter estimation via network entities, which eliminates the need to forward raw statistics to the controller. This reduces the signaling traffic overhead while guaranteeing measurement consistency without additional control plane delays [287].

Authors in [287] introduce a synergistic interface combination between NT and SDN for monitoring purposes in 5G networks to fully leverage the built-in SDN functionalities of the programmable control plane and the OpenFlow switch polling without introducing additional specialized hardware. It is shown Further, the inferred information here can be utilized for traffic engineering, fault detection and management, load balancing, and SLA compliance applications. NT monitoring performs link-level parameter estimation based on end-to-end path-level measurements collected from the network edge without the involvement of the internal nodes in the topology. This is opposed to traditional monitoring systems that measure directly the performance of links with active probes, employing diagnostic tools such as traceroute, path char, and network characterization service (NCS), where these techniques impose high measurement overhead and demand cooperation from internal nodes. Also, NT monitoring conducts origin-destination path-level traffic matrix estimation based on link-level measurements (loads) obtained using the simple network management protocol (SNMP) under the network topology [288]. Along with this, NT monitoring systems have been tested for cellular networks and thus UAV-based systems are still lacking in the literature, taking into account the dynamic topology, limited on-board capacities, and mobility.

B. TYPES MONITORED SIGNALS

Along with the control and data signals, the radio spectrum is monitored to capture specific signals of interest that include accidental interference, intentional interference, illicit signals, and baseline signals [289].

Accidental Interference: This is attributed to electronics components and radio planning challenges, such as cell over-coverage due to adjustments in antenna elevation and azimuth and power levels. Other causes include passive intermodulation in signal carriers occur when two strong signals exist with some form of diode, harmonic distortion caused by faulty power amplifiers can broadcast a comb of signals over large portions of the RF spectrum.

Intentional Interference: This can arise from RF and GPS jammers and attackers that can interfere with UAV communications, cellular links, emergency services, and navigation.

Illicit Signals: Citizens band radio (CB) radios, amateur radio, and pirate FM broadcast stations attract the attention of spectrum regulators in terms of allowed operating bands and transmittable power levels, where surveillance and countermeasures are taken. Further, network operators and regulators monitor spoofing base stations, excessive radiated emissions from digital devices, and base stations transmitting on the wrong frequency. Another type of illicit signal is the one generated from the acoustic miniature (itty-bitty) transmitter. Baseline Information: Spectrum agencies and regulators demand from network operators to provide baseline information on the RF spectrum that shows the RF activity by frequency, shape, and time. This information is used to analyze spectrogram patterns linked to usage, interference, efficiency, capacity, and peak times.

Challenges of Spectrum Monitoring: A key challenge to spectrum monitoring is the increased signaling overhead to collect control and coordination information for both centralized framework and decentralized networks. This creates a burden on the UAV nodes to continuously report spectrum state, which can drain power usage. Also, the monitoring process adds challenges to the processing units and adds network latency.

XVII. SPECTRUM PATROLLING

Spectrum sharing allows opportunistic UAV users to coexistent with licensed and unlicensed bands, which requires fine granularity of time, space, and frequency to avoid interference and achieve high spectral efficiency and capacity. The open nature of the spectrum can result in unauthorized usage for some nodes (UAVs). This requires enforcement policies to ensure fair and rightful usage of shared frequency bands regulated by federal, civilian, or enterprise. This is realized by spectrum patrolling that protects licensees from encroachment by granting them exclusive rights to communicate on their bands licensed spectrum and detects any violations in signal transmission, thus acting as the law enforcement agency for spectrum operations. Spectrum patrolling aims to detect unauthorized spectrum use or access in licensed or unlicensed bands such as transmissions in unauthorized bands, transmitting harmful signals, non-compliant transmitting, jamming, and malicious attacks targeting terrestrial and aerial UAV networks.

Spectrum patrolling involves signal detection and thereby existing spectrum patrolling techniques leverage crowdsourcing (or crowdsensing) [290]- [291] for detecting spectrum violations. These techniques collect spectrum usage data and enhance spectrum efficacy while selecting suitable nodes (UAV) with sufficient power and reduced operational cost. Moreover, crowdsourcing harnesses the collective power from participating nodes in the crowd, where patrolling decisions are dependent on nodes' proximity and quality of evidence. The latter also depends on the node's ability and willingness to accurately witness and record spectrum violations and non-compliance [291]. The distributed crowd nature assists spectrum enforcers and policymakers to collect infraction activities in varying locations at which the cost of spectrum patrolling is high (e.g., cost of infrastructure) as it is difficult to install static detectors at each location. Here crowdsourcing is compelled to model the spectrum of individual nodes that impacts the patrolling performance. For instance, the assignment of spectrum sensing to a specific sensor (UAV) is contingent upon its detection probabilities and false alarm rates, along with configuration cost that incorporates [292].

Another challenge in spectrum sensing-based crowdsourcing is the UAV selection and fusion in which local sensor decisions are fused to form a global decision. Existing schemes assume that sensor decisions are conditionally independent, which may not hold in spectrum sensing due to the correlated observations in sensor locations [292], which results in similarities in sensing decisions.

First, the work in [293]discusses the general premise of spectrum enforcement with a focus on ex-ante and ex-post paradigms of enforcement. Authors in [294], discuss the requirement and design criterion for federal frequency bands that are crucial for practical implementation, without proposing enforcement strategies. In [295] an enforcement strategy is proposed harnessing coding theory and detection against infractions.

The work in [291] aggregates reported violations from distributed heterogeneous nodes in efforts to enhance the credibility of the evidence, locate the source of infractions with high accuracy and lower the frequency of policy infractions over time. The efficacy of the patrolling system highly depends on the accuracy of evidential information and the speed of adjudication. Hence signal detection here is based on a pre-defined SNR threshold, termed as operating points (OP) that is selected by the enforcer (e.g., service providers) to detect spectrum infractions.

Authors in [292] leverage machine learning to develop spectrum sensing models for signal detection. Namely, the maximum relevance minimum redundancy (MRMR) algorithm [296] processes sensor's configuration and SNR as input dataset, after which it estimates detection performance and cost. Also, a technique for sensor selection and fusion is developed that assumes conditionally independent sensors, without prior information on the sensor locations. Convex optimization and greedy node selection approaches are introduced in [297], [298], respectively, to select the nodes that participate in the patrolling process. Fusing and decision-making techniques include multiple sensor decisions in [299], a collaborative sensing approach across multiple nodes to patrol the spectrum [296]. It is shown in [300] that detection of intermittent transmitters is improved by collective fusing from multiple nodes.

XVIII. SPECTRUM ENFORCEMENT

Spectrum sharing comprises various sets of heterogeneous wireless users of different access schemes, priorities, QoS, subscription, application, and lifetime. The coexistence of these users in a common scarce source implies security and privacy challenges, at which spectrum enforcement becomes a critical component to assure the spectrum of fair and proper use. Along with this, spectrum enforcement aims to maintain the validity of spectrum sharing. This includes the following as discussed in [301], [211], [302].

Confidentiality: The Spectrum database (service provider), exchanged signals between users and signals between registered users and database must maintain information confidentiality against disclosure to unauthorized users.

Integrity: The data stored in the database and communicated among users should be protected from malicious alteration, insertion, deletion, or replay.

Availability: Users need to access spectrum and its database when required.

Authentication: Spectrum entities and components need to verify user identities and credentials and establish a database for authorized users.

Nonrepudiation: Users must be unable to deny the reception of transmission of signals to the shared spectrum, as well as not denying spectrum access at a specified location and time. Compliance: The network needs to detect non-compliant activities that cause harmful interfering signals.

Access control: Users need an access mechanism and validated credentials to enter the spectrum database.

Privacy: Privacy deals with the protection of sensitive and private information of the UAV and UE and other entities that share the spectrum.

A. SPECTRUM SECURITY AND PRIVACY THREATS

Spectrum access and sharing can be susceptible to various security and privacy threats as studied in [302].

Spectrum Data Falsification: Spectrum sensing approaches are susceptible to spectrum sensing data falsification (SSDF) attacks in which malicious adversaries transmit false observations about the propagation environment [303], [304]. Consequently, a secondary user that senses the spectrum acquires an incorrect perception about the propagation characteristics, which leads to inaccurate transmission decisions that deteriorate communication links. The primary user emulation (PUE) attack [305], [306] is one attack in which an adversary emulates signals of legitimate users and illegally forces other secondary users to vacate the spectrum.

Beacon Falsification: Control channels can be vulnerable to attacks from rogue transmitter, thus corrupting the control channel through DoS attack [307], [308]. Spectrum coordination requires beacon signaling to announce the presence of secondary users that require spectrum coexistence and sharing. Here a malicious adversary can conduct a beacon falsification attack to disrupt vital network functions, such as intercell spectrum contention and intercell synchronization [309], [302].

Back-off Windowing: Carrier sensing can be deployed for collision avoidance in spectrum access. Following the sensing procedure, users back off at a random time before transmission. If a collision of transmitted signals occurs by any two users, then users double the backoff window and retransmit. However, a malicious user can use a small backoff window attack and gain priority over other users [310], [311].

Lion attack: A malicious adversary can launch attacks to force the target UAVs or base stations to perform frequency handovers, thereby causing transmission interruptions attributed to the handovers that can further cause aggregated delay, degraded throughput, and bandwidth deficiency.

Location Privacy: UAVs are equipped with geo-location capabilities to facilitate spectrum access and sharing. For instance, secondary UAV users need to transmit location information to the database to receive information on the set of available channels in their region. Therefore, their location privacy can be threatened by an untrustworthy database and location inferring attacks [312], [302], which allows an attacker to infer the UAV location from the used channels. Furthermore, spectrum database faces privacy threats as drafted by the Internet Engineering Task Force (IETF) [313]. This includes the following.

User Masquerading: In the absence of robust protection protocols, an attacker can modify a device to masquerade as another certified device. This enables the attacker to listen to spectrum registration exchanges, and later register with the database by claiming the identity of another user.

Spoofed Database: The spectrum database can be spoofed to enable malicious responses users that suffer from increased levels of interference.

Modifying Access Query: If an attacker changes query information of the secondary user such as the location, subsequently the database responds with incorrect information regarding available spectrum or maximum allowable transmit power, thus causing interference to primary users. This attack also applies to access responses from the spectrum database.

B. SPECTRUM ENFORCEMENT MEASURES

The aforementioned attacks, infringe usage and threats require spectrum enforcement countermeasures to enable secure and safe spectrum operations, including preventive and punitive measures [302].

(1) Preventive Measures

Reasoner-based Spectrum Policies: Spectrum control compels user transceivers to adapt to access policies based on incumbent security threats in the occupied bands. This requires reconfiguration in the equipment firmware against unauthorized modification and rogue transmissions. This firmware needs to evolve with spectrum access policies and rapidly vary application requirements by decoupling the spectrum policies from device-specific implementations, i.e., firmware in users' devices invokes adaptive situational actions based on policy specifications and current spectrum environment [314], [302]. Decoupling mechanisms are carried out by specialized software modules termed as policy conformance components (PCCs) [315], where policies are interpreted and transmission strategies are determined to enforce these policies using reasoners. The latter can leverage a rule-based policy to encode the axioms of the new enforcing policies [316], [317], [318]. Note that one limitation here is the added overhead and policy's interoperability challenges, since rule-based policies do not support the sharing of policy structure among different service providers. Therefore, complex spectrum policies become difficult to specify and manage [302]. Alternatively, ontology-based policies can be used for spectrum access rules [319] to overcome these challenges.

Tamper Resistance Methods: They protect UAV UE software against unauthorized modifications as proposed in [320] against thwarting static attacks, where static information is extracted by examining the software codes. Authors in [321] employ power fingerprinting approach to perform integrity assessment of software-defined radios (SDR), where it detects tampered executions by patrolling the power consumption of the radio platform.

Exclusion Zones: This is a regulatory approach that employs spatial regions without permitting secondary users to emit in-band transmissions [322]. Here primary and secondary users agree on the exclusion zones to arrange spectrum sharing without interference.

Privacy-Preserving Methods: Several privacy preservation algorithms can be applied to UAV networks to overcome the aforementioned threads related to geo-location-based UAV access. These solutions exist in the context of other applications and thereby research efforts are required to apply them to UAV networks. One common solution is the perturbative masking (randomization) method [323] that intentionally adds distortion via noise to mask the attributes and records of users. Other prominent privacy-preserving algorithms comprise generalization-based syntactic model such as k-anonymity [324] that deals with relational data privacy [325], l-diversity [326] and t-closeness [327] that use suppression to increase the granularity of data representation in order to preserve the privacy of sensitive data [302]. Differential privacy-preserving algorithms [328] deliver semantic privacy models with strong protection guarantees that capture the amount of disclosed and published sensitive data. These algorithms can be applied to preserve UAV location privacy from untrusted service providers in location-based services. Furthermore, location privacy can enhanced by risk mitigation techniques [302]including transmission of a time- or space- obfuscated version of user actual location [329], applying mix zones to hide user location [330], sending fake queries that are indistinguishable from real access queries [331], and applying anonymity to location privacy [332], [302].

(2) Punitive Approaches

Violations in spectrum usage result in punitive enforcement measures that are designed to remediate malicious or unauthorized acts. Here enacting punitive actions occurs in three phases identification, localization, and punishment [302].

Identification of Rogue Transmissions: Spectrum regulators such as the FCC enforcement bureau first need to recognize non-compliant, malfunctioning, and rogue transmissions and distinguish them from authorized and compliant transmissions. Therefore, UAV users need to incorporate physical-layer authentication schemes that are robust against circumvention by adversaries, in particular intrinsic and extrinsic schemes. The first leverage intrinsic features of the waveform or channel medium as unique signatures to authenticate and identify transmitters, such as include RF fingerprinting, and electromagnetic signature identification [332]– [333]. Meanwhile, the latter extrinsically embeds an authentication signal (authentication code or digital signature) to the transmitted signal, which can be retrieved by the intended receiver. Authentication schemes that need to be examined in UAV networks include watermarking [334]– [335] and transmitter authentication [336]– [337]. Note that extrinsic authentication schemes result in signal superposition by conceiving the added authentication signal as noise [302], which can degrade the SNR and adds constraints to power control.

Localization of Rogue Transmissions: Localization follows the identification of non-compliant rogue transmitter. A key challenge here is that non-compliant transmitters do not report their legitimate location to service providers, where these transmitters may manipulate their location information. Hence non-interactive localization techniques are required here due to the non-cooperative nature of the rogue UAV transmitters.

Punishment of Rogue Transmissions: This phase aims to impose a penalty for the noncompliant transmission [338], [293], where the efficacy of deterrence against rogue transmissions depends on the probability and severity of punishment when the perpetrator is identified. Furthermore, the cost of the spectrum vandalism needs to be gauged to determine appropriate punishment levels, while considering implications of imperfect enforcement [302]. Two major methods exist for punishing non-compliant transmitters that can apply to UAV users [338], [339]. First, rogue transmitters are not allowed to access the spectrum for a specific amount of time that is commensurate with the severity of the spectrum harmful act, e.g., revoking spectrum license. Second, economic punishments such as fines can be imposed that is also proportional to the severity of the harm.

XIX. OPEN RESEARCH DIRECTIONS

Despite the efforts in the domain, there are still essential open research areas that require further investigation before the development of UAV networks. In this section, some of the key open research areas are summarized.

A. RADIO FREQUENCY (RF) PLANNING

RF planning is a key spectrum management tool that involves selecting sites for radio equipment installation, configurations, and spectrum assignment on each cell. The goal is to provide adequate coverage, high service quality, and efficient use of spectrum. Due to the dynamic structure of UAV networks, multiple challenges arise in UAV cell planning and the structure of the cells. These cells will vary based on applications, coverage areas, number of UAVs, and their altitude, mobility, and density patterns. Hence ground-to-air communication requires further investigation when integrated with 3GPP networks at a wider scale. The dynamic behavior of UAVs will impact the traffic and coverage analysis, expected capacity, type of traffic collected, growth, and updated traffic and coverage analysis. Analytical models for UAV RF transmission footprint are highly required here.

Furthermore, the dynamic network topology in UAV networks deems rapid variations in cell shapes. Another aspect that adds to the dynamic topology is the short battery life and limited payload capacity of UAVs, e.g., UAVs can hover and fly at varying speeds and altitudes, which results in aerial dynamic network topology. Furthermore, the altitude dimension allows for multiple UAVs to exist at different levels, which can form overlaid UAV networks. For example, multiple UAV networks can coexist, thus forming overlaid hierarchical layers of UAV networks. Along with this, multi-tier spectrum sharing models can be developed here that incorporate dynamic decision-making based on UAV configurations, positions, and UAV trajectories. Existing spectrum sharing models in [340]- [341] need to be implemented in the context of UAV networks.

B. SERVICE DISRUPTION AND DOWNTIME

The varying topologies and orientations of UAV, along with the assigned spectrum can yield service disruption and discontinuity, which is intolerable for mission-critical applications. Therefore, it is essential to have developed low-latency, proactive, and scalable spectrum management to handle dynamic network changes without abrupt service disruption, e.g., during handover and network transition. For example, microwave frequencies can be leveraged for control and non-payload transmission due to the robust propagation characteristics. Further, it is essential to assure network isolation, scalability, and QoS.

Spectrum downtime (operation and maintenance) is defined as the periods over which the UAV is not in operation due to maintenance, mobility, low battery lifetime. Here it is vital to develop operation and maintenance approaches for UAS systems with dynamic spectrum allocation, the maintenance lifetime, and density of spectrum allocation during UAV downtime.

C. SPECTRUM LICENSING MODELS

The FCC spectrum policy task force defines three models [342] for spectrum management. First, the command-and-control model assigns frequencies for specific uses, which are constrained by rules that limit the characteristics of transmissions. The efficiency of this model is enhanced by spectrum and information efficiency and by spatial reuse technologies. Second, the exclusive use model provides the licensee the rights to the spectrum within a defined geographic area and then that licensee manages that spectrum for its optimal use, transferring the right to use it, e.g., mobile phone networks [343]. Finally, the commons model allows significant numbers of unlicensed users to share the spectrum where usage is governed by technical standards or protocols. There is no right to protection from interference. The wireless applications are authorized for parts of the ISM band. Along with this, these models need to be revisited in the context of UAV systems coexisting with 3GPP networks, at various geometries, altitudes, density, speeds.

D. DESIGN OF RF CIRCUITRY

The spectrum designation impacts the design of electronics in UAV transceivers. As per the selected frequency, variations occur in circuitries for signal generation, antennas, filtering, and size. For example, a ±0.01 % drift in a 1 MHz carrier signal has a variation of 200 Hz, whereas the same drift in a 1 GHz carrier signal would be 200 kHz [343]. Further, filter design highly depends on operating frequencies, e.g., a measure of the quality of a bandpass filter (Q-factor) and bandwidth. The circuit construction and size of components will also differ and impact the weight of UAVs. For instance, the selection of upper bands yields in reduced sizes at the expense of higher cost and complexity, e.g., circuit components approach wavelength dimension and acts as antennas, thus interfere with themselves and generate/transmit signals that interfere with other devices.

E. NETWORK SLICING AND SPECTRUM ISOLATION

In ground-to-air networks, virtualization enables the physical nodes to accommodate various network functions, thus replacing dedicated hardware. As a result, network providers can be tenants that share common infrastructure, i.e., sharing cell sites, which yield an efficient deployment and operation over a common physical infrastructure. These virtual network functions (VNF) are offered as slices for deployment over the physical network. Hence conventional infrastructure is converted into a general-purpose architecture that runs VNF instances for various NFs such as spectrum management, baseband processing, mobility, and handover management. The slices are customized as a logical network to support service level agreements of various service operators. Each slice represents a specific VNF instance, which may also vary the spectrum requirements. Hence sharing the physical resources requires dynamic spectrum allocation and spectrum isolation at high spectrum efficiency, while considering scalability at the increased number of tenants, investigating system complexity, and repeated configurations, which can also yield in processing delays and denial of service, as compared to dedicated resources. Here network slicing is transparent to end-users, which must assure low latency and security in the isolation process, in particular for mission-critical applications.

Spectrum allocation can include static fragmentation per radio resource, where all slices use the same chunk, regardless of deployed VNFs. This approach guarantees spectrum isolation, albeit inefficient resources utilization when slices require fewer bandwidths. Moreover, different radio access technologies may be required per installed slice, as per the network operator, subscription, and required service. This compels the general-purpose hardware to accommodate various access technologies. Another method is the dynamic assignment based on the hosted VNFs in the slice, this allows higher utilization at the detriment of isolation challenges. Further, it is interesting to study the content-popularity and granularity level of required VNFs run for different tenants, which can allow for a single instance serving multiple UAVs.

Network slicing allows the utilization of ground physical resources for UAV networks, i.e., shared between ground cellular networks and UAV networks, i.e., in particular when ground networks have access capacities. Moreover, spectrum assignment methods are required to achieve spectrum and traffic isolation over the multi-tenant network, in particular the frequency allocation to carriers (resource blocks) to provide sufficient coverage and service for the UAV footprints and spatial distribution.

Overall, network slicing efforts in UAV networks are still in the early stage and limited to testing effectiveness and feasibility, e.g., separation of control and payload slices [344]. Work in [345] investigates applications of flying modes in the frame of a 5G network supporting network slicing and virtualization. In [346], network slicing is enabled with differentiated QoS support for UAV applications. Authors in [347] formulate a network slicing problem that general-purpose slice that accommodates various applications. Then deep neural networks and optimization methods are leveraged to provide logical UAV slices customized for specific requirements at low latencies. Along with this, new studies are required for VNF slicing and isolation, taking into account the type of virtualization method (e.g., hypervisors and virtual machines) and service function chaining.

F. BEAMFORMING DESIGN

Beamforming technology enhances network coverage and user capacity and reduces interference levels, which allows spectrum reuse and extends the use of dormant bands. Beamforming designs are based on phased arrays and precoding solutions that need to match with the onboard capabilities and available power for UAV transceivers. First, UAV networks can possess more LoS links versus terrestrial networks. Hence, transmit diversity based on digital or hybrid beamforming can be inefficient, due to lack of obstacles and reflections, thus resulting in a poor scattering signal profile. This motivates the design of power-efficient beamforming designs that enhances the throughput and can achieve efficient spatial multiplexing, i.e., to better exploit spectrum resources. One attractive solution for UAV transceivers is the adoption of analog beamforming, time-division multiplexing (TDM). Hence studies need to investigate the latter for UAV networks while investigating spectral efficiency and sum rates.

Further, various operating bands require specific beamforming architectures that comprise different geometries, aperture sizes (impacting the number of impinged spatial signatures), directivity, and gain. Also, the operating bands entail radiation patterns and sidelobes. In UAV networks, sidelobes can play a major factor in interference with ground base stations. Here the design of low sidelobe levels is an open research area, e.g., utilization of circular arrays. Existing beamforming designs for UAV networks are limited to hybrid structures that support millimeter wave bands (mmWave) [348]- [349], with a focus on capacity, sum rate, and SINR performance. Hence there is a pressing need to propose beamforming designs that address the various challenges mentioned here.

G. INTERFERENCE MITIGATION

Three prominent types of interference can arise in UAV networks. First is the uplink interference, where low altitude UAVs can suffer from leaked radio signals transmitted by ground base stations, i.e., antenna down-tilting includes undesired sidelobes in the boresight directed towards UAV networks. Second, downlink interference on ground UEs due to UAVs transmission to ground stations. Third, UAV-UAV interference (UUI) between adjacent air cells.

Various interference management can be applied for UAV networks. One approach is to develop power control mechanisms such that the received power is sufficient to demodulate the signal only, with distinct levels for control and data channels. The power levels need to be aligned with the propagation paths and separation distances, considering UAV density, separation distances, and available power at ground base stations. Here open loop power control can be more applicable to real-time applications in UAV networks when slow variations are prominent in the received signal. Meanwhile, closed-loop power control can be applied to delay-tolerant and data computation requests, where the power level is adjusted based on target SINR levels. Further, the open-loop can be used for control signaling in UAV, leaving the closed-loop to the data plane, particularly for cellular-UAV networks. Also, the enhancement of the receiver sensitivity, antenna efficiency and design of physical aperture contributes to reduced power levels, without redundant levels that can cause interference, which in turn enhances the battery life at the UAVs.

Beamforming can be beneficial in mitigating interference effects, where radiated beams need to focus energy to the desired spatial direction. Along with this, the development of antenna arrays for UAV networks is vital, where designs need to feature symmetric patterns, minimum side and back lobes, and low insertion and return losses, e.g., the use of a uniform circular array seems a suitable approach for UAV, as opposed to uniform or rectangular arrays that suffer from enlarged sidelobes. Further, sidelobe suppression techniques also apply here, along with filtering and windowing techniques. Other approaches include joint-UAV inference detection, RF planning, frequency reuse, direct sequence, and frequency hopping. Additional conventional interference types can also be present in UAV networks, likewise to any wireless system that deploys RF circuitry for radio propagation. This can include intermodulation interference due to non-linear behavior of some components that distort the signal, self-interference attributed to simultaneous transmission and reception over the same channel (full-duplex modes), adjacent channel interference (ACI) due to out-of-band leakage. Further, it is vital to extend the aforementioned inference mitigation to inference exploitation, cancellation, and avoidance. The UUI can be more dominant due to the enhanced propagation conditions, e.g., reduced blockage effects, and dominant LoS links.

Existing interference management research for UAV networks focus on coordination and cancellation mechanism. First, authors in [350] investigate inter-cell interference coordination (ICIC) in air-ground networks to maximize the weighted sum rate by jointly optimizing the power allocations. Likewise, power control is optimized in [351] for interference coordination, while considering UAV flying speed, altitude, and collision avoidance. Other efforts develop interference avoidance mechanisms such as the work in [352] that plan the optimal positions and distributions for single and multiple UAVs at maximized signal-to-interference-ratio (SIR). The work in [353]- [354] propose a cooperative interference cancellation method for uplink cellular-based UAV networks between adjacent co-channel BSs, i.e., formulates the achievable rate function of the UAV's transmit power. Further, cognitive radio (sensing approach) is deployed in [355] for interference coordination, i.e., by treating terrestrial users and UAVs as primary and secondary users, respectively. Finally, it is also essential to look into interference exploitation [356], [357] and its benefits (e.g., sidelobe exploitation in [358]) in the context of UAV networks.

H. SPECTRUM AGGREGATION

The growth of UAV networks will require them to support high data capacities at one stage. One approach to cope with the growth in data demand is spectrum aggregation that enables multi-carrier transmission by gathering scattered and discrete (disjoint) spectrum fragments into a wide chunk. First, non-contiguous intra-band allocation refers to few gaps within the same operating band, whereas non-contiguous inter-band refers to gaps between different bands. Further, contiguous intra-band aggregated channels from the same band without separations thus forming a single enlarged channel. In general, this yields in capacity and coverage maximization, efficient spectrum utilization by reducing the number of unused frequency blocks, increased network revenues and enhanced QoS, higher peak data rate and throughput. Spectrum aggregation here can support high bandwidth communication using discontinuous bands, Here the configuration of component carriers can be independently applied on the uplink and downlink, depending on the usage requirements. The aggregated spectrum can be contiguous or non-contiguous, applied to both intra- and inter-bands. When applied to UAV networks, various scenarios and challenges arise. For example, in the contiguous intra-band assignment, two ground base stations can provide two links on two carriers to enhance coverage and mobility, where one carrier can be static for continuous macro coverage and dynamic (tracking) for abrupt mobility. while achieving load balancing at the stations. Further, noncontagious intra-band can be supported for marginal improvement in through puts, such as aggregating truncated frequencies that arise from poor channel assignment or abrupt traffic patterns. An example of a noncontagious inter-band is the support of a control plane by a microwave link and data plane by mmWave link, or between cellular links and local area networks.

Spectrum aggregation can yield various challenges when applied on UAV networks. This includes timing and synchronization of the multi-carriers, variations in the path lengths due to the dynamic UAV patterns, which continuously vary the channel statistics. Further, aggregation over wide-band (e.g., mmWave bands) results in challenges for the transceiver design at the UAV. This includes nonlinear increment in path loss at the higher frequency, Doppler shifts, Noise power, and spurious emissions, selectivity, and adjacent channel leakage. The latter complicates the design of multiplexers that requires simultaneous parallel transmit and receive radio fingers (antennas), which further requires more input power. Further, design in filters includes sharp cross-spectrum isolation to prevent interference between aggregated non-contagious bands, i.e., attenuating out-of-band signals for each carrier to prevent excess undesired energy on other bands. Hence the design of multiplexers, frequency splitters, and filters with low insertion losses and high cross-spectrum isolation and for UAV networks remains an open research area, i.e., applied for different carrier spacing and band allocation.

I. SPECTRUM BORROWING

Spectrum borrowing refers to the temporary lending of unused or dormant frequency bands to congested zones from neighboring cells. This borrowing procedure follows spectrum assignment from the resources pool. Hence it is a dynamic spectrum allocation technique that enhances the network capacity and provides service continuity at abrupt traffic congestion. Borrowing here occurs between the same or different ground and aerial UAV networks or between UAV-to-UAV networks, such as in the case of overlaid networks. In dynamic channel assignment, each cell is initially assigned spectrum based on traffic models, UAV mobility patterns, locations, applications, and ground user density. This results in uneven spectrum partitioning that can also lead to load imbalance among ground base stations and UAVs. Hence selective channel borrowing strategies for load balancing is an open research area for UAV networks, where unused spectrum is migrated from the under loaded zones to the overloaded ones while investigating borrowing decisions, dynamic thresholding, borrowing periods, spectrum locking, and co-channel borrowing loops.

Furthermore, the study of traffic densities, cell load levels (high, moderate, low) and UAV patterns per geographical areas, classification and selection criteria of lending stations, and borrowing regulations, borrowing revenue for and cost for both donor and lending networks, along with request network functions is further required to specify the spectrum allocation and borrowing procedures. It is also important to investigate the power penalty and budget at the donor ground or aerial stations, study co-channel inference models, and whether additional transmitters are required at the lender's sites to use the borrowed set of channels.

J. SPECTRUM PARTITIONING

Spectrum partitioning is important for co-existence between multi-tenant UAV networks and the spectrum between UAV and cellular networks. Partitioning techniques for UAV networks can either be static (offline) that pre-provision spectrum chunks before the start of service or online (dynamic) based on incoming traffic, peak loads, required bandwidths. Here both techniques need to be applied on UAV networks considering applications, traffic models, mobility, network topologies, fairness, convergence, and time-varying UAV channels, channel selection, subframes and transmit power control.

K. SPECTRUM BREATHING

Self-organizing spectrum breathing mechanisms are required for UAV networks to promote effective admission control, service continuity, and load balancing among UAVs. Spectrum breathing pertains to adaptive adjustments to cell bandwidths, boundaries, and coverage areas using beamforming architectures and power control mechanisms. Here it is essential to develop breathing techniques for UAV networks considering spatial traffic distribution, congestion scenarios, coverage prediction models, user association, user privacy and security, breathing boundaries and cell margins, average offloading time and latency, cost and capacity rates at participating UAVs, along with the associated loads. Further, offloading schemes are required from ground stations to UAVs or between UAVs.

L. DUAL POLARIZATION

Spatial polarization diversity can be realized using dual-polarized transmissions via beamformers, thus providing azimuth and elevation 3D planes. Here UAV networks leverage a high probability of LoS links with reduced reflections and scattering, this maintains wave isolation and reduces polarization leakage and disorientation of the propagated perpendicular plane waves. Therefore, the cross-polarization and self-polarization effects are less dominant in UAV operations as compared to ground-rich-scattering networks. This opens a potential for efficient spectrum assignment by doubling the spectral efficiency and throughput without extending assigned bands, i.e., allowing dual (non-interfering) multiplexing channels on the same frequency slots. Along with this, power-efficient dual-polarized beamforming architectures are required for UAV transceivers that consider mobility and altitude.

Furthermore, it is important to investigate the type of polarization for UAV transceivers (e.g., linear, circular, etc). The low scattering profile in UAV networks promotes linear polarization, whereas, in cases of high reflection and signal loss, circular polarization can be more suited, links in UAV to ground or links in swarm UAV networks. Also, circular polarization can be more suited at higher altitudes, where the wave spinning nature in 2D can be more robust versus the 1D linear counterpart.

The work on polarization diversity in UAV networks is limited to [359] that studies polarization behavior of UAV-to-ground links over multipath environments using ray-tracing simulations. Other efforts focus on polarized antennas for attitude determination [360] robust transmission [361]. For example, the latter estimates the relative attitude between two UAVs based on polarized MIMO transmissions, where the goal is to extract Euler angles at reduced estimation errors and moderate SNR ratios. Along this, polarization diversity needs further investigation in the context of UAV networks, see [362]- [363] for background studies for polarization deployment in wireless technologies.

M. NETWORK ACCESS

Spectrum users need to discover available spectrum before network association. Namely, ground base stations periodically broadcast bearer signals, or beacon signaling from access points and UAVs. The potential of beamforming-based UAV transmission triggers directional transmission and reception modes, i.e., the absence of Omni-directional transmission. Therefore, the discovery of bearer or beacon signals becomes challenging. Here the UAV and other entities are compelled to perform a spatial search to detect the presence of control bearer signals. This yields increased computational complexity and signal measurements at beam directions, prolonged search times, and extended-spectrum occupancy during the control plane. Hence UAV networks require fast and adaptive access schemes that yield in short times and lean spectrum occupancy rates, which also saves power and energy consumption. Here metaheuristic algorithms and compressive sensing tools can be leveraged to reduce the search complexity and yield faster access. In [364], information broadcasting, access, initial attach and detach procedures are defined for LTE networks, where similar procedures need to be developed for UAV networks.

Existing work on network access is limited to joint user association to achievable rates, network delay, and sum rates, without addressing the aforementioned factors. For instance, user association scheduling and power allocation are optimized in [365] with a terrestrial and aerial BS suing Markov decision process (MDP) at reduced transmit power consumption levels. Meanwhile, in [366], the user is associated with cellular and UAV networks with the aid of D2D connections for disaster recovery, i.e., leveraging a learning-based clustering algorithm to maximize the sum rate. Further, the work in [367] deploys supervised learning (neural networks) for user association with terrestrial BSs based on received signal powers, separation distances, and locations of potential interferers. Likewise in [368], UAV association with terrestrial BSs is proposed optimal transport theory, with emphasis on average network delay. Another joint user association in [369] is modeled as a mixed-integer non-convex optimization problem to maximize users' total achievable data rates.

XX. CONCLUSIONS

Given the unprecedented growth of UAV applications in recent years, this article identifies the need for dedicated radio operations and access schemes for UAV networks. Along with this, a survey is presented on spectrum management for UAV networks that span physical, medium access, and network layers. The survey outlines standards and regulations related to spectrum operations, along with the use cases and architectures. Then, the survey identifies deterministic, opportunistic, and competitive spectrum access and sharing schemes. Furthermore, it addresses suitable traffic management methods such as scheduling and power control. Finally, it identifies key challenges and open research directions for future investigation, where spectrum management tools can be leveraged (e.g., optimization, machine learning, and blockchain).

XXI. ACRONYMS

The abbreviations used throughout the paper and their definitions are listed bellow.

3DSTS	3D spatial-temporal sensing
3GPP	third-generation partnership project
A2A	air-to-air
A2G	air-to-ground
ACI	adjacent channel interference
ADS-B	Automatic Dependent Surveillance-Broadcast
AF	amplify-and-forward
AGIN	Air-ground integrated networks
AI	Artificial intelligence
AN	artificial noise
ANN	artificial neural networks
ANSI	American National Standards Institute
AO	alternating optimization AO
AP	access point
API	application programming interface
AS	assistive slots
ASE	area spectral efficiency
ASTM	American Society for Testing and Materials
ATIS	Alliance for Telecommunications Industry Solutions
BC	broadcast channel
BDMA	Beam Division Multiple Access
BER	Various bit error rate
C2	command and control
CAAC	Civil Aviation Administration of China
CB	Citizens band
CDMA	Code-division multiple access (CDMA)
CNPC	Control and non-payload communications
CPM	continuous phase modulated
CR	cognitive radio
CSI	channel state information
C-UAVs	civilian unmanned aerial vehicles
DAA	detect and avoid
DFS	Doppler frequency shift
DNN	deep neural network
DoD	department of defense
DoS	denial-of-service
DoT	department of transportation
DPC	dirty paper coding
DPoS	Delegated Proof of Stake
DRIP	drone remote ID protocol
DSCs	drone small cells
DT	digital twin
DUAVs	D2D-based UAV
EE	energy efficiency
EM	expectation-maximization

EUROCAE	European Organization for Civil Aviation Equipment
FAA	Federal Aviation Authority
FANETs	Flying Ad-Hoc Networks
FBMA	Filter Bank Multicarrier
FCC	Federal Communications Commission
FD	full-duplex
FDD	frequency division duplex
FDMA	Frequency Division Multiple Access
FDMIMO	Full dimension multiple-input and multiple-output
FHSS	Frequency Hopping Spread Spectrum
FL	federated learning
FR2	frequency range
G2A	ground-to-ground
GBS	ground base station
GCS	ground control station
GEO	geosynchronous earth orbiting
GOFAI	good old-fashioned
GSM	global system for mobile communications
GUEs	cellular ground users
HD	half-duplex
HFH	hover-fly-hover
ICA	independent component analysis
ICIC	inter-cell interference coordination
IETF	Internet Engineering Task Force
ILP	integer linear programming
IoT	internet of things
ISM	industrial, scientific, and medical
ITU	International telecommunication union
KI	key issues
KNN	K-nearest neighbor
KPI	key performance indicators
LAANC	low altitude authorization and notification capability
LAP	low altitude platform
LEO	Low earth orbiting
LoS	line-of-sight
LSTM	long-short-term memory
LTE	long-term evolution
LTE-U	LTE-unlicensed
LTV	linear time-varying
LWA	LTE-WLAN aggregation
MAB	multi-armed bandits
MAC	medium access control
MANETs	mobile ad-hoc networks
MASPS	minimum aviation system performance standards
MBB	mobile broadband
MDPs	Markov decision processes
MDPs	Markov decision process
MEC	mobile edge computing
MILP	mixed integer linear programming
MIMO	multiple-input multiple-output
ML	machine learning
MLE	maximum likelihood estimation
MMSE	minimum mean-square error
mmWave	millimeter wave
MOPS	minimum operational performance specification
MPCs	multipath components
MP-MAB	multi-player, multiarmed bandit game
MRMR	maximum relevance minimum redundancy
MSE	mean-squared error
MTC	machine type communication
MTs	mobile terminals
MUD	multiuser decoding
NCMA	network-coded multiple access
NCS	network characterization service
NE	Nash Equilibrium
NF	network functions
NFV	network function virtualization
NLoS	none line of sight
NOCR	non-orthogonal cognitive radio
NOMA	non-orthogonal frequency division multiple access
NR-U	Radio unlicensed
NT	Network tomography
NTIA	National Telecommunications and Information Administration
OCSS	orthogonal chirp spread spectrum
OFDMA	orthogonal frequency division multiple access
OMA	Orthogonal Multiple Access
OP	operating points
PBFT	Practical Byzantine Fault Tolerance
PCA	principal component analysis
PCCs	policy conformance components
PDF	power delay profile
PLMN	public land mobile network
PNC	physical-layer network coding
PoB	Proof of Bandwidth
POMDP	partially observable Markov decision process
PoR	Proof of Reliability
PoS	Proof of Stake
PoW	Proof of Work
PPP	Poisson point process
PUs	primary users
RAN	radio access network
RF	radio frequency
RID	remote identification
RL	reinforcement learning
RMS-DS	root mean square delay spread
RMTP	radio monitoring transfer protocol
ROV	remotely operated underwater vehicle
RPA	remotely piloted aircraft
RPAS	piloted aircraft systems
RSS	received signal strength
SAR	search and rescue
SC	superposition coding
SCB	Support and confidence-based
SDMA	Spatial division multiple access
SDN	software-defined network
SDR	software-defined radios
SE	spectral efficiency
SIC-SC	cancellation-based superposition coding
SINR	signal to interference plus noise ratio
SIR	signal-to-interference-ratio
SNMP	network management protocol
SORA	specific operation risk assessment
SPOF	single point of failure
SSDF	susceptible to spectrum sensing data falsification
SSS	spatial spectrum sensing
SUs	secondary users
SVM	support vector machine
TDD	time-division duplex
TDM	time-division multiplexing
TDMA,	time-division multiple access
THSS	Time Hopping Spread Spectrum
TPAE	third-party authorized entity
U2U	UAV-to-UAV
UAS	Unmanned Aerial System
UAV	unmanned aerial vehicle
UAV-C	UAV controller
UL	uplink
UTM	UAV Traffic Management
UNII	Unlicensed National Information Infrastructure
USS	UAV Service Supplier
UTM	UAS traffic management
UAS	unmanned aircraft systems
UUAV	underwater UAV
UUI	UAV-UAV interference
VANETs	vehicle ad-hoc networks
VNF	virtual network function
WG	working group
WG6	working group
WLAN	wireless local area networks
ZF	zero-forcing

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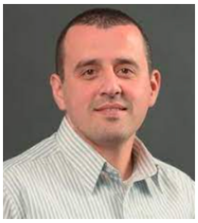

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