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A Survey on Unmanned Aerial Vehicles (UAVs) Communications: State-of-the-Art, Existing Standards, and Future Directions

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ABSTRACT With a diverse range of applications in both private and public sector, the market value of Unmanned Aerial Vehicles (UAVs) skyrocketed to 17.31 billion USD in 2024 and is expected to reach 32.95 billion USD by 2030. 3GPP considered UAVs in Release 15 and will include them in Release 18 as part of the 5G-Advanced technology. To provide smooth and safe inclusion in the current airspace, fast and reliable communications between UAVs and between ground base stations and UAVs are needed. Several research studies have been conducted, but there is no comprehensive picture of their advancements in terms of wireless communications and networking for UAVs. This survey paper provides detailed information on the current status of UAV communications and networking, including important aspects such as architectural solutions, protocols and design options related to spectrum management, resource optimization and security requirements. Efforts related to standardization and integration with different applications are also covered. The survey will help researchers and practitioners in the field of wireless communications, UAV service provision and telecommunications learn about the current state of the art and open the door to future research and development avenues in their fields.

INDEX TERMS Unmanned aerial vehicles (UAVs), unmanned aerial systems (UASs), flying ad-hoc network (FANET), Internet of Drones (IoD), communication protocols.

I. INTRODUCTION

IN THE last few decades, we have witnessed an increase in demand for Unmanned Aerial Vehicles (UAVs) and Unmanned Aerial Systems (UASs) in civilian and military domains, mainly due to their low cost, smooth deployment, and minimal life-threatening risks. The significant demand for aerial vehicles also known as drones, has led to several control and communication problems across many fields and applications. A reliable wireless communication link between swarms of drones and ground base stations (BS) is essential to automate the aerial network, e.g., Flying Ad-hoc Networks (FANETs). In the early phases, Mobile Ad-hoc Network (MANET) wireless policies were adopted in aerial networking but failed due to rapidly changing topology, fast mobility, and three-dimensional free space movements. Indeed, UAVs are characterized by greater degrees of mobility and freedom in the 3D space, which makes a big difference in the context of aerial networks in comparison to ground networks and results in a more dynamic and rapidly changing network topology. Therefore, provisioning of reliable and stable wireless communication channels and performance-oriented routing protocols is very important when designing solutions for a wide range of scenarios. In recent years, many researchers have investigated scenarios that use swarms of aerial vehicles to coordinate and exchange data packets with minimal human intervention. However, they did not employ optimal versions of an aerial network.

UAVs have the potential to boost coverage and dependability and enable energy efficient 6G wireless networks as a vertical component [1]. Despite being tested for deployment and approved for seamless integration with 5G networks in existing cellular networks by 3GPP, UAVs can only realize their full potential when their communication is extended to multiple heterogeneous networks, e.g., space-air-ground-sea integrated network (SAGSIN). This extension can be achieved more efficiently with the assistance of a 6G network. Future UAV networks are witnessing the emergence of new technical scenarios. UAV networks are becoming more advanced, as UAVs establish ad-hoc connections to provide robust experiences. These evolved UAV networks consist of nodes that continuously develop computing, communication, and control capabilities while possessing self-organizing and self-sustaining abilities to ensure connectivity. Despite these capabilities, there is still room for the next version of aerial networks by dedicated reliable wireless communication channels for UAVs networks, stable and secure operations. Moreover, the incorporation of Artificial Intelligence (AI), edge computing technologies and block-chain into UAV networks through 6G networks supports new, robust and more likely heterogeneous applications which offer solutions to various challenges faced by traditional UAV systems, including constraints in processing resources, energy efficiency, privacy, and security. Security and privacy concerns are often neglected during the design of UAVs, leaving them vulnerable to various security risks due to their limited computing and energy capabilities. Therefore, it is crucial to prioritize

security and privacy, prompting the wireless research community to pay special attention to these aspects in UAV communications and networking [2], [3], [4].

This survey aims at providing researchers and practitioners in the field with a comprehensive overview of the current state-of-the-art in UAVs communications. Indeed, this paper differs from other existing recent surveys in the literature, being mostly focused on specific scenarios or topics, such as 5G or 6G-enabled UAV communications (e.g. [5], [6]), channel modeling [7], or routing and handover [8].

The proposed survey goes beyond such specific topics and aims to provide a holistic view about the current state-of-the-art on the subject of UAV communications, identifying challenges and outlining potential research topics for further investigation. Moreover, A taxonomy of the whole paper is presented in Figure 1.

This paper is organized as follows. Section II defines the contribution of the survey paper. Section III provides background information on UAVs, UASs and flying ad-hoc networks (FANETs). Section IV describes the state-of-the-art on UAV-based network architecture and section V details different design aspects related to UAV communications. Section VI presents standardization activities related to UAV networking and section VII describes the UAV communication-based real-world experiments and testbed deployments. Section VIII discusses open issues and future research directions, whereas section IX concludes the paper with some final remarks.

II. CONTRIBUTIONS OF THIS SURVEY PAPER

This manuscript delivers a comprehensive and structured survey of wireless communication and networking technologies for UAVs, addressing developments from the physical to the transport layer. It examines various architectural paradigms including direct links, satellite-based networks, flying ad hoc networks (FANETs), and cellular-supported UAV communications along with integration in different applications for instance Reconfigurable Intelligent Surfaces (RIS), Digital Twins, Integrated Sensing and Communication (ISAC). It identifies the key challenges in UAV networking—such as dynamic topology, spectrum scarcity, mobility management, energy efficiency, and security—and proposes a roadmap for research and development toward 6G and Space-Air-Ground-Sea integrated networks (SAGSINs). The manuscript's holistic treatment of technical and regulatory aspects makes it a critical resource for academic researchers, while providing industrial stakeholders with a consolidated view of standardization and theoretical design challenges.

The main contributions of the paper are as follows.

- The survey presents a holistic, cross-layer analysis of UAV communication and networking, encompassing physical, data link, network, and transport layers—unlike prior surveys that focus on isolated layers or specific use cases.

- It is the first to systematically integrate both academic research and industry perspectives, with a strong emphasis on 3GPP standardization (Releases 15 to 18), providing a bridge between theoretical insights and practical deployments.
- The paper introduces a unified taxonomy that incorporates emerging paradigms such as Digital Twins (DT), Reconfigurable Intelligent Surfaces (RIS), and Integrated Sensing and Communications (ISAC).
- It offers an extensive comparative analysis of existing surveys, clearly demonstrating gaps in their coverage and highlighting how this work fills those gaps across communication architectures, protocols, and applications.
- The survey uniquely contextualizes UAV networking within future 6G and Space-Air-Ground-Sea integrated networks (SAGSINs), offering a forward-looking roadmap that positions UAVs as central to next-generation wireless ecosystems.

III. BACKGROUND OF AERIAL NETWORKING

A. UNMANNED AERIAL SYSTEMS

UASs or unmanned aircrafts do not carry human operators and are capable of flying autonomously or under remote control [9]. UASs basically consist of five main components [10], [11], [12], [13]:

- 1) Unmanned Aerial Vehicles (UAVs): UAVs are air vehicles that satisfy the requirements of flight air vehicles. The operation theater, capacity and performance of the UASs affect UAVs' abilities, including endurance, range, altitude, payload, etc.
- 2) Ground Control Station (GCS): GCS is a portable ground control terminal or air traffic control station that facilitates the interaction between UAVs and humans.
- 3) Payload and data processing: equipment is added to UAVs to fulfill specific mission objectives, including camera, radar, sensor, and communications equipment.
- 4) Control and data transmission links: all the equipment including hardware (HW) and software (SW) that contributes to sending and receiving any type of information both from and to the system itself and other external actors, as well as the UAVs and GCS.
- 5) Support system: provides flight speed to UAVs (and potentially other data, if needed) within a very short space of time.

With the expansion of using the UAS technology in different commercial sectors, UAVs are required to be coupled cooperatively in-between vehicles and be more autonomous in order to complete missions, including in situations without a central ground controller. A classification of different cooperation schemes for multi-UAV architecture is available in [14]:

- Physical coupling. In the physical coupling scheme, the UAVs are physically connected and the motions of each UAV highly depend on the movement of other UAVs.

Two types of control architectures (i.e. centralized and decentralized) are applicable when the number of vehicles is low.

- Formations. In the formations scheme, UAVs are flying in a specific pattern and make a particular shape e.g. star shape, rectangle, also these UAVs maintain the distance, speed and acceleration from each other to perform a cooperative task in more effective way or in simple words to avoid any damage in the field. A practical demonstration can be seen in [15] where 500 UAVs used to demonstrate different formation and are mainly successful because of reliable coordination among pre-programmed UAVs.
- Swarms. In the UAV swarms scheme, homogeneous teams of many UAVs interact with each other to generate collective global behaviors. The global behaviour of UAVs create more adoptable, robust and reliable to the dynamic environment, this is mainly because of its decentralized communication approach.
- Intentional cooperation. In this scheme, each UAV in a team is allocated a set of tasks of a global mission, and then the movements of UAVs of the team follows predefined trajectories of individual tasks where two types of control architectures are applicable either centralized or decentralized.

Although formations, swarms, and intentional cooperation are presented as distinct cooperation regimes, modern UAV missions increasingly operate in hybrid and adaptive modes, where a fleet may dynamically transition between these regimes during different mission phases. The taxonomy adopted in this work should therefore be interpreted as a classification of dominant control and coordination structures at a given time-scale, rather than as rigid mission categories. In this sense, hybrid UAV operations can be formally modeled as regime-switching systems, where the active cooperation mode evolves according to mission objectives, environmental conditions, and network state.

B. UNMANNED AERIAL VEHICLES

With a market value of 17.31 billion US dollars reported in 2024 and predicted to reach 32.95 billion US dollars by 2030. With such large amount of market value and investment by different stockholders different categories of UAVs are pitched according to the application and requirements.

1) UAVs CLASSIFICATION BY TYPE

UAVs are classified into three major categories: (a) fixed-wing (b) wing rotary-wing and (c) hybrid (combination of both a and b) [16]. Fixed-wing UAVs have several advantages including high speed, longer endurance, greater stability and heavy payload, mostly used for large scale applications e.g. boarder surveillance. Unfortunately, these UAVs can only fly forward and require ample space to execute large, sweeping turns when changing direction for instance 360° turn. Hence, this category of UAVs is not suitable for stationary mission

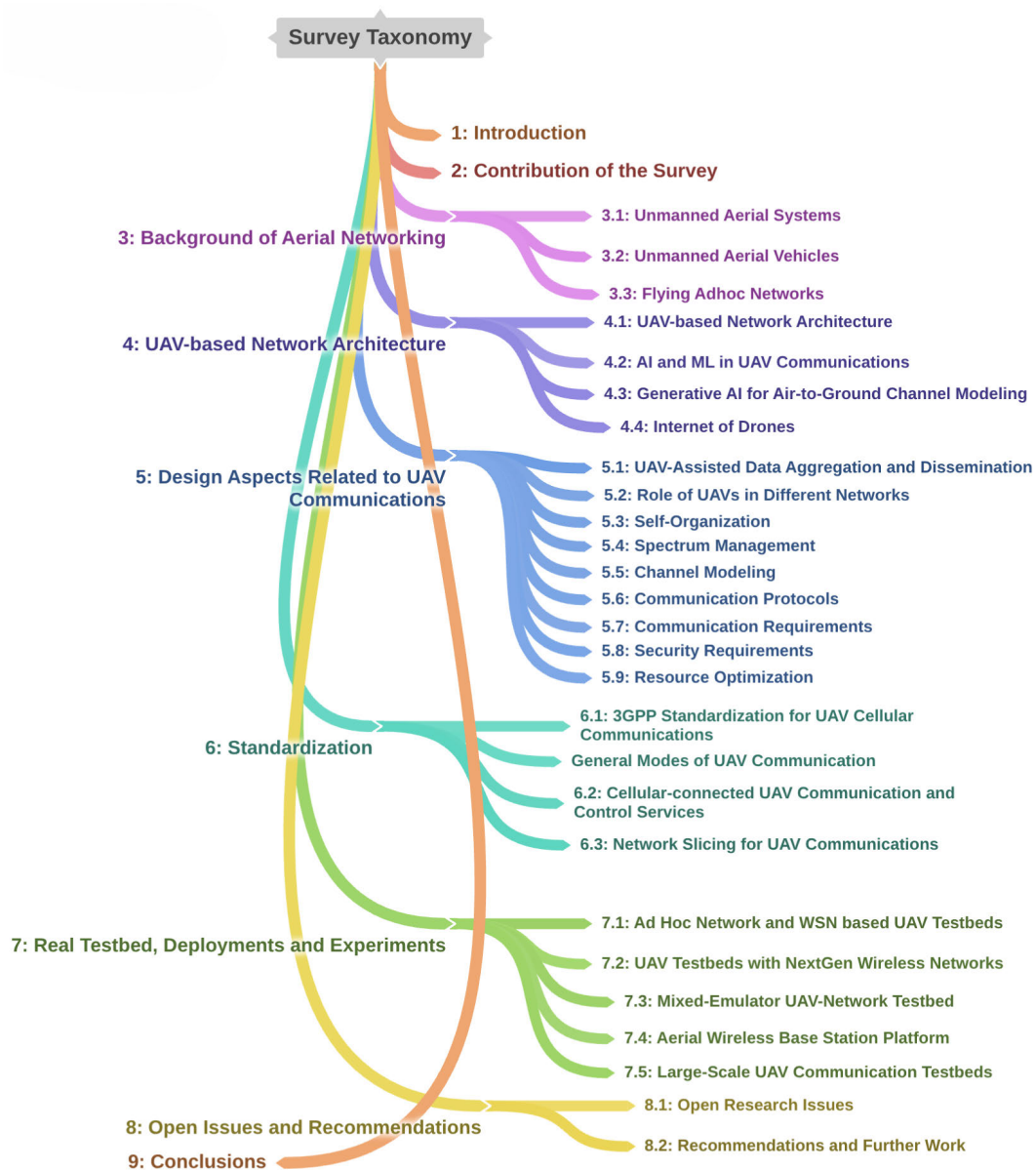


FIGURE 1. Survey taxonomy: the distinct colors represent various sections and their corresponding subsections.

such as close inspection. Contrary, rotary-wing UAVs are able to change direction quickly, as well as to hover, take off and land vertically. However, rotary-wing UAVs also have limitations such as low speed, limited mobility and reduced payload, while hybrid UAVs are the combination of both fixed and wing rotary-wings which provide the facility of vertical Takeoff and Landing (VTOL). Therefore, the choice of UAVs depends entirely on the targeted application [17].

2) UAVs CLASSIFICATION BY SIZE

Apart from the type of UAVs, different sizes of UAVs appear according to budget and applications; for instance, (i) small UAVs (also called mini-UAVs), (ii) medium UAVs, and (iii) large UAVs [12]. Large UAVs are mainly operated

by government agencies, while medium and small UAVs provide their services to civilian applications, which alternatively provide a good level of comfort in agriculture, infrastructure inspection, package delivery, and even emergency response [18], [19], [20]. However, both sizes of UAVs have limited capacity, and using multiple UAVs in coordination requires government-level approval, an appropriate mission model, and precise control. With that, path planning and logistics become increasingly challenging for wide adoption in multiple UAV systems or applications.

C. FLYING AD-HOC NETWORKS (FANET)

The concept of a FANET is based on an infrastructure-less network formed by flying nodes of different types and sizes

(i.e. UAVs) [16]. In that concept, one of the UAVs, a.k.a. the backbone UAV, must be connected to a ground control station (GCS), a satellite, or any other core command and control station [21]. With such a mechanism, the geographical coverage grows extensively, but such advantages come with a price and challenges [21].

Building a FANET involves:

- **Network Topology:** An important and critical parameter for the flying node in a FANET to ensure the mutual connectivity among and with the command control station. Moreover, we can overcome latency, packet loss, and avoid congestion during mission time. However, the geographical position of each flying node in a FANET changes rapidly at high speed compared to its peers from for instance, MANETs, VANETs or nodes in any ground network, causing major communication problems between UAVs and controlling station [22]
- **Mobility Model:** Mobility parameters in FANET simulations depend heavily on the target application scenario, since the 3D trajectories of each UAV—including its position, velocity and acceleration—evolve dynamically over time [23].
- **Node density:** In this, we usually calculate how many flying nodes should be deployed for communication per unit area. Generally, nodes in a FANET are scattered in the sky, and thus node density is much lower than in MANETs and VANETs [24], but we cannot overload our network with unnecessary deployments.
- **Radio propagation model:** In this parameter design, we try to predict link quality and reliability among different flying nodes with varying speeds, velocities, and positions, as well as with the command and control station, either in direct line-of-sight (LoS) or in non-line-of-sight (NLoS) [25].
- **Power consumption:** Apart from internal consumption, extra payloads attached to UAVs also contribute to battery drainage [26], and it is recommended by industrial experts to avoid such practices.
- **Localization:** Every flying node during a FANET mission possesses critical data, and keeping an eye on each node is extremely important; this is mainly possible with reliable, precise connections among the UAVs and with the command and control station at all times [27]. The loss of a flying node may expose the entire mission information to any unwanted entity.

Beyond flat ad-hoc connectivity, FANETs have evolved toward cooperative distributed architectures, particularly for small and mini UAVs with tight payload/energy budgets. A common approach is to form hierarchical or cluster-based FANETs, where a subset of UAVs dynamically assumes gateway (cluster-head) roles to relay traffic between aerial nodes and ground/vehicular infrastructure, improving scalability, survivability, and energy efficiency. Early work explicitly framed this as a cooperative distributed unmanned-aerial-vehicular networking problem for small/mini drones,

highlighting distributed gateway selection and stability control mechanisms [28]. More recently, research has continued to refine cluster-based FANET routing and inter-cluster coordination (including learning- and bio-inspired routing), and broader UAV-vehicular surveys have consolidated emerging air-ground cooperation models and system challenges [29], [30], [31].

IV. UAV-BASED NETWORK ARCHITECTURE

This section covers the state-of-the-art network architectural aspects and the major steps performed towards the creation of the Internet of Drones.

A. COMMUNICATION ARCHITECTURE

There are several representative communication architectures for networked UAVs in the literature and they are mainly based on: 1) direct links, 2) satellite UAV networks, 3) cellular networks [40]. Next, they are discussed in turn.

1) DIRECT LINKS

Employing direct links between UAVs and ground platforms over an unlicensed band (e.g., the designated ISM band (industrial, scientific, and medical) at the frequency of 2.4 GHz) is the simplest classic architecture considered, where the ground communication node is generally a pilot, a remote control unit, or a ground station (GS). Due to its simplicity, this approach has been widely adopted for most UAVs in the current market, especially for consumer-grade applications. However, such a solution is usually limited to line-of-sight (LoS) communications, which greatly reduces its operation range and prevents its use cases in practical and challenging scenarios. For instance, the LoS links are highly susceptible to blockage caused by terrestrial obstacles in urban areas (e.g. tall trees and high-rise buildings) and this will lead to reduced communication reliability [41]. In fact, extending this approach to support beyond LoS operations opens up a promising avenue for many applications dependent on reliable content delivery. Typically, in this case, the ground platform is so positioned to be the central gateway for both UAV-UAV (indirect) communications and support of Internet connectivity. In general, this leads to long delays and does not support high-data rate applications [42]. Furthermore, this simple architecture is typically sensitive to safety and interference issues, which may make it difficult to legitimately monitor and manage.

2) SATELLITE COMMUNICATIONS-BASED NETWORKS

Supporting UAV-based applications using satellite communications approaches is of great interest because of the wide geographic coverage, especially for Non-line-of-sight (NLoS) communications. Specifically, communication satellites are very good at relaying signals around the curve of the Earth and it is easy to establish effective links between widely separated UAVs and terrestrial communication nodes. This is well suited for communication with UAVs in remote parts of the world (i.e. over the ocean) where standard radio (WiFi

TABLE 1. Navigating the landscape: Comparative analysis of UAV network architectures across surveys ✓: Fully Covered ∂: Partially Covered x: Not Covered.

Ref:	Communication Architecture						Internet of Drones
	Content	Direct Links	Satellite-based Networks	Communications-based Networks	Cellular-supported Communications	UAV	
[32]	Content	✓	∂	×	×	0	×
[33]	Content	∂	×	×	×	0	×
[34]	Content	∂	×	×	∂	2	×
[35]	Content	∂	∂	∂	∂	2	∂
[36]	Content	∂	✓	✓	✓	2	×
[37]	Content	×	×	×	×	0	✓
[38]	Content	∂	✓	×	×	2	✓
[39]	Content	∂	∂	✓	✓	0	∂
[5]	Content	∂	∂	∂	∂	0	×
This Survey	Content	✓	✓	✓	✓	3	✓

TABLE 2. Unleashing the potential: Comparative analysis of UAV applications across surveys.

Ref	UAV-Assisted Data Aggregation & Dissemination	UAV Network Formations		Reconfigurable intelligent surfaces (RIS)-assisted UAV Communications	UAV-assisted Integrated Sensing and Communications
		UAVs' Functionality	Multi-UAV Architectures		
[32]	∂	×	×	×	×
[33]	∂	×	×	×	×
[34]	∂	×	×	×	×
[35]	∂	∂	×	×	×
[36]	∂	∂	×	×	×
[37]	×	∂	×	×	×
[38]	✓	✓	✓	×	×
[39]	∂	∂	∂	×	×
[5]	×	∂	∂	×	×
This Survey	✓	✓	✓	✓	✓

TABLE 3. UAV designs: Key features and specifications.

Ref	Self-Organization	Spectrum Management			Communication Protocols				Communication Requirements	Security	R.Challenges
		Spectrum Allocation	Spectrum Sharing	Number of compared techniques	PL	DL	NL	TL			
[32]	×	∂	∂	0	×	∂	∂	∂	∂	×	✓
[33]	×	×	×	0	×	×	∂	✓	∂	×	✓
[34]	×	×	×	0	∂	∂	∂	∂	∂	×	✓
[35]	×	×	×	0	×	∂	∂	∂	✓	✓	✓
[36]	×	×	×	0	✓	∂	∂	∂	∂	×	✓
[37]	×	×	×	0	×	×	✓	×	∂	×	✓
[38]	∂	×	∂	0	✓	∂	∂	∂	∂	×	✓
[39]	×	✓	×	2	✓	∂	∂	∂	✓	∂	✓
[5]	×	×	×	0	✓	×	×	×	×	✓	✓
This Survey	✓	✓	✓	3	✓	✓	✓	✓	✓	✓	✓

or cellular) coverage is limited [43]. In addition, the satellite communications system can be interfaced with the Internet infrastructure to obtain Internet services and satellite-based services (e.g., GPS) can be used to enhance application support for navigation and localization [44]. Importantly, the use of satellite-link frequencies (e.g., the Ku/Ka band) for drones to connect to satellites was approved at the World Radiocommunication Conference 2015 [45]. Several leading satellite firms including Inmarsat have started to provide satellite wireless services for drones since 2017 [46].

Despite promising, there are several disadvantages when using satellite-connected drone/UAV communication networks. First, the propagation latency is very large (e.g., it even reaches 0.12 second) because of the large communication link distance between satellites and UAVs at low

altitudes (height less than 500 m). Note that it is very difficult to satisfy the high requirements to support safety-critical applications, including ultra-reliable low-latency communication (URLLC) applications. Secondly, UAVs typically have different size and payload restrictions, and carrying heavy satellite antenna systems (e.g., antenna) is another challenging issue, which may not be even feasible. Thirdly, this solution is often associated with an excessive operation cost and introduces constraints during large-scale deployment on consumer-scale applications. Finally, satellite transmissions are often affected by rain, snow, and other precipitations and their scalability in terms of supporting communications involving future a large number of UAVs in a local region may be questionable since there is short supply of bandwidth resources.

Recent studies have demonstrated the growing importance of multi-modal intelligence and learning-driven resource management in satellite-ground integrated networks. In particular, Gong et al. [47] propose a multi-modal learning-based multi-task offloading framework that jointly exploits heterogeneous data modalities (e.g., channel state, task characteristics, and network context) to optimize computation offloading decisions across satellite and terrestrial segments, significantly improving latency and system efficiency in highly dynamic environments. Complementarily, the same authors introduce a multi-modal federated learning-based resource convergence approach [48] for satellite-ground twin networks, where distributed learning enables efficient coordination of communication and computing resources while preserving data locality. These works highlight how multi-modal learning and federated intelligence can effectively address the challenges of heterogeneity, scalability, and limited connectivity inherent in satellite communication-based networks, and motivate the adoption of similar learning-driven designs in emerging integrated space-air-ground systems.

3) CELLULAR-SUPPORTED UAV COMMUNICATIONS

Most commercial UAV networks adopt the Wireless Local Area Network (WLAN) (i.e., IEEE 802.11) to support information exchange and control. Considering UAVs' 3D maneuverability, high velocity, and especially altitude adjustment, it is difficult for IEEE 802.11 to satisfy all real-time service demands for many UAV use cases. For example, in the unlicensed band, UAV operation is related to critical concerns in terms of reliability as well as safety and security. In light of this, cellular networks are a promising option for UAV communications. In particular, the existing network infrastructure, in terms of coverage, reliability, security, and data rates, offers sufficient support for many applications. However, conventional cellular networks are not designed and implemented to support aerial users. There have been some initial standardization considerations recently, which have identified the need to address some aspects, especially in relation to wireless coverage, cell handover, and interference mitigation, in order to make the integration of drones into next generation cellular networks, e.g. 6G.

UAVs may serve different roles when considering their integration within cellular services. First, they can be deployed as part of cellular infrastructure, e.g., as aerial base stations or flying relays. This is known as *UAV-Assisted Cellular Communication* [49]. The main objectives are to boost coverage, connectivity as well as capacity, or to provide on-demand deployment of a wireless network in some regions without cellular service. The implementation of drones mounted small base stations is detailed in [41] and [50] and the usage of drones as flying relays is in [51] and [52]. Such a setup is particularly beneficial for some specific scenarios, including replacement of damaged infrastructure due to disasters or provision of on-demand coverage for sport events and concerts with massive numbers of users.

Secondly, a drone can also be an important aerial user in contact with ground users. As such, a drone may exploit the uplink channel to send information to the terrestrial base station and the latter may exploit the downlink to send commands to steer and control the drone. This communication approach is also known as *Cellular-Connected UAVs* and is trying to achieve reliable air-ground communications [49]. Cellular-connected UAVs offer several appealing advantages; the potential benefits and specific communication as well as spectrum demands were described in [53] and [54]. How to implement cellular-connected UAVs to provide safe and reliable aerial services was studied in [55] and how to exploit cellular signaling to realize more resilient drone navigation and complement GPS navigation was elaborated in [56] and [57]. Cellular-connected UAVs are believed to provide a win-win case not only for UAVs, but also for cellular networks. They support an ideal business model by bundling UAV command and control and diverse kinds of data services into existing wireless networks. This model would help to integrate UAVs into the airspace ecosystem.

Comparison of UAV Communication Architectures:

Table 4 shows a comparison of different UAV communication architectures as described before. It shows that different types of architectures are suitable in different application scenarios, e.g., direct links are suitable for point-to-point communication between UAV and ground station, whereas satellite based communications are preferred to serve large number of UEs and especially in rural settings where other network infrastructures are not available. In these settings, the range and coverage of communication are very important, which can be fulfilled by augmenting UAV relay communications. On the other hand, in urban and suburban environment with ultra dense users and demands, cellular communication is desirable facilitating both cellular-assisted UAV and UAV-assisted cellular communications. The table also shows the key performance indicators, e.g., latency, throughput, spectrum efficiency, interference, service outage, power efficiency considered in different network architectures. The reported experimental benchmarks shows the strengths and weaknesses of different architectures. For example if very high data rate is required, direct link will be preferred although it is not scalable. The satellite communication though provide long range connectivity and low power outage, it can incur long propagation delays. If moderate data rate with dense user population needs to be served with lower interference, then cellular communication based architecture will be preferred. Apart from the immediate performance indicators, these architectures also differs in terms of reliability, safety and security aspects which motivates the need for constructing hybrid UAV network architectures consisting of different types of links with respective priorities.

B. AI AND ML IN UAV COMMUNICATIONS

AI and ML are becoming central tools for designing, optimizing, and securing UAV communication systems [58], [59].

TABLE 4. Comparison of different UAV Communication architectures.

UAV-based Network	Network Scenario and Architecture	Highlighted Component(s)	Performance Indicators	Reported Benchmarks
Direct Link	Ground-to-UAV UAV-to-UAV [44]	- UAV Adhoc network - Multi-Group UAV Network - Multi-Layer UAV Ad Hoc Network	Data rate	CDL downlink (UAVs to the ground station) data rate can be configured to be either 10.71 Mbps, 137 Mbps, or 274 Mbps
Satellite	UAV relay from Satellite via High Altitude Platform (HAP) [45]	- Network control and connectivity - Satellite-to-HAP: Free Space Optical (FSO) Link - HAP-to-UAV: RF Link	Outage Probability, Average Tx rate, Spectrum Efficiency, Avg. bit error rate (ABER)	- Achieves 2.45 Gbps data rate, compared to 1.77 Gbps from fixed-rate - Lower average BER even with higher achievable data-rate - At 20dBm power, it achieves spectrum efficiency of 6.8 bitsymbol compared to 6.2 bitsymbol for 128-QAM
	IoT Use Case for Rural Areas Applications [46]	- UAV-to-UE Communication - Technologies: LTE, 5G, LoRa, Sigfox, ZigBee, NB-IoT	- Delay - Throughput	- High Throughput Satellite (HTS), e.g., ViaSat-2: 300 Gbit/s, delay: 256 ms - MEO/LEO: altitude lower than 10,000 km, delay: 10 - 70 ms - LeoSat: 78-108 high throughput Ka-band satellites - OneWeb (constellation of 720 LEO satellites): 50 Mbit/s and low latency lower than 50 ms
Cellular	Control and Non-Payload Communication (CNPC), Payload Communication [51]	- UAV-Assisted Cellular Communication - Cellular-Assisted UAV Communication - UAV-UAV Communication Technology: 5G/B5G	- Data Rate - Latency	- CNPC Data rate: 100Kbps - Payload Data rate: 50Mbps - Latency: 50ms
	Flying Base Stations as Substitute of Ultra-Dense Small Cells [52]	FlyRAN achieved through either FlyBS or Fly-RRH	- Throughput - Energy Efficiency	- FlyRRH throughput is 11 times higher than that of Small Cell - FlyRRH achieves 5.3x energy efficiency compared to the small cell
	Micro Unmanned Airborne Communication Relays [53]	- Low altitude relays with small UAVs in urban and rural environments - Conducted with field tests	- Upload and download Data rate - Latency	At 15 m altitude for a single UAV: - Download data rate: 5Mbps - Upload data rate: 1.5 Mbps - Ping latency: 100ms
	Joint path planning and power allocation of a cellular-connected UAV [54]	UAV aims to: - maximize uplink throughput - minimize interference to ground UEs connected to neighboring cellular BSs - considering the shortest path and - flight resource constraints	- Throughput - Power - Interference	- Mean throughput on uplink: 0.0175 Mbps - Mean UAV interference on UEs over downlink: 0.1 dBm
	5G-Connected Drones Performance in Non-Urban Areas [55]	- Real-world deployment with drone connected with cellphone Collected data from LTE, 5G SA low-band, and 5G SA mid-band simultaneously	RSRP, RSRQ, Throughput	- Mid-band 5G throughput (downlink) is multiple times higher than that of LTE and low-band 5G. - Higher velocity decreases the downlink throughput.

These tools enable UAV links and networks to adapt in real time to highly dynamic channels, traffic, and mobility, which may be difficult to achieve with purely model-based methods [60], [61]. Researchers proposed AI/ML techniques for many use cases including the following:

- Optimize trajectories and radio resources jointly (e.g., transmit power, spectrum allocation, user association) under complex and often non-convex constraints [60], [62].
- Enhance physical and medium access control layer performance, including channel estimation, beam/antenna management, and interference handling in dynamic 3D channels [58], [61].
- Automate network-level functions such as mobility management, routing, and load balancing for single UAVs and UAV swarms [58], [63].
- Improve security and resilience (e.g., intrusion and anomaly detection, jamming identification) in vulnerable multi-hop aerial networks [64].

C. GENERATIVE AI FOR AIR-TO-GROUND CHANNEL MODELING

The development and examination of UAV communications critically depend on precise models of electromagnetic propagation [7], [65], [66]. Existing statistical models, crafted by standardization entities like 3GPP, facilitate the creation of random instances of channel characteristics for specific links: propagation path angles, gains, and delays. These models

are derived from theoretical considerations and empirical data, a process increasingly challenging due to the systems' growing complexity and diversity, including new and wider frequency ranges, extensive antenna arrays, and unconventional deployments and user sites. In aerial contexts, this complexity is exacerbated by additional factors such as UAV heights, their three-dimensional orientation, and the heights of buildings. Accurately modeling these relationships is crucial for advancing multi-antenna aerial communication systems, though such implementations are notably intricate [67]. Furthermore, operating these channel generation systems can become highly resource-intensive in scenarios with numerous radio links. For UAVs, this involves managing LoS connections with several BSs, each contributing interfering signals that must be considered. 3GPP channel models, partly rooted in terrestrial measurements which significantly differ from aerial contexts, especially in the mmWave bands, are not adequately calibrated. Additionally, these models, originally designed for BSs targeting ground users, fail to replicate the characteristics of specialized uptilted deployments aimed at UAV pathways, such as those on rooftops. These models are statistical, designed to simulate various scenarios with varying degrees of realism rather than specific propagation environments like a city or district. While digital twins of specific propagation environments can be created using ray tracing, this method demands an exhaustive blueprint, including the dimensions, forms, and positions of all obstacles, as well as their electromagnetic traits. The high computational demands often prevent real-time extensive network

optimization. Both conceptual and operational complexities of channel modeling are impeding the progress of aerial communications research.

Site-specific channel modeling using data-driven methods has recently been introduced, correlating physical locations with channel characteristics via regression [68], [69], [70]. In contrast, deep generative neural networks offer a means for non-site-specific propagation modeling [71], [72], which requires minimal assumptions and can still mimic specific propagation environments and capture complex probabilistic relationships. For example, in [73], a dual-stage architecture was employed, initially predicting the link condition (LoS vs. non-LoS) before channeling this information into a conditional variational autoencoder that computes the path losses, delays, and angles for all propagation paths. Alternative methods for creating synthetic multipath channel realizations involve standardizing channel parameters and converting them to images [74]. The image formation is beneficial as it enables the use of deep convolutional generative networks, adept at performing edge detection and learning (non-linear) spatial correlations among the image pixels. Nonetheless, most existing models only yield independent channel snapshots, unable to depict signal fluctuations over time. This is generally sufficient for average performance evaluations where only a marginal distribution is needed, but it falls short and may introduce errors when assessing advanced PHY algorithms for multi-antenna communications and sensing or when enhancing radio access networks to accommodate user movement. Another key consideration worth pointing out is the generalization ability of these generative models [75], which is necessary across various heterogeneous environments such as urban, suburban, and rural scenarios, which differ in terms of scattering density, building morphology, and elevation statistics.

More recently, [76] introduced a framework based on the transformer time-series conditional GAN (TTS-CGAN) [77] and the multivariate time series conditional GAN (MTS-CGAN) [78] for spatially consistent channel modeling. This model specifically depicts the large-scale channel behavior as the local-average received signal strength (RSS) of a UAV navigating typical urban trajectories. In particular, the set of conditioned channel parameters for the k -th trajectory is represented by \mathbf{x}_k , while the evolution of the distance between the user and the gNB is denoted by \mathbf{u}_k . The objective of this model is to capture the dependencies within the large-scale channel gains across multiple gNBs for a series of typical trajectories, thereby modeling the conditional distribution $p(\mathbf{x} | \mathbf{u}, c)$. While this methodology enables the generation of RSS sequences along designated trajectories for specific base stations, additional efforts are needed to incorporate small-scale fading and thereby deliver a complete multipath channel response, including path gains, delays, and angles, which are essential for crafting site-specific deployments and for the development and validation of AI/ML-based multi-antenna PHY algorithms.

Key Insights and Lessons Learnt: The development of UAV communications relies on accurate electromagnetic propagation models, which are challenging due to the increasing system complexity and diversity of aerial communication systems. Standardized state-of-the-art statistical models, derived from empirical data and theoretical considerations, struggle to keep up with the evolving nature of UAV systems with additional variables such as UAV altitude, flying speed, acceleration, and 3D orientation. Data-driven methods have been proposed for site-specific channel modeling, but they require extensive data and may not capture the intricacies of UAV-specific propagation. Generative AI, particularly deep generative neural networks, offers a promising approach to non-site-specific propagation modeling, capable of mimicking complex propagation environments and capturing probabilistic relationships. However, further research is required to more accurately model large-scale channel behavior and incorporate small-scale fading. This would enable the generation of a comprehensive multipath channel response, crucial for advanced UAV communication system design and AI/ML-based PHY algorithm validation. In addition to this, ensuring spatio-temporal consistency in the generated channel samples remains another key challenge, especially for trajectory-aware simulations where channel evolution must be modeled over time and space. This becomes critical for evaluating time-sensitive algorithms and real-time link adaptation mechanisms in UAV deployments scenarios [79].

D. INTERNET OF DRONES

Coordination of access to UAVs in a regulated airspace is made possible by the emerging Internet of Drones (IoD) [80]. Among other aspects, IoD encompasses protocols that introduce the idea of treating the airspace, especially the low-altitude one, as a limited resource. Additionally, IoD includes several specific activities, such as drones management, flight control, resource optimization, and mission planning. It also allows for network connection integration between UAVs and the Internet.

An important aspect related to drones is that they communicate with remote web services, for data upload on the cloud, sensors data streaming, and data processing and analysis. They may also integrate with other services available at the edge. Indeed, thanks to the IoD, UAVs are equipped with the ability to utilize low-latency communications and access crucial geographical information. This includes data pertaining to air traffic control (ATC), weather forecasts, as well as the precise whereabouts and operational conditions of ground recharging stations [81].

Overall, this is made possible with the introduction of ad-hoc networking and the principle of a Zone Service Provider (ZSP) [80]; the former ensures coordination between local UAVs, while the latter characterizes the backbone of the IoD ground communication infrastructure. The IoD architecture depends on the cyber-physical environment

that is available in a certain geographical zone, which may be subject to physical obstacles and service access restrictions.

The physical access is organized as a structured airspace, which is divided into *zones*. For intra-zone and inter-zone flights, each *zone* offers *airways* (flight paths similar to the roads) and *intersections* (formed where two or more airways meet), respectively. By leveraging regulated flight paths, drones are capable of accessing *nodes*, which represent specific points of interest. These nodes allow drones to perform various actions such as takeoff, landing, recharging, or engaging in missions by traversing through these designated routes. With this arrangement, a ZSP controls an entire zone and UAV collisions are minimized [80].

In this scenario it is critical that the drone is able to continuously broadcast its coordinates in order to be led by ZSP and guarantee that its intended trajectory and actions follow the mission plan. On the contrary, the ZSP is responsible for relaying control information from remote services, as well as ATC and weather updates. Furthermore, the ZSP must be capable of dealing with emergency situations, including the possibility that a drone would be unable to continue its journey due to hardware and/or software faults, sudden power loss, or uncontrolled flight [80].

As the IoD extends the networking paradigms into a cyber-physical system, it is crucial to re-evaluate handover processes and congestion control, as they also involve the airspace management. As a result, it is necessary to develop algorithms capable of optimizing UAVs courses, while taking into consideration other aspects such as mission objectives and drone autonomy [80], [81].

Recent advances in the scientific literature propose middleware solutions to provide a unified control structure that are vendor-independent. In this way, the entire software stack becomes predictable by UAV providers and operators to ease drone provisioning, their remote control, and ensure that all relevant mission-critical algorithms are provided [82]. Furthermore, provision of a comprehensive simulation environment should aid in the development of more resilient protocols and UAV-oriented remote services [83].

Key Insights and Lessons Learnt: The choice of communication architecture for networked UAVs depends on specific use cases and requirements.

- 1) **Direct links** between UAVs and ground platforms are simple and widely used for consumer-grade applications, but are limited by line-of-sight communication, especially in urban areas with obstacles. Extending direct links beyond line-of-sight introduces complexities related to delays, data rates, safety, and interference concerns [84].
- 2) **Satellite communications**-based networks offer wide geographic coverage, making them suitable for beyond-line-of-sight communication [85]. However, they face challenges such as propagation latency, payload restrictions, and high operation costs, which may limit their scalability and efficiency, particularly for safety-critical applications.

- 3) **Cellular-supported UAV communication** offers promising solutions for reliable and secure communication, but requires careful consideration of factors such as wireless coverage, cell handover, and interference mitigation [86].
- 4) **Internet of Drones** architecture relies on ad-hoc networking [3] and the principle of a zonal service provider for coordination between local UAVs, providing a backbone for the IoD ground communication infrastructure. The IoD emphasizes the importance of re-evaluating handover processes, congestion control, optimizing UAV courses, and considering mission objectives and drone autonomy.

V. DESIGN ASPECTS RELATED TO UAV COMMUNICATIONS

This section presents and discusses major design aspects in relation to UAV communications, from data collection, aggregation and exchange to spectrum management, protocol selection and resource optimisation.

A. UAV-ASSISTED DATA AGGREGATION AND DISSEMINATION

UAVs are big source of relief to many networks and applications, a UAV-based/supported network is deployed to sense, collect, and consolidate important sensor data [87], [88], [89], [90], [91], [92]. In such scenarios, the unique characteristics of UAVs—strong LoS communication links, agile and dynamic 3D deployments, and low node density—make them preferable over other networks [93]. UAVs also have the capability to process and share real-time data across long geographical distances with the command-and-control station [89]. To extract the best out of UAV-based/supported network, here are the key components which take part in the collection of sensor data:

- 1) **Sensor Deployment:** Successful UAV-supported sensing, starts with carefully planning the deployment of the sensor(s). Choosing the right sensor modalities—high-resolution RGB cameras, multi spectral or hyperspectral imagery, LiDAR scanners, thermal-infrared detectors, or gas analyzers—should be guided by the mission's target signatures as well as the required spatial and spectral resolution. Before flight, strict radiometric and geometric laboratory calibrations and in-flight checks (dark-frame removal, vignetting correction) ensure accurate and repeatable measurements. Equally critical is stabilizing the sensor(s) against vibration—through the deployment of gimbals for active or passive stabilization or the use of dampers to suppress airframe-induced oscillations—so the data remain crisp and properly oriented. Last but not least, integrating each sensor with a highly accurate GNSS/INS and synchronizing timestamps through pulse-per-second (PPS) signals or Network Time

- Protocol ensures every data point is geo-referenced and time-aligned properly in multi-UAV deployments.
- 2) **UAV Platform and Flight Planning:** The type and size of the UAVs along with proper flight planning profoundly affect both data quality and mission efficiency. For long flight time fixed-wings UAVs are best choice but it require launching system which provide specific level of force to push the UAV in the air while wing rotary-wing has the capability to takeoff without any launching system but at the expense of shorter mission time. Alternative, hybrid is the only solution to those of the above issue but it also add complexity and weight. In-short, each parameter should be calculated properly either battery usage against payload or path planning that could find best optimal flight paths with carefully defined way-points, altitude layers, and overlap parameters.
 - 3) **Command and Control Station:** The ground-based command and control station represents the nerve center of UAV operations and delivers reliable telemetry, mission uplink/downlink, and safety monitoring. Dual or redundant RF links (e.g., 2.4 GHz and 900 MHz) or satcom guarantee low-latency control on flights beyond line of sight, and high-definition video downlinks (COFDM or digital HD) facilitate real-time collection and dissemination of intelligence, surveillance, and reconnaissance (ISR). The operator interfaces through graphically driven mission-planning software that combines maps, real-time sensor inputs, and health displays, and allows integration of custom automation through open APIs or SDKs (e.g., QGroundControl or DroneKit). Embedded failsafe behaviors—lost-link return-to-home, low-battery auto-land or loiter patterns—coupled with ongoing health monitoring (battery voltage, motor ampere draw, GPS signal quality) trigger alerts or automatic safety responses upon threshold violations.
 - 4) **Communications and Network Infrastructure:** Fast, reliable, and secure communication infrastructure is very important to support the large data payloads gathered by different sensors attached to UAVs. For mobile operations, ground access points should be equipped with high-gain directional antennas, fixed or vehicle-mounted, with AES-256 encryption, frequency hopping, authentication protocols, and anti-jamming strategies to secure the overall command and control.
 - 5) **Edge and Cloud Data Processing:** To accelerate data processing, both edge and cloud services are utilized in majority of applications to reduce burden on-board edge system should be equipped with real-time filtering, compression and inference—object detection. Once these sensor data arrived at these services, automated ingestion pipelines extract metadata. Ultimately, data fusion layers combine information from UAVs with GIS systems like ArcGIS and QGIS, as well as other sensor networks. Meanwhile, stakeholders can

use web-based dashboards, such as Grafana or specialized React applications, to visualize, query, and share actionable insights related to any specific services.

- 6) **Quality Assurance and Feedback Loop:** To improve sensor data quality, iterative feedback is implemented to ensure continuous improvement. Moreover, in some mission-critical applications, automated checks are embedded to detect missing frames, signal-to-noise anomalies, and GPS dropouts. After each mission, log files are examined to identify deficiencies and improve the next deployment.

Leveraging UAVs is a highly effective approach for efficiently collecting the rapidly increasing sensor data encountered in the Internet of Things (IoT) systems [90]. In real-time IoT applications, the timeliness of the received data is of paramount significance for various scenarios, including intelligent transportation systems, command control systems, Tactile internet applications, and more. Age of information (AoI) is introduced to quantify the freshness of received data by assessing how promptly it aligns with its time of origin at the data source. The deployment of UAVs with adaptive aerial mobility and positioning capabilities, are ideally to serve as assistant tools in these scenarios. Their agility and flexibility enable them to optimize the communication process and minimize the AoI. This ensures that the most recent information is efficiently delivered to its intended recipient. UAVs can swiftly collect data from various sensors, thereby reducing delays in data transmission. This approach significantly enhances the timeliness and reliability of data transfer in IoT applications, ultimately leading to improved system performance and responsiveness.

Several studies in the existing body of research have explored the potential of utilizing UAVs for data aggregation and enhancing the freshness of data collected. In [91], the authors proposed optimal time allocation for energy harvesting to minimize average AoI and assess the impact of self-interference on the performance of the full-duplex UAV-assisted wireless powered communication system. Authors of [89] have introduced a new metric known as correlation-aware AOI to assess the freshness and degree of correlation in gathered information. The study evaluates correlation-aware AOI in scenarios where a UAV collects data from ground devices monitoring various physical processes. An optimization problem is formulated to minimize the normalized weighted sum of the time-average correlation-aware AOI, and an ant colony optimization algorithm is devised to address this problem. The importance of timeliness in aerial networking has been further underscored in [94] that establishes that UAV maneuver dynamics, especially during high-curvature flight, can significantly disrupt AoI enhancement and reliability requirements, highlighting the necessity for mobility-aware scheduling and control mechanisms in cooperative UAV systems.

Expanding beyond data aggregation, utilizing UAVs to facilitate data dissemination in infrastructure-less IoT

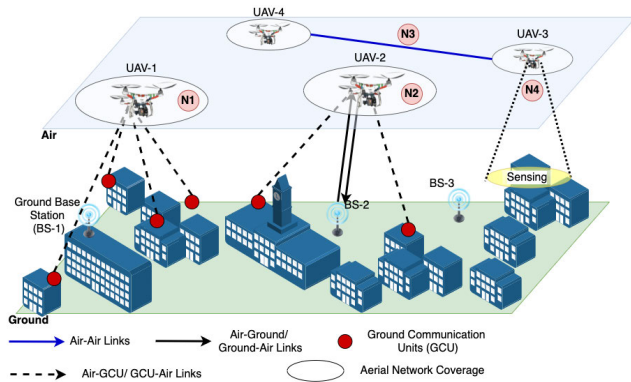


FIGURE 2. A representation of UAVs forming aerial networks for multiple scenarios, performing various tasks across different terrains.

scenarios holds significant promise. One key application is the deployment of UAVs as data dissemination enablers for maintaining synchronized data across widely dispersed IoT devices, such as in precision agriculture or environmental monitoring. UAVs act as data carriers, collecting information from various sensors and delivering updates to IoT devices. By optimizing resource allocation and UAV mobility in three dimensions, the delay in data synchronization is significantly reduced. Additionally, UAVs-assisted data dissemination plays a vital role in emergency services and public safety by supporting rapid data dissemination. In disaster-stricken areas or critical situations, UAVs can efficiently disseminate real-time information to relevant emergency response teams that can aid in timely decision-making, improving disaster response, and public safety. Moreover, UAVs can proficiently transport healthcare and telemedicine data from remote locations to healthcare facilities, ensuring timely medical attention and diagnosis.

The research presented in [90] aims to maximize the efficiency of UAV-assisted data dissemination among geographically dispersed IoT devices by jointly optimizing resource allocation strategies and UAV mobility in 3D. The problem is formulated as a non-convex optimization task, considering parameters like individual data requirements for IoT devices, practical UAV mobility constraints, and energy constraints. To address this, an efficient algorithm is devised using a combination of alternating descent and concave-convex procedures.

B. ROLE of UAVs IN DIFFERENT NETWORKS

C. UAVs' Functionality

Fig. 2 envisions a functionality-based scenario where UAVs are used for a multitude of tasks in different scenarios. Individual use-cases are denoted by N1-N4 in Fig. 2. Depending on the intended usage of UAVs, the following roles can be allocated to UAVs: 1) UAVs as base stations, 2) UAVs as relay stations, and 3) UAVs as sensors and/or actuators. These roles and their associated challenges are outlined next.

1) UAVs AS BASE STATIONS

The use of UAVs as base stations [95] enables continuity of communications by expanding the communication coverage and acting as protocol converters (whenever required). Both N1 and N3 in Fig. 2 illustrate the use of a UAV as an aerial base station. The UAV acts as a regular base station and can operate on its own to extend the communication infrastructure in previously uncovered zones. UAVs (UAV-1 in the figure) can act as base stations to allow communication from ground communication units (GCU) (N1) or between aerial units (UAV-3 and UAV-4 in N3). This serves as a really good motivating example for the use of UAVs in disaster-hit areas to quickly establish a workable communication infrastructure.

Major challenges related to the deployment of UAVs as base stations addressed in the literature include: energy optimization [95], [96], [97], communication coverage [95], [98], bandwidth optimization [98], trajectory and path planning [99], [100], [101], [102], wireless power transfer [103] and wireless security [104].

2) UAVs AS RELAY STATIONS

Another avenue for potential UAV deployment is UAV use as communication relays [105], [106], [107]. This is primarily to extend the communication range of an already established communication infrastructure. N2 in Fig. 2 shows the exemplar use of an UAV as an aerial communication relay, where it extends the communication range of a communication system to cover previously out-of-range areas (UAV-2 connects BS-2 to nearby GCUs). In contrast to the use of UAVs as base stations, this category of UAV usage aims only to extend communication from an already available communication infrastructure.

The literature discussed major challenges related to deploying UAVs as aerial relays and they include: communication relaying [105], [107], Battlefield Information Transmission System (BITS) [106], relay positioning [108], throughput maximization [109], trajectory or power optimization [110], specialized communication network healing [111] and wireless security [112].

3) UAVs AS SENSORS AND/OR ACTUATORS

Finally, the use of UAVs also includes sensing and actuation tasks [113]. Often, UAVs are also used as aerial sensors and actuators, especially in domains such as surveillance [114], surveying [115], agriculture [116], and others [117]. Most of the typical applications of UAVs as sensors and actuators are not bandwidth-intensive, rather they rely on enhanced communication range and prolonged duration of operations. Some typical examples of these are UAVs in agriculture [118], and forestry. Normally, most of the processing from the UAV sensors is done onboard the UAVs themselves, requiring robust processors on the UAVs. The communication and networking requirements are normally restricted mostly due to the cost-limitations of long-term and sustainable UAV usage in these domains. Sometimes, the UAVs

may be enablers for ground-based sensor and actuator networks [113], or may act as data mules [116]. UAV-3 in N4 in Fig. 2 illustrate the use of UAV as a sensor. Multiple such UAVs can come together to form an aerial network using the network formation N3.

The major challenges of deploying UAVs as aerial relays addressed in the literature involve: optimal UAV placement, energy optimization, wireless power transfer and enhancing communication range from the ground control stations.

Key Insights and Lessons Learnt: From a technological maturity perspective, we distinguish between challenges that are relatively mature at the algorithmic level and those that remain open from a system and deployment perspective. Hence, the challenges outlined above do not share the same degree of technological maturity, despite often being discussed within the same context. For example, energy optimization has reached a relatively advanced stage at the methodological level, supported by numerous analytical models and optimization frameworks for UAV base stations and relaying systems [95], [96], [97]. These contributions provide robust theoretical tools for addressing energy-aware deployment, mobility control, and power management. However, important gaps remain in terms of real-world implementation, particularly with respect to real-time decision making, uncertainty in energy profiles, battery behavior, and integration with onboard control systems. Trajectory and path planning exhibit an intermediate level of maturity, with a significant body of deterministic and learning-based approaches for UAV mobility and coverage optimization [99], [100], [101], [102], [108], [109], [110]. Nonetheless, their effectiveness in complex, large-scale, and safety-critical operational scenarios is still not fully established. Conversely, security and trust management for UAV networks remain at an early stage of development. Existing efforts mainly build upon traditional communication security paradigms [104], [112], while comprehensive defenses against spoofing, jamming, coordinated attacks, and adversarial swarm behaviors are still largely open research problems.

D. Multi-UAV Architectures

Depending on the way how the UAVs organize themselves in a 3D space, the communication challenges can be grouped on the basis of the employed UAV network architecture [116]. The architectures can be single/flat layered or multi-layered. Fig. 3 illustrates the various nuances of multi-UAV architectures. A1 and A2 represent a layer-based view of the architecture, whereas C1-C3 represents a communication gateway-based view of the architecture. The top layer of networked UAVs denoted by A1 in Fig. 3 shows a single-layered multi-UAV architecture.

Multi-UAV architectures present some unique and interesting challenges. Some of the prominent ones include selecting the optimal mode of communication between the UAV layers and an external control station/ receiver. The overall A2 in Fig. 3 shows a general multi-layered multi-UAV network deployment in 3D space. In organized UAV networks, for

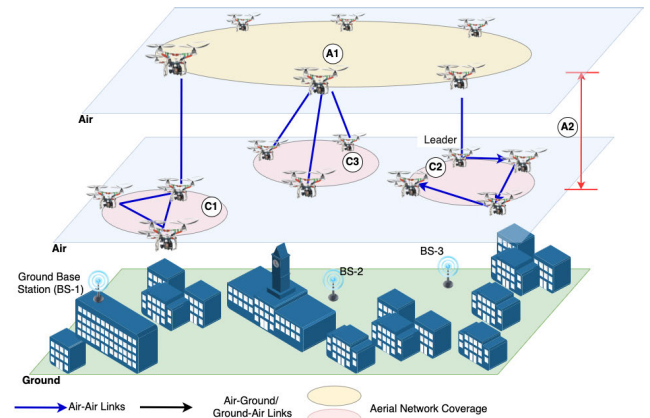


FIGURE 3. A representation of multi-UAV architectures and their configurations.

the sake of ensuring architectural stability and to primarily maintain the physical formation of the UAVs, ideally a leader UAV is selected as shown by configuration C2 in Fig. 3. The leader acts as the communication gateway of each layer with external entities (outside the layer) as well as decides formation controls and UAV placements. Typically, communication and networking in this architecture can be either star (C3) or mesh (C1). The star and mesh-based architectures can be made more layered to achieve multi-star and hierarchical mesh configurations [8]. Approaches for selecting a leader UAV in each of the layers and even across the layers include: static leader-follower [119], [120] and distributed leadership [121].

Some of the challenges associated with multi-layered UAV network architectures discussed in the literature include: communication delay minimization [122], routing protocols [123], power transfer [124], UAV traffic management [125] and communication relaying [126].

1) RECONFIGURABLE INTELLIGENT SURFACES (RIS)-ASSISTED UAV COMMUNICATIONS

Reconfigurable intelligent surfaces (RIS) [127] refers to electromagnetic (EM) materials that can be electronically controlled [128]. By controlling how radio waves interact with objects that are coated with reconfigurable EM layers [129], [130], telecommunication operators are able to provide continuous connectivity and high quality of service (QoS) for users. The mounting of RIS on UAVs has the great potential to improve UAV communication performance [131], [132], as shown in figure 4. For instance, air-to-ground communication is often poor in urban environments due to obstructions of the line of sight (LoS) channel. As a solution to this challenge, Li et al. design a new UAV-mounted RIS communication system where air-to-ground signals are reflected and enhanced taking into account both UAV trajectory and RIS's phase-shift [133], [134]. Results show a significantly increased achievable rate. An extensive study of RIS is conducted by You et al. [135], demonstrating six scenarios of integrating RIS into UAV networks: 1) data

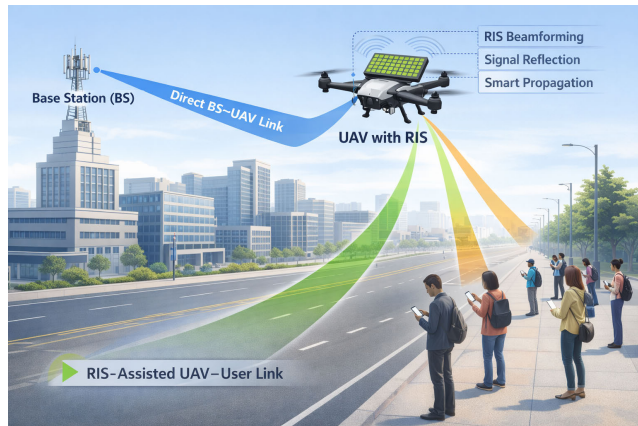


FIGURE 4. RIS-assisted UAV–user communication architecture, where a RIS-mounted UAV exploits adaptive beamforming and signal reflection to enhance air-to-ground links.

collection: increasing the number of RIS elements near sensor nodes leads to higher data collection rates and less hovering time for UAVs; 2) ubiquitous coverage: deploying RIS can extend the reachability to ground users that are not covered by UAVs; 3) data relaying: deploying RIS near terrestrial gateway increases the backhaul capacity of air-ground channels; 4) PHY layer security: RIS can mitigate eavesdropping attack from malicious ground users; 5) data and energy transfer: RIS requires low energy consumption and can improve the efficiency of information-and-power transfer (SWIPT) systems; 6) cellular-connected UAV communication: RIS is able to alleviate interference between UAVs and non-associated base stations. A case study is presented by Yang et al [136], who deploy RIS on a building as relays to improve the coverage and reliability of UAV communication systems. Both ground-to-RIS channel and RIS-to-UAV channel are modelled to estimate the outage probability, average bit-error rate and average capacity. Recent advances in RIS-assisted UAV communication demonstrate that trajectory planning must increasingly account for fast-varying channel geometry and learning-driven adaptation; for example, the multi-threaded federated optimization framework in [137] shows that RIS–UAV co-design introduces high-dimensional coupling between mobility and beamforming, requiring real-time trajectory updates that reinforce the need for hybrid and adaptive aerial cooperation architectures.

2) UAV-ASSISTED INTEGRATED SENSING AND COMMUNICATIONS (ISAC)

A wide variety of sensors (such as radar, camera, laser) and air interfaces (such as WiFi, LoRa, 5G/6G, etc) are available to UAVs to facilitate navigation, target tracking, and communications. In spite of this, barriers still exist that prevent broader use of UAVs. Many UAVs perform missions in either dense urban environments where path planning is difficult due to narrow space, or in extreme environments where both cellular and GPS signals are non-existent. A solution to these

challenges could be found by utilising integrated sensing and communication (ISAC), which has been recognized as an emerging technology towards 6G [138]. ISAC enhances UAV communications by facilitating mutual benefits of sensing and communication [139]. On one hand, sensory data of a UAV’s location, velocity and channel environment can be used to mitigate interference, reduce the delay of beam tracking, and improve the communication performance. On the other hand, wireless signals of UAVs can be used to detect and avoid obstacles, reconstruct the environment 3D map and improve positioning accuracy.

While research activities on ISAC have been conducted in several fields, the performance of ISAC for UAV applications is still not fully investigated. A major challenge is joint design of sensing, computing and communication systems with UAVs. As an example, continuous sensing and communication can consume a lot of battery power, and co-channel interference may occur when UAVs provide both communication services and radar sensing. Chang et al [140], design a joint scheduling method for sensing, communication and control for UAV communications with mmWave/THz interfaces. A beamforming strategy is determined by considering both communication data rate requirement and sensing-control pattern. Zhao et al [141], study how jittering affects the UAV communications and develop a channel estimation method based on ISAC in which sensing, communication, and control all work together for improved performance. Research in [142] explores how ISAC assists multi-target tracking with a swarm of UAVs. With the help of an ISAC-based cyber-twin model and UAV collaboration framework, UAVs can sense and track mobile targets on the ground in real-time and with low cooperation overhead.

By using ISAC technology, we can push the physical limits of UAVs and enable them to adapt reliably, agilely, and efficiently to complex as well as extreme environments. Researchers from broader communities are encouraged to promote multidisciplinary innovations in high-performance ISAC systems and UAV applications. Where relevant, future research is encouraged to cover the design, techniques, methods and testing tools that enhance the performance of ISAC-enabled UAVs in real-world tasks.

3) MULTIPLE-INPUT-MULTIPLE-OUTPUT (MIMO)-ASSISTED UAV COMMUNICATIONS

MIMO technology represents a foundational advancement in modern wireless access systems. Conceptually, MIMO exploits spatial diversity and multiplexing through multiple antennas at both transmitter and receiver ends to enable parallel data streams over the same time-frequency resources. In this way, the spectral efficiency and network capacity can be dramatically enhanced without additional bandwidth. Also, the communication link reliability can be significantly improved through spatial diversity gain, mitigating multipath fading and boosting bit-error-rate performance. Moreover, the increased number of antennas enables precise spatial

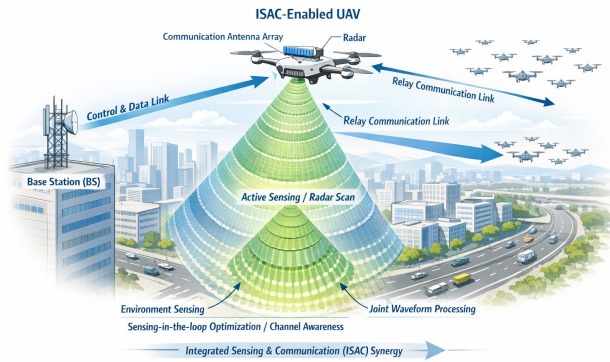


FIGURE 5. An Integrated Sensing and Communication (ISAC) smart city scenario. A base station (BS) links to an ISAC-enabled UAV, equipped with both a communication array and a radar. The radar performs active sensing of the environment, and this real-time information is used to optimize and steer the UAV's communication beams, demonstrating the core ISAC synergy.

beamforming, which increases the signal strength. In fact, the development of MIMO technology signifies the progress of mainstream commercial wireless networks such as 4G LTE and 5G NR.

The integration of MIMO technology into UAV communications offers promising opportunities to enhance spectral efficiency, coverage, and reliability. For instance, Huang et al. propose a deep reinforcement learning framework that leverages massive MIMO to optimize UAV navigation through real-time signal strength analysis, achieving improved coverage and convergence over conventional schemes [143]. Feng et al. studies the UAV-aided data collection optimization for IoT devices via virtual MIMO links, where an iterative algorithm is proposed to maximize the collection efficiency using only large-scale CSI [144]. Li et al. investigate dual-functional MIMO systems capable of simultaneous communication with legitimate users and jamming of unauthorized UAVs, presenting a joint beamforming design that operates effectively even when the total number of devices exceeds the antenna count [145]. Furthermore, Chen et al. introduce a CSMA/CA-based multi-user MIMO MAC protocol for UAV ad hoc networks, incorporating integrated sensing and backscatter communication to enable real-time address resolution and concurrent uplink transmissions, thereby improving throughput and reducing access delay [146]. In addition, Huang et al. addresses the challenges of massive MIMO for cellular-connected UAVs, such as pilot contamination and 3D beam tracking, by proposing innovative solutions, such as interference-cancellation-based pilot decontamination and Kalman-filter-based channel tracking, to maintain reliable aerial links [147]. Future MIMO advancements will further enhance UAV communication reliability, capacity, and scalability, enabling advanced applications like massive UAV swarms and ultra-reliable aerial networks.

4) DIGITAL TWIN for UAVs

Digital Twins (DTs) are virtual replicas of physical systems that use data from sources like Internet of Things (IoT) to model, monitor and improve network performance in real time. Their operation involves three primary steps that is; data acquisition, data processing, and data application. During the data acquisition stage, data is gathered from the physical network with the help of sensors and IoT devices [148]. This data is then analyzed and processed using sophisticated algorithm and machine learning process in the data processing segment [149]. The processed data is used to update the digital twin within the data application stage, so the real time results may be monitored, analyzed, and decisions may be made [150]. It is worth to note that incorporating DTs in the Unmanned Aerial Vehicle networks will definitely benefit from the enhanced efficiency and reliability. Sensors that may be mounted on UAVs, also known as drones, include those that provide information on the UAVs' state, the environment, and the network [151]. This data is consequently relayed to increase the DT's virtual model with real-time updating. The integration process involves establishment of a link between the UAV's and the (Digital Twin) DT through a wireless connection, which can include 5G or LoRaWAN [152]. The UAVs send the collected data to the DT through this link while the later processes this data and returns feedback to the UAVs with regards to their conduct [149]. DTs can give information on UAV flights in almost real time, thus ensuring that any uncharacteristic behavior is corrected and could go a long way in minimizing risk and ensuring reliability in UAV operations [151]. They can also shorten the time and cost spent on UAVs maintenance by predicting the likely breakdowns and planning for maintenance routines [149]. In addition, DTs can improve the effectiveness of UAV networks by adapting the networks' paths and tasks according to real time information resulting in cutting down UAV network power consumption and an increase in its performance [153]. Further, the NDTs can also be applied for the training of UAV operators in a simulated environment so that they can enhance their competency in various real life operation [149]. In line with 3GPP standards, digital twins for UAVs are generally aligned with the standards specifically, the integration of digital twins into UAV operations is in line with the enhancements introduced in 3GPP Release 15 [154]. This release marked the first substantial efforts to connect UAVs via 3GPP networks, particularly through LTE enhancements that cater to aerial user equipment (UEs). These enhancements focus on ensuring reliable communication, improved mobility, and enhanced network efficiency for UAVs, which are critical for the accurate and real-time operation of digital twins. Furthermore, Release 16 built upon these advancements by introducing further support for UAV communication, including network slicing and edge computing capabilities, which are essential for the high data throughput and low latency requirements of digital twins. Subsequent releases, such as Release 17, have continued to refine and expand these capabilities [155]. Release 17 introduced enhancements for

non-terrestrial networks (NTNs), which provide improved connectivity for UAVs operating in remote or challenging environments. These developments ensure that digital twins operate seamlessly, offering precise simulations and real-time analytics that are crucial for applications ranging from surveillance to delivery services. By leveraging these 3GPP standards, the integration of digital twins with UAVs not only enhances operational efficiency but also ensures adherence to global communication protocols, thereby supporting scalability and interoperability. Introducing Digital Twins can improve the functioning and control of UAV networks based on real-time updates and analytics, as well as decision-making solutions. The incorporation of DTs into the UAV networks creates enhanced safety, reliability, firmness, and creativity in UAV systems.

Key Insights and Lessons Learnt: UAVs are highly useful in infrastructure-less and infrastructure-oriented IoT scenarios and excel in gathering vast amounts of synchronized sensor data and distributing updates in real time due to their 3D mobility and flexibility. In data-related aerial operations, UAVs can minimize the age of information, ensuring that the most recent information is efficiently delivered to its intended recipient [156]. UAVs can play a vital role in emergency services and public safety by enabling rapid data dissemination in disaster zones. Additionally, UAVs can efficiently transport healthcare and telemedicine data from remote locations to healthcare facilities, ensuring timely medical attention and diagnosis.

UAVs can be used in various roles, including as base stations [95], relay stations [105], [106], [107], and sensors/actuators [113], each with its own set of challenges and opportunities. Challenges include but are not limited to, energy optimization, optimal UAV placement, communication coverage, bandwidth optimization, trajectory and path planning, network management, wireless power transfer, and wireless security. These challenges can be mitigated by employing emerging technologies such as RIS-assisted UAV communications [133] and UAV-assisted ISAC [138], [139]. RIS can improve UAV communication performance, extend communication range, enhance data relaying, improve PHY layer security, and enable efficient information-and-power transfer. ISAC, on the other hand, can enhance UAV communications, enable joint design of sensing, computing, and communication systems, improve obstacle detection and avoidance, enhance positioning accuracy, and enable real-time target tracking.

E. SELF-ORGANIZATION

Self-organization represents the process that allows UAVs to form an ad-hoc network and maintain communication with each other as part of this network. Termed also as *ad-hoc networks in the sky* [157], [158], self-organized ad-hoc networks of UAVs enable sharing of critical information such as airspace hazards, obstacles observed during the flight, emergency situations, sudden changes in weather, turbulence,

and vehicle health in real-time between its vehicles. IEEE created the P1920.1TM working group to develop the first standard for aerial ad-hoc networks in 2016. This working group completed a draft standard [159] in December 2022. The IEEE standard P1920.1TM defines the air-to-air communications for self-organized ad-hoc aerial networks [159]. The development of IEEE P1920.2: Vehicle-to-Vehicle Communications is currently in progress [160].

1) SELF-ORGANIZATION IS AKIN TO FLOCKING

There are strong similarities between self-organization and flocking, a behavior that is very routinely observed in nature among birds and animals. In a seminal work, Craig Reynolds captured the essence of flocking [161]. Later, he modelled and simulated flocking behavior with the help of agents which he named *boids* [162]. Reynolds defined flocking as an interaction of individual agents, adhering to a set of three simple rules for separation, alignment, and cohesion [162]. When high-quality wireless links are established among UAVs, it is reasonable to model self-organization by flocking from certain perspectives. In practice, this similarity is limited by wireless link qualities, which are related to factors such as channel fading, communication delay, and protocol overhead.

2) A RECIPE FOR SELF-ORGANIZATION

The framework for self-organization is somewhat different for UAVs due to the fact that UAVs are mechanical objects and are not as agile as birds and animals. The communication range among UAVs is also much larger in scale compared to that of birds. Further, wireless channels need to be established prior to creating an ad-hoc network, and aspects of consideration include the antenna design, spectrum availability, and transmit power, among other factors. Assuming that that such a framework of networking capability is pre-established, the recipe for establishing a self-organized aerial network can be summarized in the following few steps:

- **Aerial node addressing schemes:** Leverage existing standards from IEEE, Federal Aviation Administration (FAA) remote drone identification [163] and any other relevant standards or regulatory bodies to establish an addressing scheme that supports unicast, multicast and broadcast schemes,
- **Neighbor discovery:** Develop a strategy for discovering neighboring UAVs that are within the communication range,
- **Network formation:** Enable mechanisms for aerial nodes to join and leave the network in a dynamic fashion, and
- **Path planning and routing:** Provide support for efficient strategies for path planning and routing between any pair/group of UAVs interested in sharing real-time information.

It is worth noting that the creation and maintenance of ad-hoc networking of UAVs is an extremely challenging task, primarily due to the high mobility of UAVs. Hence, in the

real-world, UAV networks are usually augmented through some form of partial infrastructure such as satellite or cellular networks.

F. SPECTRUM MANAGEMENT

The fast-growing interest in using UAVs in commercial and civilian applications such as package delivery, disaster management, surveillance and traffic control involves various challenges in terms of radio spectrum management. A major issue is the lack of a dedicated spectrum for commercial drones, which would have helped, especially in a context where reliable operation, safety and security of drone operations highly rely on their spectrum access, in particular for command and control communication [164], [165].

Dynamic spectrum access for UAV networks and integration with legacy wireless networks involve new challenges related to the coexistence of terrestrial communication technologies due to the mobility pattern, and highly dynamic nature network topology. Therefore, the wide-scale operation of commercial UAVs, particularly small UAVs operating at low altitudes, is dependent on the development of new regulations and spectrum management strategies to guarantee continuous coverage, required QoS, identification and tracking, while imposing minimal interference to other networks. These strategies need to take into account the distinctive characteristics of UAV networks including the node 3D mobility, high velocity and limited lifetime, rapid time-varying communication channels, as well as other aspects such as mission, safety, privacy, and security. Unfortunately, the major concerns and issues related to UAVs' flight policy and regulations, safety, and security have detracted attention from other challenges, especially those related to spectrum scarcity which is an important concern given the fast-increasing demands for UAV-enabled services.

1) CURRENT SPECTRUM ALLOCATION FOR UAVs

Commercial UAVs primarily operate on the ISM bands (900MHz, 2.4 GHz and 5.8GHz) for C2 and payload communications. While the 900MHz-band offers favorable propagation characteristics for aeronautical communications, it cannot support high data transmission rate for payload communications. On the other hand, the 2.4GHz and 5.8GHz bands suffer from spectrum congestion and short communication range, particularly in urban areas. Noting the limitations of these ISM bands in terms of reliability, data rate, and high chance of interference to serve the increasing demand for UAV communications, the FCC is considering the use of 60-64 GHz band for drone operations with unlicensed field disturbance sensors to be used by collision avoidance systems.

Realizing the full potential of UAV systems in terms of advancing their commercial applications requires the allocation of a dedicated spectrum to these systems to enable traffic management, tracking, safe operation as well as payload communications. Radio Technical Commission for

Aeronautics (RTCA) has allocated a dedicated spectrum for C2 communications to medium and large UAVs, however, no spectrum band has been yet allocated to small commercial UAVs [166], [167], [168]. FCC investigated the feasibility, conditions, and required regulations for the operation of UAVs over several bands including 960-1164 MHz and 5030-5091 MHz [169]. An FCC report published in August 2020 concluded the suitability of the 5030-5091 MHz band for UAV operations and recommended developing service and licensing rules to enable the utilization of this band for UAV systems, while also raising concerns regarding the use of the 960-1164 MHz band for this purpose due to interference caused for Aeronautical Mobile Satellite (Route) Service (AMS(R)S) systems operating in the adjacent 960-1164 MHz band [170]. In January 2023, the FCC published a notice of proposed rule making to allow the operation of UAS command and non-payload communication in the aeronautical VHF band (5030-5091 MHz).

Furthermore, as discussed in Section VI, employing cellular-connected UAV communications is a promising solution that offers global coverage, remote identification, and reliable security if the strong interference caused to terrestrial UEs and base stations is addressed [6], [171], [172], [173]. Specifically, mmWave communications can offer high data transmission rates for payload in UAV-ground communications if a LoS link can be maintained through optimal positioning, trajectory planning or beamforming techniques [174], [175], [176]. mmwave communication is also an appropriate choice for UAV-UAV communications given the high probability of LoS communications among the drones.

2) SPECTRUM SHARING IN UAV NETWORKS

Several spectrum sharing schemes have been developed to enable dynamic spectrum sharing between the UAV networks and terrestrial networks such as WLAN, and cellular networks. Employing one of these schemes is a viable solution to the spectrum scarcity challenge for UAV systems [177], [178], [179], [180], [181], [182], [183]. These schemes rely on various spectrum sharing techniques including overlay, underlay and interweave. The spectrum access techniques for UAVs can be generally classified as follows:

- **Opportunistic Spectrum Access:** In this spectrum sharing approach, the UAVs are secondary unlicensed users and utilize the spectrum gaps of licensed users, also called as primary users. This method involves considerable energy consumption at the UAVs to search for the spectrum holes using temporal-, spatial- or spatial & temporal- spectrum sensing, and requires a fast decision making mechanism at the UAV to identify when and for how long use the spectrum is possible [184], [185], [186], [187], [188]. Noting the rapid movement of UAVs, the spectrum sensing measurements may become quickly invalid as UAVs move to new locations. This fact calls for low-computation yet accurate spectrum

sensing techniques to be deployed at UAVs as well as accurate spectrum prediction models to predict potential spectrum holes, as to reduce the size of spectrum search space [185].

- **Competitive Spectrum Access:** Competitive spectrum access involves unlicensed users (spectrum buyers) placing bids for getting spectrum access from single or multiple competing sellers using one of existing spectrum auction mechanisms such as forward, combinatorial, online, or collusion-resistant. For instance, the authors of [189] developed a decentralized open market solution for spectrum leasing for UAV base stations when several mobile network operators (MNOs) are available as spectrum sellers.
- **Cooperative Spectrum Sharing:** When considering cooperative spectrum sharing, the primary users coordinate with the spectrum seekers (e.g., UAVs) to share with them a portion of their spectrum access (in time, space or frequency). In order to get spectrum access, the primary users may charge the UAVs with a spectrum access fee or the UAVs can provide the primary users with a service such as cooperative relaying when the licensees are located in an area with poor signal coverage or cooperative jamming to enhance the primary users service [181], [190], [191], [192], [193]. These cooperative schemes can guarantee an orthogonal (interference-free) spectrum sharing mechanism while offering benefits for both the licensed users and UAVs. However, these schemes often involve an overhead signaling for coordination and require knowledge of users' locations and their instantaneous CSI levels.

Several challenges related to spectrum sharing among UAV and licensed users need further investigations. Some future research directions include developing agile spectrum sharing models, power control, beamforming and interference mitigation techniques, which are tailored to UAVs' high speed, dynamic network topology, 3D mobility and limited lifetime, while preserving the privacy of UAVs' information (e.g. location), particularly during sensitive missions.

G. CHANNEL MODELING

The development and examination of UAV communications critically depend on precise models of electromagnetic propagation [7], [65], [66]. Existing standardized channel models typically decompose the air-to-ground link into (i) large-scale effects (LoS/NLoS state, path loss, shadow fading, penetration loss) and (ii) small-scale effects (multipath delays/angles, cluster powers, Doppler, polarization), which are then instantiated stochastically to support MIMO and beamforming evaluations. For UAVs, a key requirement is altitude-aware modeling of LoS probability and large-scale parameters, since elevation changes both the dominant angles and the interference geometry (many more base stations may become LoS interferers). Moreover, the relevant physics is strongly frequency-dependent: sub-6 GHz links may

retain viable NLoS through diffraction and rich scattering; mmWave links are typically sparse and blockage-/reflection-dominated, making link-state/outage and beam misalignment central; and above 100 GHz, atmospheric absorption and weather losses can dominate.

Existing statistical models, crafted by standardization entities like 3GPP, facilitate the creation of random instances of channel characteristics for specific links: propagation path angles, gains, and delays. These models are derived from theoretical considerations and empirical data, a process increasingly challenging due to the systems' growing complexity and diversity, including new and wider frequency ranges, extensive antenna arrays, and unconventional deployments and user sites. In aerial contexts, this complexity is exacerbated by additional factors such as UAV heights, their three-dimensional orientation, and the heights of buildings. Accurately modeling these relationships is crucial for advancing multi-antenna aerial communication systems, though such implementations are notably intricate [67]. Furthermore, operating these channel generation systems can become highly resource-intensive in scenarios with numerous radio links. For UAVs, this involves managing LoS connections with several BSs, each contributing interfering signals that must be considered. 3GPP channel models, partly rooted in terrestrial measurements which significantly differ from aerial contexts, especially in the mmWave bands, are not adequately calibrated. Additionally, these models, originally designed for BSs targeting ground users, fail to replicate the characteristics of specialized uptilted deployments aimed at UAV pathways, such as those on rooftops. These models are statistical, designed to simulate various scenarios with varying degrees of realism rather than specific environments like a city or district. Rigorous UAV propagation modeling requires altitude-aware link-state and antenna-pattern considerations (to capture interference geometry), and frequency-aware inclusion of blockage and scattering mechanisms. While digital twins of specific propagation environments can be created using ray tracing, this method demands an exhaustive blueprint, including the dimensions, forms, and positions of all obstacles, as well as their electromagnetic traits. The high computational demands often prevent real-time extensive network optimization. Recent GPU-accelerated (and even differentiable) ray-tracing frameworks, such as Sionna RT [194], can generate channel impulse responses and radio maps from detailed 3D scenes orders of magnitude faster than classical RT pipelines, enabling site-specific calibration and learning-based surrogate modeling at scale [195].

Both the conceptual and operational complexities of channel modeling are impeding the progress of aerial communications research.

Site-specific channel modeling using data-driven methods has recently been introduced, correlating physical locations with channel characteristics via regression [68], [69], [70]. In contrast, deep generative neural networks offer a means for non-site-specific propagation modeling [71], [72], which requires minimal assumptions and can still mimic specific

propagation environments and capture complex probabilistic relationships. For example, in [73], a dual-stage architecture was employed, initially predicting the link condition (LoS vs. non-LoS) before channeling this information into a conditional variational autoencoder that computes the path losses, delays, and angles for all propagation paths. Alternative methods for creating synthetic multipath channel realizations involve standardizing channel parameters and converting them to images [74]. The image formation is beneficial as it enables the use of deep convolutional generative networks, adept at performing edge detection and learning (non-linear) spatial correlations among the image pixels. Nonetheless, most existing models only yield independent channel snapshots, unable to depict signal fluctuations over time. This is generally sufficient for average performance evaluations where only a marginal distribution is needed, but it falls short and may introduce errors when assessing advanced PHY algorithms for multi-antenna communications and sensing or when enhancing radio access networks to accommodate user movement. Another key consideration worth pointing out is the generalization ability of these generative models [75], which is necessary across various heterogeneous environments such as urban, suburban, and rural scenarios, which differ in terms of scattering density, building morphology, and elevation statistics.

More recently, [76] introduced a framework based on the transformer time-series conditional GAN (TTS-CGAN) [77] and the multivariate time series conditional GAN (MTS-CGAN) [78] for spatially consistent channel modeling. This model specifically depicts the large-scale channel behavior as the local-average received signal strength (RSS) of a UAV navigating typical urban trajectories. In particular, the set of conditioned channel parameters for the k -th trajectory is represented by \mathbf{x}_k , while the evolution of the distance between the user and the gNB is denoted by \mathbf{u}_k . The objective of this model is to capture the dependencies within the large-scale channel gains across multiple gNBs for a series of typical trajectories, thereby modeling the conditional distribution $p(\mathbf{x} | \mathbf{u}, c)$. While this methodology enables the generation of RSS sequences along designated trajectories for specific base stations, additional efforts are needed to incorporate small-scale fading and thereby deliver a complete multipath channel response, including path gains, delays, and angles, which are essential for crafting site-specific deployments and for the development and validation of AI/ML-based multi-antenna PHY algorithms.

Key Insights and Lessons Learnt: The development of UAV communications relies on accurate electromagnetic propagation models, which are challenging due to the increasing system complexity and diversity of aerial communication systems. Standardized state-of-the-art statistical models, derived from empirical data and theoretical considerations, struggle to keep up with the evolving nature of UAV systems with additional variables such as UAV altitude, flying speed, acceleration, and 3D orientation. Data-driven methods have been proposed for site-specific channel modeling,

but they require extensive data and may not capture the intricacies of UAV-specific propagation. Generative AI, particularly deep generative neural networks, offers a promising approach to non-site-specific propagation modeling, capable of mimicking complex propagation environments and capturing probabilistic relationships. However, further research is required to more accurately model large-scale channel behavior and incorporate small-scale fading. This would enable the generation of a comprehensive multipath channel response, crucial for advanced UAV communication system design and AI/ML-based PHY algorithm validation. In addition to this, ensuring spatio-temporal consistency in the generated channel samples remains another key challenge, especially for trajectory-aware simulations where channel evolution must be modeled over time and space. This becomes critical for evaluating time-sensitive algorithms and real-time link adaptation mechanisms in UAV deployments scenarios [79].

H. COMMUNICATION PROTOCOLS

Communication is a crucial issue when deploying high mobility multi-UAV systems. The protocols of FANET need to adopt the dynamic topology, changing link qualities, the high mobility of UAVs and their limited power issues. In this section, we discuss various solutions proposed at the lowest layers (physical, data link, network, and transport) in the OSI network model.

1) PHYSICAL LAYER

The physical layer consists of the signal transmission technologies of a network. Signal transmission and reception are achieved using diverse antenna types and different UAV-specific aspects greatly influence the transmission process. For instance, typical large distances between UAVs indicate that the signals are prone to interference. Nodes in FANET are usually far away from the ground, the communication between UAVs mainly relies on the line-of-sight (LoS) paths. The radio propagation in a FANET is close to free space environment. The communication quality is sensitive to the doppler effects, changes in communication distance, and blocking LoS by the aircraft body. Directional antennas introduce higher antenna gain and have the potential to increase transmission range and data rate. A directional and multiband antenna proposed in [196] effectively addresses the co-channel interference between UAVs and the ground station. The key solution in this study is to reduce the antenna weight by designing a directional antenna employing a lightweight woodpile reflector. The lightweight woodpile reflector not only maintains the antenna radiation performance but also extends the flight time of the UAV, resulting in contributing to the widespread of long life UAV-aided wireless networks. Research work carried out by [197] proposed a directional antennas based medium access control (MAC) protocol to adapt the the FANETs architecture. In this study, multiple directional antennas are used on a single UAV with IEEE 802.11 protocol. The solution addressed the some

unique challenges of using directional antennas and improved the overall performance of the network.

The physical layer is related to hardware aspects of the network like voltage and power control for the network hardware devices, establishing their inter-linking, encoding, decoding, modulation, demodulation, accessing the physical medium and transmitting on it. In FANETs, the link characteristics are impacted by the form physical dimensions of UAVs and their onboard limited power batteries. Out of service UAVs might lead to session expiry and frequent network partitioning. Efficient algorithms bring the transmission power requirement to an optimum level to maintain the connectivity. Harvesting energy from the drone vibrations was studied in [198] to have long areal flights. Authors in [199] proposed a scheduling of beaconing periods using game theory to reduce the processor power of the UAV. "Sleep and Rate-adaptation" scheme introduced in [200] adopts power optimization by switching network interfaces to sleep mode during short idle timings.

2) DATA LINK LAYER

The high mobility and varying distances and direction between UAV nodes continuously change the network architecture in a FANET system, which directly impacts on the design of the FANET media access control (MAC) layer. Several MAC protocols for FANETs have been studied in literature, the transmission delay, throughput, and collision detection were the key concerns for designing MAC protocol for FANET. Full-duplex radio and multi-packet reception (MPR) and directional antenna are promising technologies for improving the performance of the MAC protocols in FANET systems [12]. The authors in [201] designed a multi-channel MAC frame structure for the safety packets (i.e., location and traffic accident) in FANETs to provide necessary information for the alignment of directional antenna. The protocol combines the advantages of multi-channel and directional antenna to provide different QoS guarantees for safety and service packets. However, in FANETs, the performance of UAV communication systems is significantly affected by the UAV lifetime. Designing energy-conservation protocols at data link layer can be achieved by clustering nodes, avoiding collisions, avoiding overhearing and improve duty cycles. An energy-efficient and location-aware MAC protocol was proposed in [202]. The protocol uses an efficient time slot mechanism to save energy and obtain location without affecting the quality of service (QoS). In [203], the authors proposed an energy consumption and channel gain cooperative MAC protocol by appropriately selecting relay mode based on the estimate transmit power, the residual energy and position of the node. The protocol optimizes the energy consumption of the UAVs, results in extending the lifetime of the network and improving the network performance.

3) NETWORK LAYER

The network layer provides the mechanisms for interconnecting different network nodes by forwarding packets

over network routes. Due to the specific characteristics of FANETs, the protocols need to adopt the dynamic topology, changing link qualities, the high mobility of UAVs and their power limitations. Power-aware routing protocols are required to enhance network lifetime. Optimised multi-UAV network planning should consider the effects of full coverage of UAVs, intermittent connections, network re-formation, changing schemes of UAVs, awareness of the backhaul, varying QoS and signaling overhead [204]. Joint topology control and routing (JTCR) protocol proposed in [205] focuses on addressing the topology control challenge and efficient energy management challenge of a UAV swarm. The protocol utilizes a two-phase topology control to offer a stable FANET topology at each time when the routing protocol forwards the sensed data to the base station. It balances the energy consumption of UAVs with reasonable control overhead. In result, it improves the network performance in terms of less number of re-transmissions, less end-to-end delay, better packet delivery ratio and connectivity rate. The research work carried out in [206] uses adaptive Q-learning to timely detect the topology changes with low overhead and accordingly adjust routing decisions in a distributed and autonomous way. Authors in [207] enhanced existing routing protocols using an adaptive hello interval algorithm, energy efficient hello (EE-Hello) to address the high energy consumption problem in FANETs. The EE-Hello algorithm calculates the network density in real-time to determine the necessary number of UAVs that can satisfy the network performance requirements with minimal energy consumption, and then the hello message feedback mechanism and the appropriate hello interval provide the better network throughput.

Active UAVs can reform a network through sub-netting and then achieve the optimal energy utilization. Cluster-based routing protocols of UAV networks are studied in [208]. Clustering can efficiently breakdown a large network into subgroups and dynamically adjacent groups each other geographically, optimal allocate radio resources, energy and location, and route and backbone format networks. Hence, Clustering technique offers an effective mechanism to address scalable issues in FANETs [209]. Authors in [208] divides the cluster-based routing protocols into two categories: probabilistic cluster-based routing protocols and deterministic cluster-based routing protocol. The major difference between two types of cluster-based routing protocols is the election of the cluster head (CH), where a random election of the CH is used in the probabilistic cluster-based routing protocols and using confident metrics to select a CH is used in deterministic cluster-based routing protocols. Reference [210] introduced an energy efficient cluster-based routing protocol that combines k-means and black-hole algorithms. In this work, the k-mean is used to form the initial clusters and the fitness value of each node computed by black-hole algorithm is used to find the CH of the cluster.

There are many reactive routing protocols proposed for FANET networks, such as ad-hoc on-demand distance vector (AODV), time-slotted AODV (TSAODV), and dynamic

source routing (DSR) [12], [211], [212]. The traditional route discovery process cannot fully explore the most connected and durable paths, which result in frequent link failure and high overhead seriously affect the data transmission [213]. Authors in [214] proposed a robust route discovery process that explores the paths with considering the balanced energy consumption among UAVs, predict the link breakages prior to their occurrence and the connectivity degree of the discovered paths. A cross-layer and energy-aware AODV routing protocol was proposed in [215], where an AODV routing strategy and Glow Swarm Optimization based CH selection were implemented on the network layer with the help of cooperative MAC protocol on the data layer. This cross-layer approach greatly reduces the network link breakages.

4) TRANSPORT LAYER

A transport protocol for FANETs requires these features: reliability, congestion control and flow control. In a UAV network, congestion is commonly caused by the high speed motion of UAV nodes and varying traffic rates. If a transient link is possibly unstable, the TCP congestion control should not be run unless lower speed transmission is required [216]. In multi-UAV system, multiple UAVs can often overload the receiver due to simultaneous operation. An open Predictably Reliable Real-time Transport (PRRT) protocol [217] leverages the PRRT protocol with other off-the-shelf networking and software components to provide latency-awareness and -predictable solution for supporting UAV applications. Low-Latency Reliable Transport (LRT) [218] protocol is a UDP-based solution that provides low latency transmission service with the same reliability of TCP. The protocol exploits online network coding that offers the similar rateless property and more flexibility to facilitate network-connected UAV applications. [219] proposes an adaptive offloading with multipath TCP architecture that addresses the limited computing resource and battery power in mobile UAV systems. The research work carried in [220] addresses the declined throughput in conventional multipath TCP if TCP algorithms are employed in high speed congested network. The research work proposes a multipath QUAD congestion control algorithm, a novel Cubic Congestion Control (CUBIC) TCP-based high-speed congestion management technique to mitigate the decreasing throughput of MTCP flows in the conventional congestion control algorithm. Similarly, [221] presents adaptive slow-start threshold TCP that addresses the connection instability in a UAV network due to frequent node mobility and routing update. The modified TCP can quickly restore unnecessarily reduced throughput by adjusting TCP parameters. The protocol is suitable for a FANET environment and improves the transmission speed of the overall UAV network.

I. COMMUNICATION REQUIREMENTS

3GPP has laid down specific guidelines to ensure efficient communication with UAVs. To begin with, the UAS nodes

must complete identification and registration procedures within the network, while also maintaining a consistent flow of status updates. Remote identification plays a crucial role in accomplishing this task. Following that, the terrestrial cellular network serves as the means to enable essential functionalities such as C2 and a diverse range of wireless services. These functionalities encompass operating the UAV from a remote location through either a designated controller, ground control station, or UAS Traffic Management (UTM) over the cellular communication network. Additionally, the cellular network allows for common broadband and UAV services, including video streaming and surveillance. The aforementioned details have been extracted from the 3GPP report, as presented in [222].

1) C2 COMMUNICATIONS

Controlling UAV flight operations involves four distinct C2 modes: steering to waypoints, direct stick steering, automatic flight by UTM, and approaching autonomous navigation infrastructure [223]. Each approach entails a defined prerequisite such as the timing between packets, size of messages, end-to-end delay, and other relevant metrics. In Table 5, you will find a comprehensive overview of the key performance indicators (KPI) associated with these modes. The established links for exchanging control packets operate bidirectionally, allowing for message interchanges between the UAV and the UTM, or between the UAV and its controller, or both. Properly acknowledging the receipt of all UAV-terminated C2 packets is crucial. This is because these transmissions may contain essential guidelines that are necessary for controlling the flight of the UAV. If the requirements of a new mode can be met, switching to an alternative C2 mode during operation is feasible. For further details, please refer to Table 5 which provides an in-depth analysis of the KPI pertaining to these modes.

For facilitating direct stick steering, the utilization of video feedback is recommended by 3GPP. To delve into further specifics, please refer to Table 6, which outlines the suggested parameters for video transmission.

2) ALTERNATIVE WIRELESS TECHNOLOGY-BASED SERVICES AND APPLICATIONS

The 3GPP standardization is expected to facilitate support for a variety of UAS applications and services to enable efficient incorporation and seamless collaboration between these technologies, as stated in [224]. These applications primarily revolve around the delivery of videos and photos captured by the UAV, serving purposes such as environmental/situational awareness, surveillance, and entertainment. The UAV-assisted wireless services, defined by 3GPP [223], include various deployment applications based on altitude. In urban and scenic areas, the live broadcast video service supports 8K resolution with data rates of 100 Mbps (uplink) and 600 kbps (downlink). It is suitable for virtual reality and healthcare applications. AI surveillance, designed for urban

TABLE 5. C2 mode KPIs defined by 3GPP TS 22.125, V176.0.

Control Mode	Packet Timing	Maximum UAV Speed	Packet Size	Time Delay	Acknowledgment
Waypoint steering (UAV terminating)	<1 s	Up to 300 km/h	100 bytes	1 s	Mandatory
Waypoint steering (UAV originating)	1 s	Up to 300 km/h	84-140 bytes	1 s	Not necessary
Direct stick steering (UAV terminating)	40 ms	Up to 60 km/h	24 bytes	40 ms	Mandatory
Direct stick steering (UAV originating)	40 ms	Up to 60 km/h	84-140 bytes	40 ms	Not necessary
UTM-guided autonomous flight (UAV terminating)	1 s	Up to 300 km/h	<10 kB	5 s	Mandatory
UTM-guided autonomous flight (UAV originating)	1 s	Up to 300 km/h	1500 bytes	5 s	Mandatory
Approaching Autonomous Navigation Infrastructure (UAV terminating)	500 ms	Up to 50 km/h	4 kB	10 ms	Mandatory
Approaching Autonomous Navigation Infrastructure (UAV originating)	500 ms	-	4 kB	140 ms	Mandatory

TABLE 6. Video feedback requirements for direct stick steering.

Operation	Data Rate	Resolution	Frames per second	Max. latency
Visual Line of Sight (VLOS)	2 Mbps	480p	30	1 s
Beyond VLOS (BVLOS)	4 Mbps	720p	30	140 ms

and rural areas, provides $4 \times 4K$ resolution with uplink and downlink data rates of 120 Mbps and 50 Mbps, respectively. Controlling UAVs remotely through high-definition video requires a minimum of 25 Mbps (uplink) and 300 Kbps (downlink) and is usable in urban and rural areas without LoS requirements. Real-time video streaming enables diverse camera options for entertainment experiences, with an uplink data rate of 0.06 Mbps. For public safety, emergency surveillance, and law enforcement purposes, intermittent static image service is available with an uplink data rate of 1 Mbps. Lastly, video streaming supports 720p and 1080p resolutions with data rates of 4 Mbps and 9 Mbps, respectively, suitable for exploration, inspections, and search & rescue missions. It is worth noting that these services are delivered through payload data, distinct from the C2 data that pertain to flight control operations.

J. SECURITY REQUIREMENTS

UAVs are cyber-physical systems (CPS) with unique natural characteristics such as small size, manoeuvrability and maintenance, which make them more vulnerable to cyber attacks. These attacks often target UAVs’ physical and software

components, the interface between the components, and the wireless communication channels. UAV communication systems such as FANET systems face even more serious security problems due to their specific unmanned nature, including high speed motion, remote wireless communication, dynamic topology, collaborative manners and uncontrolled environment. FANETs convey sensitive data and are vulnerable to the privacy threats. Furthermore, FANETs have more broader and wider coverage areas than other similar networks, such as MANET or VANET. Hence, providing security for UAV-based self-organizing networks is very difficult and challenging. Security and privacy in FANETs are major concerns to focus on.

Further, the UAVs can be easily jammed, and the network can be brought down; it is also physically dangerous and challenging. In [3], a set of threat vectors is identified based on the classification of FANETs in terms of connection, node, and communication protocol categories. The security threats based on the threat vectors and the security impacts according to the aspects, Confidentiality **C**, Integrity **I**, Availability **A** and privacy **P** are analyzed. Table 7, Table 8 and Table 9 outline the security threats and their associated security impacts. We provide a brief explanation of some of the major aspects.

Confidentiality. The UAV nodes in FANET systems require security mechanisms to mitigate information exposure. It is also important to hide the information exchange within the FANETs, for example, outside nodes should not know what a FANET (indeed a swarm) is going to execute.

Integrity. Integrity ensures that the FANET has adequate security mechanisms to guarantee that the transferred information has not been intentionally or unintentionally altered. There are many ways, including the side channel information

TABLE 7. Security threats according to connection vector.

Connection Vector [3]	Threats	Impacted Aspects (C,I,A,P)
“Connection between client terminals and GCS”	Eavesdropping Insider Replay	C, P C, I, A, P A
“Connection between GCS and backbone UAV”	Eavesdropping Jamming MITM Replay	C, P C, A, P C, I, A A
“Connection between backbone UAV and other UAVs in a FANET”, or “Connection among legitimate UAVs in a FANET”	Eavesdropping Jamming MITM Replay	C, P C, A, P C, I, A A
“Connection of a FANET with an unknown UAV”	Impersonate	C, A, I, P
“Connection to a cloud service from the backbone UAV, other UAVs, or ground devices (GDs)”	Data tampering Eavesdropping	C, I C, P

TABLE 8. Security threats according to node vector.

Node Vector [3]	Threats	Impacted Aspects (C,I,A,P)
“GCS & Backbone UAV”	Single point of failure (SPOF)	A
“UAVs”	DoS Selfishness Flooding attack Backdoor malware	A A A C, I, A, P
“Cloud Server & Storage”	Data tampering	C, A, I, P

or different communication modalities, to ensure the integrity of the messages on the primary channel in FANETs.

Availability. The nodes in FANETs can be jammed, thereby bringing the network down. Further, most FANET nodes depend on GNSS; GNSS jamming poses a threat to availability. Denial-of-service attacks can be mitigated through frequency-hopping mechanisms. Further, the IMU based navigation is also used.

Privacy. The nodes in FANET are required to keep the identification information and also the transactions. This is important to avoid breaches, etc., as well as preserving privacy. Mainly *Data privacy* – protecting sensitive information); Protection of *Routing and/or protocol information privacy* – strategies to protect user privacy while enabling collaboration among flying nodes; *Application and position privacy* – where the exchange of information between nodes and their status/relative position is protected.

The security mechanisms for FANETs must be included in the design of FANET systems. In the literature [3], [12],

TABLE 9. Security threats according to OSI layers.

OSI layers	Threats	Impacted Aspects (C,I,A,P)
Physical layer	Eavesdropping Jamming GPS spoofing	C, P C, A, P A
Data link layer	De-authentication Collisions Low link quality and high latency	A A A
Network Layer	Blackhole Grayhole Modification Rushing Wormhole	A A C, I, A A C,I,A,P
Transport layer	SYN flood	A

[38], [225], seven main security and privacy requirements for FANET systems are studied in detail. As given in Table 7, various connection vectors have different threats. These threats and the corresponding impacted aspects are also listed. For example, communication between GCS and terminals must address all four aspects. The table also lists threats related to cloud services and UAVs, including data tampering in the cloud and/or eavesdropping. The impacted aspects are C, I and P.

Table 8 provides security threats according to node vectors. For example, GCS and Backbone UAV each have a single point of failure, resulting in reduced availability. Similarly, DoS, Flooding attacks, and Backdoor malware can result in a lack of availability. Data tampering is an issue at the cloud service.

Table 9 consolidates all the threats and the corresponding threat impact at every OSI layer. PHY is affected by eavesdropping or jamming as well as GPS spoofing, where availability, confidentiality, and privacy are compromised. Datalink layers can be affected by jamming, leading to reduced availability. The network layer being open to multiple types of attacks can lead to all aspects being impacted. At the transport layer, lower-layer threats can affect the transport layer indirectly. However, an attack on a SYN packet can lead to a lack of availability or denial of service.

Leveraging onboard devices is promising for avoiding any infrastructure changes in the drones. Wu et al. proposed a distributed cooperative Spectrum Sensing (CSS) data fusion algorithm, which uses improved Q-learning and the Density-Based Spatial Clustering of Applications with Noise (DBSCAN) method. This algorithm effectively opposes different kinds of Spectrum Sensing Data Falsification (SSDF) attacks and improves the efficiency and accuracy of CSS [226]. An intelligent Sybil attack detection scheme was proposed for FANETs-based IoFT in [227]. The proposed scheme utilizes a supervised machine learning

TABLE 10. Security requirements and mitigation and challenges.

Security Requirement	Mitigation and Challenge
Confidentiality	The UAV nodes in FANET systems require security mechanisms to mitigate information exposure. Encryption mechanisms are usually used for protecting information leakage. However, limited power and computing resources are the main concerns UAV systems.
Integrity and Message Authentication	The UAV nodes in FANET systems require security mechanisms to guarantee the transferred information has not been intentionally or unintentionally altered. A successful man-in-the-middle attack compromises the content of the message. Thus, the requirement of detecting and preventing any message alteration is crucial in any communication scenario of FANETs.
Non-repudiation	The UAV nodes in FANET systems require security mechanisms to enforce non-repudiation and ensure the authority and responsibility of operators.
Authentication	The UAV nodes in FANET systems require to guarantee the submission of real identities of nodes. An unauthorized UAV should be identified from legitimate UAVs.
Access Control	The UAV nodes in FANET systems require security policies to guarantee the granted access of its resources is only to the authorized operators. The security policies are required for all devices, services, and protocols of UAV systems.
Availability	The UAV nodes in FANET systems require to perform and support the functionalities of UAV system within its life cycle at any time and any conditions. A Denial of Service (DoS) attack often targets any layer of the protocol including media access control, networking (routing), or application.
Trust and Privacy	The UAV nodes in FANET systems require to keep the identification information of the nodes private. The preserving privacy is required for all actors in FANET systems. Trustworthiness evaluation is required to be available to all UAV nodes, sensors and their GCSSs.

approach and physical layer characteristics of the radio signals, so it is less susceptible and does not require additional communications overhead of the UAV nodes.

Efficient and secure communication among the drones is critical in the FANETs. Hyperelliptic Curve Cryptography (HECC), a much more advanced version of elliptic curve, is employed in a certificate-based access control and key agreement scheme [228] to address the issue of concomitant threats at the Medium Access Control (MAC) layer. A deep learning-based secure multicast routing protocol (DLSMR) was proposed to establish a high-stability multicast tree and improve the security performance against wormhole attacks in FANETs [229].

The blockchain is a decentralized and distributed digital ledger that is especially useful in dealing with decentralized systems [230]. A blockchain stores a collection of transaction records in blocks that are connected via a hash pointer [231]. Every block contains a hash of the previous block, so the record cannot be retroactively changed without altering all subsequent blocks and the network’s consensus [232]. Blockchain employs cryptographic techniques so that it is an immutable and tamper-proof ledger. Blockchain and FANETs are both growing research areas. Blockchain-based approaches for various aspects of securing UAVs’ networking are proposed in some recent research.

A cluster-based routing scheme is proposed in [233] to address optimal cluster head selection and secure routing of data in FANETs. A lightweight blockchain consensus

algorithm is proposed to utilize the optimal cluster head for mining.

Key management for FANETs not only affects the performance of UAV communication and may also be an attack target. A blockchain-based key management scheme is studied in [234], which implements a newer lightweight miner election algorithm for heterogeneous FANET to reduce the computation time. The scheme allows each UAV can have its own “transaction chain” for updating its public/private key pairs and migrating between clusters. The solution can also revoke malicious UAVs based on the traceability of the blockchain in order to prevent external and internal attacks. Similarly, a lightweight blockchain-based routing algorithm proposed in [235] leverages 5G New Radio (NR) technology to improve the security of the routing for swarm UAS networking. The algorithm also extends the scale of deploying swarm UAS networking by reducing the routing consumption. The authors of [236] introduced blockchain technology for global navigation satellite system (GNSS) spoofing detection for multi-UAV system to enhance the security of FANETs. Blockchain-enabled zero-trust UAV networking has recently advanced through mobility-aware byzantine fault tolerance (BFT) mechanisms. In particular, an adaptive chained Byzantine fault-tolerant (ACBFT) protocol is introduced in [237] tailored for UAV ad hoc networks, incorporating dynamic committee election, micro-block pipelining, and mobility-aware fault handling to achieve significantly lower consensus latency and overhead than traditional practical BFT-derived schemes.

Table 10 summarizes the mitigation mechanisms and challenges for seven main security requirements. In the following, we discuss various modern technologies employed in security countermeasures for FANETs.

Key Insights and Lessons Learnt: The integration of UAVs into commercial applications brings challenges in spectrum management and communication protocols, impacting reliable, safe, and secure communication operations. The increasing demand for UAV-enabled services has led to a shortage of dedicated spectrum for UAV operations [177]. The use of dynamic spectrum access and sharing schemes, such as opportunistic spectrum access, competitive spectrum access, and cooperative spectrum sharing, can help alleviate the spectrum scarcity challenge [238]. Further research on developing agile spectrum sharing models, power control, beamforming, and interference mitigation techniques is needed to address the challenges in UAV spectrum management. Multi-UAV communication protocols need to be designed carefully considering the unique challenges in a high-mobility dynamic aerial environment [239]. Communication protocols, from radio propagation to flow control, guarantee dependable UAV operations by managing transmission, collision detection, routing, and data exchange across multiple layers including physical, data link, network, and transport.

Security requirements for UAVs focus on confidentiality, integrity, non-repudiation, authentication, access control, availability, and privacy. These requirements aim to protect UAV nodes from information exposure, unauthorized access, and data alteration, while also ensuring operator accountability and system availability [240]. Blockchain has been a promising solution for secure UAV networking, addressing key management and routing [241]. The communication requirements for UAVs are extensive and 3GPP standardization is expected to support a wide range of UAV-assisted applications and services under various control modes, with a particular focus on video and photo delivery for a range of purposes, from environmental awareness to entertainment.

K. RESOURCE OPTIMIZATION

1) ALGORITHMS

The proliferation of UAVs has given rise to several applications and services in different fields due to their unique properties such as the high scale of autonomy, controllability, aero dynamicity, and programmability. Their tangible potential continues to grow with advances in miniaturization and ubiquitous connectivity. Characteristically, UAVs are equipped with batteries, microprocessors, and micro radio devices of limited capacity. Hence, effective use of the scarce resources is essential.

Resource allocation is a fundamental and evolving part of many problems in classical and modern computing and communication systems including UAVs. Specifically, for UAVs, the techniques applied in the state of the art over the last two decades cover several aspects and address several challenges.

A natural classification of existing solutions is as follows:

- **Centralized/distributed:** Often, algorithms addressing the various challenges associated with UAVs are evaluated on a small scale using a centralized approach. However, for scalability reasons it is more suitable to design distributed algorithms.
- **Optimization Framework (convex/non-convex)** In many cases, the problems that arise in connection with UAVs are formulated and modeled using principles and theories borrowed from mathematical optimization. These include convex and non-convex optimization. Convex problems are simpler to analyze and solve than non-convex optimization problems, although they can be NP-hard. At last, the advantage of these tools is that they provide theoretical guarantees and optimality gaps.
- **Heuristic/Meta-heuristic** The most commonly used techniques in the literature are heuristics and meta-heuristics. In general, heuristic approaches are related to the problem at hand, while meta-heuristics exploit different evolution mechanisms and operators providing a high level of abstraction.
- **Graph-theoretic-based Models** The interactions that occur in the investigated problems can be modeled by static [108], [242] or dynamic graphs [243]. Furthermore, the vast majority of studies use (static) graph theory [108], [242] to represent and model them.
- **Online/Offline** Online algorithms arise in any situation in which decisions must be made and resources allocated without knowing the future requests. In contrast, an offline algorithm takes decisions and allocates resources based on a full knowledge of the requests.

2) INNOVATIVE APPROACHES

Aerial deployment of UAVs has attracted considerable interest in the literature [41], [95], [244], [245], [246], [247], [248], [249], [250], [251]. In particular, the 3D placement of UAVs (e.g., UAVs as base stations, as relay stations, and as sensors and actuators) and coverage probability are the main problems of interest.

In [244], a particle swarm optimization stepwise process was proposed to serve all the users with few UAV-BSs while optimally calculating and setting their 3D spatial coordinates. Alzenad, Mohamed, et al. in [95] investigated the 3D UAV-energy-efficient BS's placement problem to achieve the maximum user coverage while requiring as little transmission power as possible. The proposed nonlinear integer problem is used to find the optimal 2D and 3D coordinates in a decoupled way and is solved using the CVX solver. In order to establish the combined optimization of 3D access point (AP) placement with the minimum number for adequate coverage, authors in [245] availed application of the principles of 3D random geometric graphs. Then, a particle swarm optimization method is suggested along with an effective iterative algorithm. They considered the placement of each AP to be a different optimization problem. As a result, they

can be placed sequentially, according to a strong assumption stated in this research effort. Another research effort in [246] investigated the use of a genetic algorithm-based evolutionary optimization technique for a similar problem to maximize users' QoS requirements.

An exact and realistic mathematical model is developed to increase user connectivity in a geographically designated area while deploying as few UAVs as possible in [247]. The formulated problem was devised considering real-world network conditions and was solved by leveraging the branch and bound solution method. A simple heuristic is also suggested to solve the formulated problem exhibiting linear complexity. A spiral-based strategy for optimizing UAVs-MBs, utilizing the convex hull algorithm operated on each of them, was suggested in [248] for providing GUs wireless coverage. A study [249] suggests the effects of different channel models that relate to building geometries and urban form, including reflection and propagation in the UAV placement optimization models [41] on the air-to-ground path loss modeling.

The work proposed in [250] models the deployment problem with conflicting cost functions aiming to use a few UAVs and maximize their load distribution. It proposes a hybrid method to serve the GUs while guaranteeing robust wireless network coverage evenly. In contrast to earlier research efforts, the authors in [251] suggested a new method for arranging multiple flying base stations, simultaneously maximizing the throughput and conserving the GUs' limited energy. Moreover, to attain these optimization goals, the suggested evolutionary genetic algorithm adjusts the positions of UAVs-MBs following the motion of GUs.

To tackle the multi-UAV placement and user association joint-problem in uplink MIMO networks, a suite of decomposition-based strategies including a clustering technique and a successive convex approximation technique was proposed in [252]. In this work, a clustering algorithm is used to provide an initial guess of the cardinality the UAVs set under coverage constraints. Yet, to solve the user association and scheduling challenges, the successive convex approximation scheme is leveraged to aid in satisfying network capacity and coverage constraints.

Another research work [242] leveraged graph-theoretic concepts to propose an efficient process to crack the backhaul connectivity and arrangement of a stream of UAVs problem to provide wireless coverage to users scattered over each geographical zone. In this research effort, finding the number of drones to place, the associated 3D coordinates along with the backhaul connectivity are jointly optimized, and the performance guarantees of the algorithm are discussed in detail.

Unlike the above works, two distributed algorithms based on first-order methods were proposed to optimize the UAV swarm positions to achieve the highest gain under a line-of-sight MIMO backhaul [253]. These different algorithms rely on position estimation and channel information, respectively.

The second category of research elaborated on the role of the UAVs as relay stations. In this category, several of

these studies were undertaken to accomplish different objectives [105], [106], [107], [108], [109], [110], [111].

Authors in [105] advocated using nonorthogonal multiple access technology (NOMA) for UAV communications with ground users. In this research effort, the UAV operates as a decode-and-forward relay to boost the sources' coverage. Information-theoretic system throughput and outage probability were the main performance metrics for assessing the solution and Monte Carlo simulation settings.

A multi-UAV network relaying messages from ground access points to a remote base station was investigated to study the various aspects that affect the network in the context of multiple antennas [107]. The proposed algorithms include a heading control algorithm maximizing the uplink transmission rate of a multiple UAV network and a handoff algorithm to account for the motion of UAV relays for better performance. Furthermore, a relay deployment strategy is also envisioned for the scenario when the multi-UAV network cannot sustain the demanded quality of service. However, this research effort made several simplifying assumptions.

A scenario using only a solo UAV in connection with a ground base station was researched to enable connectivity to a group of distant ground users by means of two path loss models [109]. The problem of efficiently placing a single UAV was formulated and solved using evolutionary algorithms. Regarding the optimal placement of the single UAV, the particle swarming optimization approach was employed to calculate its coordinates then, with the help of a water-filling optimization, the total throughput was maximized.

The problem of jointly optimizing UAV trajectory and power optimization for relay networks was framed using a non-convex optimization framework to minimize the outage probability [110]. A tractable decomposition gradient-descent algorithm was suggested to resolve the resulting problem through the alternating minimization optimization strategy. In this procedure, the path of UAVs is optimized first, and then the resulting power control is iterative until the convergence criteria are met.

In order to enable self-healing capabilities for fixed ground stations that account for cell failure and overload issues, interference-aware genetic positioning of air relays has been proposed to determine the coordinates of the UAVs to maximize the downlink throughput of a 4G/LTE cellular network [111]. In this research work, it is hypothesized that the UAVs operate with a random frequency hopping scheme, and the proposed approach as well grants the UAV relays to operate as a traffic offloading system in case a base station is overloaded.

Unlike the research efforts stated earlier, the UAV relay chain positioning problem for surveillance missions was formulated as a graph search problem and solved with two distinctive efficient graph-based techniques applicable to discrete space [108]. In this study, the authors consider an environment with known obstacles and a mission-specific quality measure to optimize. The first method leverages Dijkstra's algorithm with the Pareto principle. The other scheme

TABLE 11. Comparison among representative works about innovative approaches.

References	Category	Application scenarios	Advantages	Disadvantages
[95]	Convex optimization	UAV BS placement	3-D design, power efficient	Difficult to be extended
[247]	Heuristic method	UAV BS placement	3-D design, QoS-aware	Difficult to be implemented
[252]	Convex optimization	Joint multi-UAV and user association	High quality solution	Suboptimality
[242]	Graph-based method	Multi-UAV coverage	High quality solution, backhaul aware	High complexity
[109]	Heuristic method	Single-UAV relaying	High quality solution	Difficult to be implemented
[110]	Convex optimization	UAV relaying, joint trajectory and power optimization	High quality solution	Suboptimality
[108]	Graph-based method	UAV relaying, surveillance	High quality solution	Difficult to be extended

uses the dual ascent method bounded above by the cardinality of the UAVs set.

3) Research Challenges AND Opportunities

In terms of algorithms, given the proliferation of drones and their potential benefits, they can form a large-scale distributed system. Therefore, it is natural to design and implement distributed algorithms rather than centralized ones to tame this complexity. Distributed algorithms and, more generally, distributed optimization techniques must be used to design effective solutions and low-complexity algorithms [254], [255]. The study of these algorithms and the understanding of the parameters underlying their behavior and the conditions under which they converge are paramount to design such solutions. Only a handful of works attempt to address the existing challenges by using a distributed approach for scalability. Other graph-theoretic tools include hyper-graphs [256], fuzzy-hyper-graphs, and fuzzy-graphs [257] which are yet to be fully leveraged.

VI. STANDARDIZATION

A. GENERAL MODES OF UAV COMMUNICATION

Depending on their mode of communication, UAV network formations can be grouped under the following three broad categories: 1) Line-of-Sight (LoS) communications, 2) Non-Line-of-Sight (NLoS) communications through other aerial entities, and 3) Non-Line-of-Sight (NLoS) communication through ground infrastructure. Fig. 6 illustrates the three broad modes of communication (C1-C3) that UAVs can engage in during network formation or other application-specific scenarios. These modes are discussed briefly next.

- **Line-of-Sight** In this communication mode, the UAVs have to be in LoS of either the ground control station [258] or other UAVs [259]. The choice of communication technologies used with the UAVs and the mode of UAV control dictates the choice of the communication mode. The use of ISM band radios for experimental and hobby UAVs limits their operational range to LoS, mainly if a human operator manually controls the UAVs. The configuration C1 in Fig. 6 shows an example employing this mode of communication. Although the UAVs do not strictly have to be in LoS of other UAVs or ground control stations all the time, if they rely primarily on LoS operations, their mode of communication should

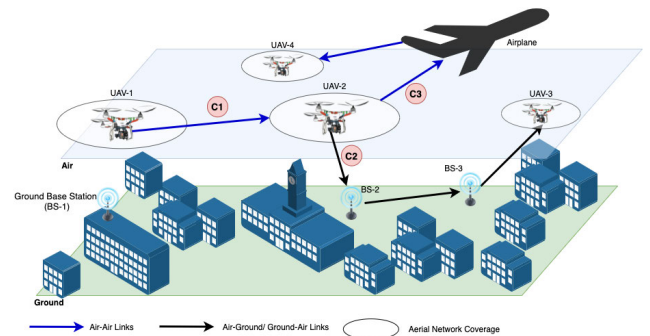


FIGURE 6. Various modes of UAV communications.

fall under this category. Next are some of the popular research topics associated with UAV LoS communications explored to date: ease of UAV control [258], energy optimization [260], aerial resource optimization [259] and constrained aerial computation [261].

- **Non-Line-of-Sight (Through Other Aerial Entities)** This communication mode is mostly deployed for extending the communication range [261] and functionalities (both computation and sensing) of the aerial network [262]. The UAVs in these applications typically need to be spaced far apart and do not rely on ISM band radios for communications. This mode of NLoS communication can be employed in a hybrid setup between UAVs and other aircrafts [263], or in a purely homogeneous deployment between similar UAVs [264]. Configuration C3 in Fig. 6 graphically represents this scenario where UAV-2 communicates with UAV-3 by bouncing signals off an airplane's communication setup. Typical challenges associated with this mode of communication in UAV networks include the following: bandwidth optimization [264], communication technologies [158], energy optimization [260], handoff strategies [265] and path/trajectory planning [264].
- **Non-Line-of-Sight (Through the Ground Infrastructure)** Similar to the previous section, this mode of NLoS communication groups approaches that have to necessarily work with a ground-based infrastructure. Configuration C2 in Fig. 6 graphically represents this mode where UAV-2 extends its communication range through BS-2 and BS-3 to eventually communicate with

UAV-3. Approaches for extending coverage of ground networks, aerial relaying, and other services fall under this category. The associated challenges are similar to the previous section for NLoS communication through aerial entities.

B. 3GPP STANDARDIZATION FOR UAV CELLULAR COMMUNICATIONS

The commencement of UAV communication standardization within 3GPP can be traced back to 2017 [86], [223], [266], [267]. This endeavor serves a dual purpose: making sure that standards for mobile communications adequately fulfill the connection requirements for UAVs to operate safely, while also preventing network users from encountering service disruptions caused by the proximity of UAVs [268], [269], [270], [271].

In Rel-15, 3GPP introduced 4G LTE support specifically tailored for UAVs. This entailed the inclusion of signaling protocols for aerial user identification based on subscriptions, reporting of UAV attributes such as location, altitude, and flight trajectory, as well as new measurement reports to tackle air-to-ground interference within a defined threshold of low-altitude UAV density. Additionally, an air-to-ground propagation channel model was defined, which has subsequently been leveraged in numerous research endeavors. Following 3GPP releases concerned application layer support and connectivity security for UAVs. Moreover, they defined the required interactions with the corresponding UAV Traffic Management (UTM) system. With the progression of 5G applications and use-cases, 5G NR Rel-18 will bring about support for aerial vehicles and devices embedded therein. This release will further explore conditional handover and additional triggers for cell reselection, dedicated uptilting of base stations antennas [272], mechanisms to signal beamforming capabilities at the UAV, and with various other enhancements [73], [273], [274], [275], [276], [277], [278].

The summary of the objectives and outcomes of the work carried out in 3GPP from Rel-15 to Rel-17, as well as the areas currently being examined for Rel-18, can be summarized as follows [6], [279].

- **Rel-15: Enhanced LTE support for aerial vehicles** Detailed in TR 36.777, suggested solutions at the user and network sides to mitigate interference both in the uplink and downlink, to address issues related to mobility, and enable identification of UAVs. Defined channel models building atop TR 38.901, taking into account the altitude of UAVs.
- **Rel-15: Enhancements to measurement report triggering** Detailed in TS 36.331, included two additional reporting events, H1 (above) and H2 (below) user height thresholds, to facilitate UAV identification by the network and mitigate potential interference.
- **Rel-16: UAV remote identification** Detailed in TS 22.825, explored the requirements and use-cases for remote UAV identification and the corresponding

services. Aimed to enable air traffic control and public safety agencies to access UAV identity and metadata through the UTM for authorization, enforcement, and regulation of UAV operations.

- **Rel-16: UAV connectivity, identification, and tracking** Detailed in TR 23.754, examined how 3GPP can support communications between the UTM and UAVs, and also enable to detect and report unauthorized aerial end-devices to the UTM.
- **Rel-17: 5G enhancements for UAVs** Detailed in TS 22.125 and TS 22.829, defined new UAV key performance indicators (KPIs) and connectivity requirements in terms of command and control link, data payload, radio access node onboard the UAV (UxNB), as well as UAV constraints on services and network exposure.
- **Rel-17: Application layer support for UAVs** Detailed in TR 23.755, explored applications to the tracking and identification of UAVs, the impact of UAV service requirements on the application layer, and UAV-UTM service interactions for managing location, route authorization, and support of group communications. Considered the reuse in aerial systems of solutions and architectures previously developed for V2X and mission-critical operations.
- **Rel-18: NR support for UAVs** Will investigate enhancements to measurement reports, signaling for UAV multicast and identification based on subscription, conditional handover and new triggering events, and beam management in FR1 (below 8 GHz), including the use of multi-antenna beamforming and dedicated BS antenna uptilt for UAVs.

C. CELLULAR-CONNECTED UAV COMMUNICATION AND CONTROL SERVICES

Ensuring the secure and dependable incorporation of UAS into airspace necessitates the provision of reliable communication services. Within this context, the 3GPP outlines a range of services and functionalities that can be categorized as follows:

- 1) AUTHENTICATION AND AUTHORIZATION OF A UAV
Among the functionalities provided by 3GPP communication systems supporting cellular-connected UAVs is the authentication and authorization via a UAS Service Supplier (USS) UAV Authentication & Authorization (UUAA) prior to granting connectivity for UAS services. The UUAA is enabled either via the 5G core (5GC) connected to next-generation radio access network (NG-RAN) or via the enhanced packet core (EPC) connected to LTE system. The authentication and authorization procedures performed by UUAA can be triggered during one of the following steps: separately as an optional step during the 5GS registration process depending on USS requirements, geographic regulations, and PLMN policies. Alternatively, it can take place during the process of creating a PDU session when a request of user plane resource demands is performed by the UAV within the operation or

through the configuration of the PDN in EPS connections. In cases where the UAV has been granted a CAA-Level UAV ID then that ID is provided within PDU session establishment and registration in the UUAA procedures. The communication systems defined by 3GPP facilitate USS authorization for establishing a connection between a UAV and a networked UAV controller (UAVC). This pairing can also occur when a UAVC is connected to the UAV through Internet connectivity. It can take place during the session establishment or while a PDN connection or PDU session is being modified. This connection can be used exclusively for C2 communication or shared with the USS.

2) UAS REMOTE IDENTIFICATION

The 3GPP and UTM that are responsible for serving UASs rely on the UAV ID, which is assigned by mobile network operators (MNOs), and the CAA-level UAV ID. These IDs are used to handle the identity and credential information of UAS nodes. Vendors define the identification and credentials information, encompassing aspects related to the UAS node, operator, or specific operational objectives status. A UAV can undergo registration with the UTM either prior to establishing a 3GPP network connection or by utilizing classical Internet connectivity. Before enrollment in 3GPP-enabled UAS services, it is necessary for the UAV to possess a CAA-level UAV ID. From 3GPP's perspective, essential parameters encompass radio frequency (RF) front-end capabilities and UAV communication subscription. However, an aerial subscription linked to a UAV necessitates the inclusion of not less than a single GPSI act in place of the designated 3GPP UAV ID.

UAS-Network-UTM Services: For UAS related services via cellular networks, both the UAV and UAVC need to register with the network. That is, the UAV-UE and the UAVC-UE first request to be attached to the network. After obtaining authorization to access the network for operating a UAV, carrying out other related tasks, receiving network services, and establishing the connection with the UTM for exchanging control information, an extra layer of authentication is activated at the application layer to enable diverse UTM applications including live position tracking and collision avoidance service for UAVs. In cases of a misalignment between the provided UAS information embedded in the attach requests and the registered subscriptions at the UTM, the request is rejected, and the operation is terminated. Furthermore, it is possible to deny the flying of the UAV if it attempts to operate within a prohibited area, commonly referred to as a no-fly zone, regardless of successful identity and credential verification. Furthermore, through remote identification, UAS nodes can provide crucial information about the UAV nodes that have been deployed, the active operators responsible for their operation, the designated geographic areas where they are operating, and other relevant data. This information plays a significant role in enhancing the enforcement of flight operations and aids in the detection of any suspicious activities that may arise.

3) C2 COMMUNICATIONS

Via a C2 connection, the UAV flight control commands get transmitted to the UAV, with the ability for the operator to initiate the commands from either the ground control station or the remote control system. C2 links must ensure seamless and accurate execution of flight control operations, guaranteeing real-time response and tracking performance. The C2 link functions as the primary conduit, facilitating the exchange of telemetry data between different UAS entities, and ensuring efficient monitoring of flight operations and flight safety procedures. The UAV possesses diverse functions for flying that a ground operator can handle effectively by utilizing the UAVC. Furthermore, the UAV and the UTM can be connected via C2 to enable the execution of various air traffic management functionalities. To meet the stringent reliability and responsiveness requirements of beyond visual line of sight (BVLoS) missions, end-to-end latency budgeting across the radio access network, transport, and application layers must be carefully designed to ensure alignment with URLLC grade service targets [280].

Leveraging the cellular 4G/5G network as a reliable transport network, multiple C2 connections can be established, including redundant links or data routing to alternative ground flight controllers. Figure 7 illustrates three C2 paths, which are described in continuation.

- **Direct C2 communications:** The UAV establishes a direct connection with its controller that is conditioned upon the authentication and registration of both nodes within the cellular network. Subsequently, the transportation of control packets ensues, utilizing a resource that can be tailored and managed by the network, all while accounting for the specific requisites of C2 communications.
- **Network-assisted C2 communications:** The communication between the ground-based control systems and the aircraft can be established over unicast C2 links that allow bi-directional transmissions of critical information between the UAV and relevant components. For such cases, distance between the UAV and its associated control systems does not pose an issue as long as these entities are properly registered with a compatible Radio Access Network (RAN), including Next Generation RANs (NextG-RANs) operating as 4G or 5G systems for the successful establishment of the C2 links.
- **UTM-navigated C2 communications:** This connection permits specific transmissions between the UTM entity and the UAV. Its primary functions include the UTM's oversight of the UAV's flight status to ensure compliance with regulations, continuous tracking of the UAV's navigation, and issuance of updated flight navigation instructions when necessitated [281]. A majority of the UTM-managed C2 links are typically set up indirectly via 3GPP networks.

Four basic C2 modes exist for controlling the operation of UAVs: steer to waypoints mode, direct stick steering mode,

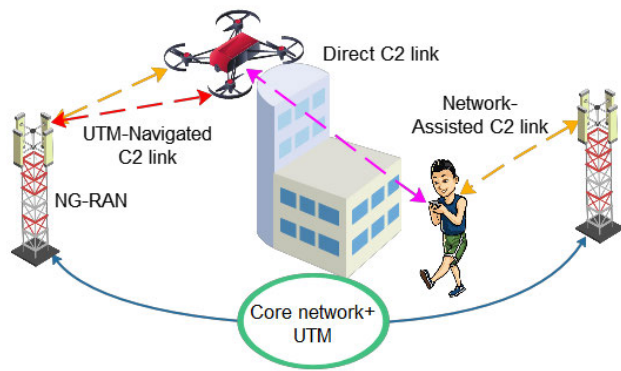


FIGURE 7. The three types of C2 communications links.

automatic flight managed by UTM mode, and approaching autonomous navigation infrastructure mode [223]. A UTM-navigated C2 connection is required for the automatic flight control and the implementation of approaching autonomous navigation infrastructure, whereas the transmission of steering to waypoints and direct stick steering can take place either directly or through assisted network connectivity.

4) UAV TRACKING

Within the context of UAV tracking, the 3GPP network leverages service exposure support directed toward the UAS Service Supplier (USS) to enable the USS to access its services by interfacing with the UAS Network Function (NF). The UAS-NF simulates network exposure functions/service capability exposure functions (NEF/SCEF) and communicates with additional network features such as Gateway Mobile Location Center (GMLC) and Access and Mobility Management Function/Mobility Management Entity (AMF/MME) to support UAV tracking. Before granting authorization to access location information pertaining to a particular UAV, the UAS-NF authenticates the requesting USS. For UAV identification purposes, the USS employs the 3GPP UAV ID, e.g., GPSI.

Three different methods are available to track UAVs within the designated region. These include: mode for reporting UAV location, UAV presence monitoring mode, and aircraft user equipment listing mode. Depending on the tracking requirements, the USS selects one of the three options and makes a suitable request to the UAS NF. If the USS wishes to receive the UAV node's location report while activating the UAV location reporting option, they must subscribe to the UAS NF by the designated 3GPP UAV ID. They also have the option to specify location accuracy and immediate versus periodic updates. Afterward, the UAS NF identifies relevant NFs such as the GMLC, and initiates processes for retrieving the location report. Subsequently, the UAS NF returns the UAV's location along with its 3GPP UAV ID. In monitoring UAV presence mode, when the USS subscribes for notification of the UAV entering or exiting a particular geographic region, the request comprises the 3GPP UAV ID and regional

details. The UAS NF employs established AMF/MME protocols to inform the USS about the UAV's presence within the region of interest, failing which it contacts the GMLC for presence monitoring configuration. Lastly, in aerial UE listing mode within a given geographic area, the USS requests a listing of all UAVs within the area serviced by PLMN bearing aerial subscriptions. This demand includes geographic area information and the aerial UE indicator to differentiate between ground-based and airborne UEs.

D. NETWORK SLICING FOR UAV COMMUNICATIONS

In network slicing, logical networks are built over shared physical networks, in order to enable high-quality dedicated services. It provides a logical solution "on demand" meant to satisfy individual service requirements and better utilize existing network resources. These requirements are very important in the context of the major 5G service types, as specified by the International Telecommunication Union (ITU-R) in M.2410 [282] and Third Generation Partnership Project (3GPP) in TS 23.501 [283]: enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and ultra-reliable and low-latency communications (uRLLC) (or mission-critical communications). These service types (i.e. eMBB, uRLLC, mMTC) have requirements which differ greatly, including in terms of, for example, coverage area, end-to-end latency, mobility, UE speed, etc. Network slicing was introduced to support both quality-oriented and resource-efficient service provisioning via an alternative architecture and innovative content delivery solutions.

1) NETWORK SLICING ARCHITECTURE

Figure 8 illustrates a network slice-supported 5G network as introduced by the European Telecommunications Standards Institute (ETSI) in TS 128530 [284] and 3GPP in TS 28.530 [285]. A 5G network can support multiple network slices (e.g. *NetSliA*, *NetSliB* and *NetSliC*) which employ network resources provided as network functions. These network functions are supported by different network entities such as core network (CN) and access network (AN) instances. Network slices manage also all the information relevant to the interconnections between these network functions. Diverse communication services (CS) are enabled by using different network slices. For example, CS_1 and CS_2 use *NetSliA* which employs dedicated network functions offered by CN_1 and AN_1 . CS_i uses *NetSliC*, which employs the dedicated network function CN_k and the shared resource AN_x . The latter is shared with *NetSliB*, which also uses the dedicated network resource CN_j .

2) GENERAL NETWORK SLICING SOLUTIONS

Extensive research efforts were put in order to propose solutions to enable best management of resources in such a network slice-enhanced 5G network environment. Bagaa et al. [286] suggested an avenue to find the most appropriate number of virtual instances at the core network

TABLE 12. Major approaches on UAV network slicing.

Publication	Year	Network Slicing Key Aspects Researched	General Slicing	Slicing with UAVs	Slicing for UAVs
Bagaa et al. [286]	2018	Presents a new slicing method that relates 4G and 5G virtual instances to satisfy mobile traffic QoS.	x		
Popovski et al. [287]	2018	Presents a theoretical communication model that accounts the requirements and characteristics of eMBB, mMTC, and URLLC services.	x		
Togou et al. [288]	2020	Presents a distributed blockchain-enabled resource slicing framework for dynamically leasing resources.	x		
Faraci et al. [289]	2020	Develops a UAV ad-hoc network by extending existing 5G network slices to offer rich computing resources for delay-constraint missions.		x	
Zhao et al. [290]	2019	Ensures reliable and flexible emergency communication by using UAVs to establish a temporal network.		x	
Yuan and Muntean [291]	2020	Presents a novel network slicing framework to enable differentiated QoS services for UAV applications.			x
Yang et al. [292]	2021	Presents a distributed learning and optimization method to allocate an eMBB slice to user traffic and an URLLC slice for UAV command control data			x
Garcia et al. [293]	2019	Demonstrates that network slicing supports all demands for both payload and command data delivery for UAVs.			x

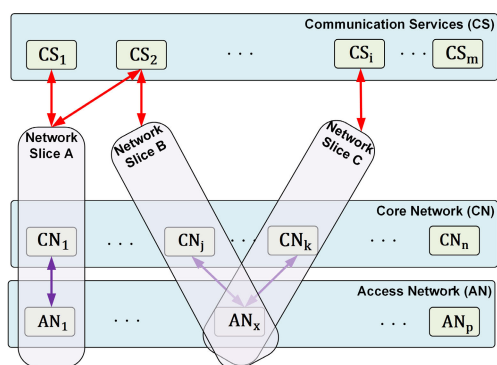


FIGURE 8. Relationship between communication services and network resources via network slices in a 5G network.

for a certain service, given its requirements. A new slicing method was developed to satisfy QoS requirements for mobile traffic by linking virtual instances of 4G and 5G. Popovski et al. [287] proposed a new communication model that takes into account the characteristics of eMBB, mMTC, and URLLC services. The authors designed an uplink slicing scheme based on heterogeneous non-orthogonal multiple access models. Togou et al. [288] provides a distributed blockchain-based framework for dynamically leasing resources for end-to-end service performance. The key aspect of the framework is the use of blockchain-based bidding to assign resources dynamically in order to enhance the user experience. This dynamic solution also reduces network providers' capital and operational expenditures.

3) UAV-BASED NETWORK SLICING SOLUTIONS

Next the UAV-based state-of-the-art network slicing approaches are discussed from two perspectives: how can UAVs improve telecommunication service provisioning and how can network slicing enhance UAV applications.

Network Slicing with UAVs: UAVs can extend the support for network slices by bringing additional computing and communication resources to the existing network infrastructure. A recent work of Faraci et al. [289] deployed a flying ad-hoc network (FANET) using multiple UAVs equipped with multi-access edge computing (MEC) facilities. MEC UAVs are equipped with computing elements (CEs) that process jobs coming from the ground. The FANET extends existing 5G network slices such that delay-constraint applications can receive additional computing resources. In [slice4], UAVs are deployed to expand the communication range and connectivity in RAN. A novel resource allocation algorithm for UAV RAN slicing is proposed to improve QoS of users, UAVs and ground control stations under limited bandwidth conditions. Other researchers like Zhao et al. [290] use UAVs to provide networking services under extreme environments, such as natural disasters.

Network Slicing for UAVs: Applying network slicing in UAV applications has the potential to increase quality of service (QoS) levels and potentially also flight safety. Network resources can be sliced to differentiate between diverse UAV applications, and place them in the context of other telecommunication services. Such services can be characterized by spectrum efficiency, data rate, end-to-end latency, reliability,

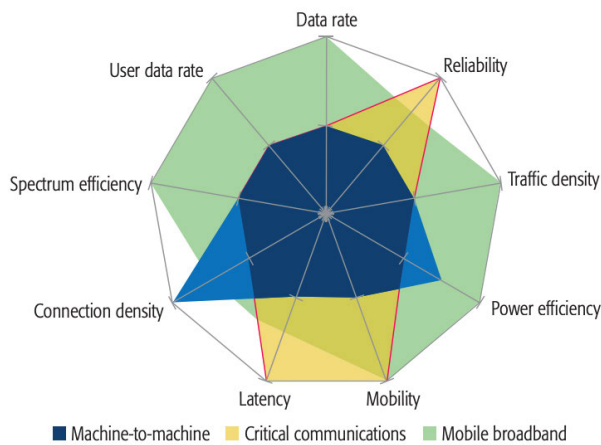


FIGURE 9. Main 5G use cases and their requirements [294].

guaranteed / non-guaranteed QoS levels, degree of security, etc, as shown in Figure 9. Then, different network slices can be allocated to diverse UAV applications based on their QoS requirements. UAV applications and their associated traffic can be classified as follows:

- 1) Applications requiring high bandwidth, including HD video streaming from UAVs (maps to eMBB).
- 2) Applications with small payload and long-term connectivity, including data on unmanned traffic management (UTM) (corresponding to mMTC).
- 3) Applications involving short-term ultra-reliable communications with small payload, such as controlling UAVs beyond visual line of sight (BVLoS) (can be associated with uRLLC).
- 4) Information/entertainment applications, which generate and exchange all other traffic that does not require special handling.

In this context, Yuan and Muntean [291] studied the network requirements for UAVs and classify them according to their QoS requirements. They proposed a novel network slicing framework, AirSlice, designed to enable differentiated quality-of-service support in 5G networks. Yang et al. proposed in [292] a distributed learning and optimization method to allocate an eMBB slice to user traffic and an URLLC slice for UAV command control data. Garcia et al. in [293] demonstrated following real-life experiments that network slicing supports all demands for both payload and command data delivery for UAVs.

4) Research Challenges AND Opportunities

Most network slicing solutions focus on solving different network resource allocation problems with the aim to balance some or all of the following aspects: utilization, flexibility, scalability and QoS [295], [296]. Approaches to addressing these problems include deep learning [297], game theory [298], evolutionary algorithms [299] and others [300].

Enable Network Slicing in Local Non-cellular Networks: Supporting different application types with different network resources is a crucial challenge in telecommunication industry. Most network slicing approaches have assumed that there exists a wireless infrastructure that provides signal coverage and channel resources. However, such wireless infrastructure might be overwhelmed in some scenarios where the number of UAVs is extremely high, or becomes unavailable due to natural disasters. In either case, network slicing policies in local non-cellular networks need to be considered.

Design a Service Level Agreement (SLA) for UAV Applications: A SLA should specify the QoS requirements (e.g., bandwidth, throughput, latency, packet delivery ratio, etc) needed for various UAV applications. However, it is very challenging to identify and correlate appropriate QoS levels with the pre-configured network slice types (i.e. mMTC, eMBB, and uRLLC), let alone for the applications which do not fully match the classic service types.

Define Dynamic Network Slicing Policies: Another key challenge is how to efficiently adjust network slicing policy as UAV topology changes in the environment, network demands change for different UAV applications, and UAV spectrum resources are heterogeneous (i.e. WLAN, cellular, satellite). There is a need to design a non-deterministic slicing strategy that adapts to the time-varying topology, variable demand for resources and intermittent connectivity. Specific questions include:

- 1) how many and how often network resource requests from UAVs should be admitted?
- 2) how to differentiate UAV services and associate prioritized network slices?
- 3) how to deploy policies considering different management and ownership?

Pursue Other Avenues: The diverse players, including academic, telecom industry and standardization bodies have already progressed from pilot studies to commercialization of network slicing solutions. The future is expected to offer tailored network slicing as a service (NSaaS) approaches offered by mobile network operators and/or network slicing service providers to UAV customers. For instance, network operators might slice the network using pre-defined criteria, including service types and QoS levels. Slice service providers could impose limits on the network slice characteristics that will be exposed to the UAV clients. Additionally, future works need to design new testing methodologies and toolkits to evaluate the performance of UAV network slicing in simulation, emulation and real-world environments as well as provide benchmarks for performance assessment.

VII. REAL TESTBED, DEPLOYMENTS AND EXPERIMENTS

There have been several efforts on the development of UAV testbeds for conducting repeatable and scalable experiments. As UAV is a complex system, involving sensing, communications and control subsystems, several testbeds focused on

only one or two individual subsystem(s). Herein, we highlight the contributions from the UAV communications perspective, for the testbeds and deployments that focus on characterizing, modeling and optimizing the UAV communications. Some of these works are based on UAV-to-ground communications over long range, while some testbeds are for UAV-swarms and supporting applications running on UAV. Moreover, some of these testbeds are end-to-end system based on real-world hardware for the UAV, sensing and communication radios, whereas some implementations are mixed emulators based on hardware-in-the-loop.

A. AD HOC NETWORK AND WSN BASED UAV TESTBEDS

Bouachir et al. [301] developed a testbed that uses IEEE 802.11g WiFi for multi-UAV-based cooperative tasks within 200 m range. The framework uses existing AODV protocol for routing its traffic through the UAV network. In [302] evaluated improved routing in a UAV mesh network by extending the Better Approach To Mobile Ad-Hoc Networking (B.A.T.M.A.N) routing protocol, however in a simulator settings using OMNeT++. Similar approach was adopted by [303], where the authors developed real-world a testbed for evaluating relaying and coding algorithms in Flying Ad-Hoc Networks (FANET). Their framework is capable of evaluating the B.A.T.M.A.N protocol where multiple UAVs form a mesh with the ground-control station (GCS). Amponis et al. [304] also developed a testbed with Raspberry Pi Zero and ESP32 and 802.11 LR (long range) with Mac-layer peer-to-peer communications which can test different channel models, mobility and routing of UAVs. In [305], a testbed for multipath communications for UAVs is developed, where UAVs use beacon sensing to probe the network quality of the available access points and select the best one at each hop to enable multihop relay with multipath communications. Some other works [306] proposed using wireless sensor networks (WSN) protocols for sending data between UAV and the GCS over hierarchical clusters. Their proposed testbed models the network over TelosB/Tmote Sky Platforms compatible with Contiki OS using IEEE 802.15.4. A UAV then uses the sensor nodes to communicate and transfer the data that it collects while monitoring a large area. Another work [307] uses a combination of Bluetooth Low Energy (BLE) and LoRaWAN for facilitating hierarchical data processing with UAV, fog and cloud computing keeping the energy constraints in consideration.

B. UAV TESTBEDS WITH NextGen WIRELESS NETWORKS

Although there are some commercially available UAVs which have cellular communications capabilities, only a few real-world testbeds are available which are open research platforms. Callegaro et al. [308] developed an edge computing platform for autonomous UAVs, that uses 4G LTE over Software-defined radios connected with the UAV. Using Universal Software Radio Peripherals (USRPs) B200mini and vertical antennas with srsLTE protocol stack [309], they

characterized the latency and jitter over LTE from the flying UAV. Similar platform was developed by [310] for testing the real-time video transmission over SDR-based LTE cellular network running with OpenAirInterface (OAI) [311]. Marques et al. [312] developed a testbed using commercial cellular networks to test the UAV operations and services in beyond visual line-of-sight scenarios. They used mobile radio probe (UXProbe) on two UAVs to measure the network coverage, performance and quality at different altitude up to 150 m. In [313], the authors built an SDR-based beamforming with 2×2 MIMO using USRP E312 to enhance the UAV communication capacity. Izydorczyk et al. [314] also created a UAV testbed equipped with directional antennas for beamforming to test the performance of uplink data transmission over cellular communication. They conducted experiments over LTE network band 3 (1.7 GHz uplink and 1.8 GHz downlink frequencies) and with a custom-designed antenna array consisting of six identical patch antennas, deployed on a hexagonal cylinder-like structure, each pointing a different directions. The testbed demonstrated that beamforming can reduce the handover and improve the connectivity of the UAV. In [315], the authors proposed a programmable software-defined testbed for visible light UAV networks using USRP N210 for signal processing and Light-Emitted Diodes (LED) and Photodetectors (PD) as the transmitter and receiver front end respectively. They conducted real-time video streaming over this setup and got up to 550 kbps data rate and maximum distance between two UAVs of 7 meters. In another work [316], the researchers developed a testbed called EuroDRONE for unmanned traffic management using a composite of different V2I and V2V communication technologies. The UAVs used for the testbed are autonomous small UAVs and the wireless technologies include 2.4/5GHz LTE and Sub-GHz communication technology.

C. MIXED-EMULATOR UAV-NETWORK TESTBED

Hardware-in-the-Loop (HITL) As there are still many constraints due to the form factor of UAVs, payload, battery etc., the development and deployment of a fully end-to-end UAV network testbed satisfying all types of experiments are not feasible. That is why there are many software-in-the-loop (SITL) simulator or Hardware-in-the-loop (HITL) emulators created by several researchers. In [317], the authors integrated OMNET++ network simulator and X-Plane flight simulator to develop a Flying Ad Hoc Network Simulator (AVENS). Another work [318] created a similar joint UAV-network simulator, called CUSCUS, which combines FL-AIR drone simulator with ns-3 over tap bridges and containers. To enhance the flexibility of multi-technology and routing, Baidya et al. [319] developed an integrated UAV-network simulator called FlyNetSim using ns-3 and Ardupilot with zeromq based middleware. Their testbed also support HITL based emulation, where real UAVs can be connected over simulated ns-3 network where various communication studies can be performed. In an alternate approach,

simulated UAVs are combined with software-defined radio based emulator called UB-ANC [320], [321] where channel models can be implemented over software-defined GNU Radio transceivers. Similar HITL emulator named SUN [322] is developed by integrating PX4-based software flight controller with radio-based communications over USRP hardware. The United States National Science Foundation (NSF)'s Platforms for Advanced Wireless Research (PAWR) program has funded a large-scale project for UAV communications, called the Aerial Experimentation and Research Platform for Advanced Wireless (AERPAW). The AERPAW emulation testbed [323], [324] is developed as a multi-level wireless emulation for UAVs, including the RF-level, I-Q level, and packet-level emulation over SDR-based 5G network. Using the AERPAW digital twin, Moore et al. [325] performed UAV-to-ground communications experiments with aerial and terrestrial base stations.

D. AERIAL WIRELESS BASE STATION PLATFORM

While the previous UAV testbeds primarily considered the network where UAV works as a user equipment (UE) communicating to a base station or access point or to another UE directly. However, another use case of UAV network is to use the UAV as a Base Station to extend the network coverage. Although there have been several theoretical research on the placement of UAV base station, capacity analysis etc., there are only few practical deployment which tested this scenarios. The researchers from the NEC Labs have implemented a prototype testbed for flying base station, first with the SkyRAN platform [326] which implemented LTE RAN on the flying UAV. They made the SKyRAN adaptive to different terrain and mobility of the ground UEs that connects to the SkyRAN. They also expanded the framework and created SkyCore [327] that implements the EPC core of LTE supporting multiple UAV base stations, and also, SkyHAUL [328] testbed which is a self organizing gigabit network with multiple replay UAVs. Sanchez et al. [329] developed a testbed for UAV base station with 60GHz mmWave band and developed a UAV-to-ground mmWave channel model through experiments. They also developed an optimal beam selection strategy through experimental insights with the UAV. Using a different two-tier UAV based relay network, Sobot et al. [330] developed a testbed to use LoRa and NB-IoT to create a low power wide area network (LP WAN).

E. LARGE-SCALE UAV COMMUNICATION TESTBEDS

A large-scale outdoor testbed is required for addressing gaps in wide-scale, system-level prototyping and testing of NextG wireless technologies for UAVs. The testbed needs to offer multiple ground and aerial communication nodes in an area which permits UAV flights and radio communications experiments. This requires the deployment of networked access points in the field, the provisioning of UAVs with contemporary radio systems, the availability safety pilots, and the

issuance and maintenance of an experimental license for RF transmission in bands of interest for R&D. Such a testbed captures the real-world UAV operation complexities, enables comprehensive data collection and design validation, and informed decision-making for advancing UAV communication system [331].

The AERPAW testbed supports programmable radio nodes, software-defined networking, and mobility-aware experimentation while providing a unique and flexible platform for validating wireless network protocols, control algorithms, and spectrum-sharing mechanisms in both digital twin and physical testbed settings [332]. The AERPAW architecture facilitates software radio experimentation by deploying one or more containers, referred to as Experimenter Virtual Machines (E-VMs), on one or more SDR host computers associated with fixed and/or portable AERPAW nodes. An E-VM can be configured to function as a 4G or 5G user equipment, a base station, a 4G/5G core network, or any other SDR software component or system offering full-stack flexibility.

AERPAW's Lake Wheeler Road Field Laboratories site serves as the primary area for conducting aerial wireless experiments. This site comprises five fixed nodes, each equipped to support canonical experiments using USRPs with custom RF front ends [333]. In addition to USRPs, several of these nodes are provisioned with advanced instrumentation, including Keysight RF sensors, LoRa gateways, and an Ericsson 4G/5G base station, enabling heterogeneous wireless experimentation across multiple protocol stacks and frequency bands. AERPAW portable nodes, which in the typical configuration consist of a small form-factor USRPs with a host computer and a custom RF front end, can be mounted on a variety of custom-built multirotor UAVs and unmanned ground vehicles [334]. The AERPAW platform has been used to design and execute a variety of UAV communication experiments, relevant to academic, government, and industry use cases. These include UAV handover experiments [335], radio performance measurements [331], aerial channel modeling [336], UAV-based RF source localization [337], spectrum awareness for radio dynamic zones [338], mmWave and Sub-THz propagation measurements [339], and O-RAN enabled aerial networking [340].

VIII. OPEN ISSUES AND RECOMMENDATIONS

A. OPEN RESEARCH ISSUES

In the section, we highlight some open research issues of UAVs networking suggested in several literature [3], [12], [341], [342], [343]:

- **Energy constraint:** On-board batteries of UAVs have limited power resource to support all the operational functions including computation, communication, and flying. Therefore, long-term deployment of UAV systems and power harvest still are key research issues.

- **UAV platform:** The flight dynamics as well as the UAVs position and orientation highly influence the communication links of UAVs networks.
- **UAV Mobility model:** For better simulating of UAVs motions in a practical environment, it needs to combine the best movement features of the proposed mobility models.
- **Routing:** In UAVs networks, the routing protocols must dynamically adapt to the network topology changes.
- **Path Planning:** In multi-UAV missions, UAV node often requires to dynamically re-compute new path in order to cooperate with other UAVs. Therefore, dynamic path planning requires new algorithms to improve the coordination between UAVs.
- **Quality of Service (QoS) provisioning:** Due to the heterogeneous and distributed nature of UAVs networks, establishment of framework for supporting QoS is difficult and challenge.
- **Fault handling:** The solutions of handling any types of faults including the problems occurred in hardware, embedded component, software, and communication links, need to be deeply explored.
- **Data processing:** Onboard unit of UAVs has limited computation power and is insufficient for data processing. Fog and edge computing offer a solution for data processing.
- **Data sharing and security issues:** The specific characteristics of UAVs networks impose new security requirements. The authenticity of relaying information directly impacts on the security of UAVs networks.
- **Standardization of FANET:** UAV systems require proper standards and guidelines to improve their commercialization for civilian application, and improve the performance in FANETs.
- **Distributed optimization algorithms:** It is paramount to design and implement distributed optimization techniques given the distributed nature of the UAVs but also for scalability purposes [255]. Indeed, most existing solutions are centralized algorithms that suffer from scalability aptitude. Another critical aspect of these techniques is the study of their theoretical properties [254] and technology readiness level that need to be boosted to their highest through real-world testing or at least simulation with built-in features for distributed algorithms.
- **Spectrum Management:** Radio spectrum management for commercial UAV operations in the absence of a dedicated spectrum requires significant attention. Current spectrum allocation techniques are insufficient to meet the growing demands of UAV communications and, therefore, require new spectrum-sharing techniques with reduced interference.
- **Network Formation and Topology Control:** Dynamic topology control in UAV networks introduces several unique challenges due to dynamic movement patterns in 3D space, varying channel quality levels, and energy limitations. Therefore, efficient clustering mechanisms

with improved coordination protocols are necessary to address scalability issues in large-scale UAV deployment.

- **Integration with Existing Networks:** Combining UAV networks with existing terrestrial, satellite, and maritime networks to create harmonious space-air-ground-sea networks is highly complex, and challenges persist in cross-domain routing, handover management, and heterogeneous resource allocation.
- **Testing and Simulation:** Current UAV simulation environments often fail to fine-tune the complex dynamics of aerial networks. This requires more realistic simulation frameworks and testing methodologies that could capture the unique characteristics of complex near-real-time aerial deployments.

B. RECOMMENDATIONS AND FURTHER WORK

UAVs have a prodigious potential in wireless communication systems, which act as wireless relays to integrate air-ground networks. Several recommendations and future work directions are proposed in [342]. It is also recommended to design and develop:

- Multi-UAV systems that are able to maintain steady communication, remotely operate control and command with unlimited coverage, secure information exchange, and support the various coexistent wireless applications. These multi-UAV systems should include adaptive beamforming approaches and directional antenna technologies to improve communication reliability and coverage while minimizing interference in highly dynamic operational environments.
- Routing mechanisms for UAV networks that are able to adapt to high mobility, network topology changes, and load balance of UAVs. These futuristic routing protocols should leverage deep reinforcement learning or hybrid-learning approaches to predict topology dynamics and optimize route selection based on channel quality, energy efficiency, and mission requirements.
- A regular registration procedure to manage identifications of UAV devices through the entire life-cycle of UAV, including manufacturing, marketing, repairing, and scrapping. The registration process should comprise blockchain technology to guarantee secure and immutable device identification and enable trusted authentication and authorization throughout the UAV lifecycle.
- UAV simulators that are able to accurately simulate different types of UAVs according to their constraints. Next-generation UAV simulators should incorporate realistic communication models, energy consumption patterns, and flight dynamics with network simulation capabilities to provide comprehensive evaluation and testing environments for realistic UAV-oriented research. It will help researchers and developers mature

the techniques that have been developed beyond the simulation level.

- Innovative network architectures that could support cross-domain applications. In this context, the network slicing-assisted architecture could provide enhanced communication services for diverse UAV applications and deployments with varying QoS requirements, i.e., from low-latency control to real-time high-throughput data transmission.
- Full security frameworks that cover all possible threats, such as jamming, spoofing, unauthorized access, and data interception, for resource-constrained aerial platforms.
- Avenues to improve existing spectrum-sharing techniques for unmanned aerial communications, including cognitive radio approaches, dynamic spectrum access, and interference coordination mechanisms to improve overall resource utilization while ensuring easy deployments with incumbent systems.
- Solutions to enhance UAV situational awareness by improving ISAC capabilities for aerial networks that utilize the optimized hardware and spectrum resources for communication and environmental sensing.

IX. CONCLUSION

UAVs have gained prominence among the scientific community over the years. Multiple UAVs can cooperatively perform complex missions, especially in unreachable areas, with the help of self-organizing UAV networking. This paper presents a technological overview of networking UAVs, including communication architecture, communication protocols, communication requirements, and security requirements. Within that, the UAV network formation and state-of-the-art solutions are discussed. Furthermore, we surveyed the 3GPP standardization for UAV cellular communication. Cellular-connected UAV communication and network slicing for UAV communication are discussed. FANET offers a novel mechanism to address scalability issue present in direct link networking. However, communication remains one of the most serious constraints that surround FANETs. Thus, the paper also presents the open research issues and further research directions suggested in the literature to encourage researchers and professionals in this domain.

ACRONYMS AND NOMENCLATURE

3D	Three Dimensional.
AI	Artificial Intelligence.
AoI	Age of Information.
AODV	Ad-hoc On-demand Distance Vector.
AMF/MME	Access and Mobility Management Function/Mobility Management Entity.
ATC	Air Traffic Control.
BS	Base Station.
BITS	Battlefield Information Transmission System.

CH	Cluster Head.
CN	Core Network.
DAG	Directed Acyclic Graph.
DCR	Data Centric Routing.
DOLSR	Directional OLSR.
DSR	Dynamic Source Routing.
D2D	Device-to-Device.
EPC	Enhanced Packet Core.
EM	Electromagnetic.
eMBB	Enhanced Mobile Broadband.
ETSI	European Telecommunications Standards Institute.
FAA	Federal Aviation Administration.
FANET	Flying Ad-hoc Network.
FCC	Federal Communications Commission.
GCS	Ground Control Station.
GMLC	Gateway Mobile Location Center.
GPMOR	Geographic Position Mobility Oriented Routing.
GPS	Global Positioning System.
GPSR	Greedy Perimeter Stateless Routing.
GS	Ground Station.
HW	Hardware.
IoD	Internet of Drone.
ITU-R	International Telecommunication Union.
IoT	Internet of Things.
ISM	Industrial, Scientific, and Medical.
ISAC	Integrated sensing and communication.
LAROD	Location Aware Routing for Opportunistic Delay.
LCAD	Load Carry And Deliver.
LLC	Logical Link Control.
LoS	Line-of-Sight.
MAC	Media Access Control.
MANET	Mobile Ad-hoc Network.
MLHR	Multi Level Hierarchical Routing.
ML-OLSR	Mobility and Load aware OLSR.
mMTC	Massive Machine-Type Communications.
MNO	Mobile Network Operator.
MPGR	Mobility prediction geographic routing.
MPR	Multi-Packet Reception.
MRPA	Mission Route Planning Agent.
NAS	National Airspace System.
NextG-RANs	Next Generation RANs.
NLoS	Non-Line-of-Sight.
NEF/SCEF	Network Exposure Functions/Service Capability Exposure Functions.
OLSR	Optimised Link State Routing.
POLSR	Predictive OLSR.
QFLR	Q-learning-based Fuzzy Logic Routing.
QMR	Q-learning based Multiobjective optimisation Routing.
QoS	Quality of Service.
RAN	Radio Access Network (RAN).
RIS	Reconfigurable intelligent surfaces.
RF	Radio Frequency.

RL	Reinforcement Learning.
RPA	Remotely Piloted Aircraft.
RPAS	Remotely Piloted Aircraft System.
RREQ	Route Request.
RREP	Route Reply.
RTCA	Radio Technical Commission for Aeronautics.
SW	Software.
SAGSIN	Space Air Ground Sea Integrated Network.
SWIPT	Simultaneous Wireless Information and Power Transfer.
TBRPF	Topology Broadcast based on Reverse-Path Forwarding.
TORA	Temporally-Ordered Routing Algorithm.
TSAODV	Time-Slotted AODV.
UAS	Unmanned Aerial System.
UAV	Unmanned Aerial Vehicle.
UAVC	UAV Controller.
UE	User Equipment.
uRLLC	Ultra-Reliable Low Latency Communications
USMP	UAV Search Mission Protocol.
UTM	UAS Traffic Management.
UUA	UAV Authentication and Authorization.
VANET	Vehicular Ad-hoc Network.
VTOL	Vertical TakeOff and Landing.
WLAN	Wireless Local Area Network).
WRC	World Radiocommunication Conference.
ZRP	Zone Routing Protocol.
ZSP	Zone Service Provider.

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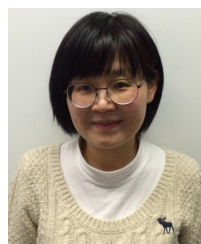
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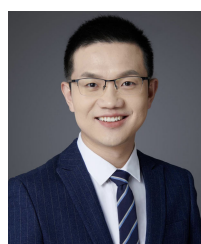
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