What Will the Future of UAV Cellular Communications Be? A Flight From 5G to 6G

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***Abstract*—What will the future of UAV cellular communications be?** **In this tutorial article, we address such a compelling yet difficult question by embarking on a journey from 5G to 6G and expounding a large number of case studies supported by original results. We start by overviewing the status quo on UAV communications from an industrial standpoint, providing fresh updates from the 3GPP and detailing new 5G NR features in support of aerial devices. We then dissect the potential and the limitations of such features. In particular, we demonstrate how sub-6 GHz massive MIMO can successfully tackle cell selection and interference challenges, we showcase encouraging mmWave coverage evaluations in both urban and suburban/rural settings, and we examine the peculiarities of direct device-to-device communications in the sky. Moving on, we sneak a peek at next-generation UAV communications, listing some of the use cases envisioned for the 2030s. We identify the most promising 6G enablers for UAV communication, those expected to take the performance and reliability to the next level. For each of these disruptive new paradigms (non-terrestrial networks, cell-free architectures, artificial intelligence, reconfigurable intelligent surfaces, and THz communications), we gauge the prospective benefits for UAVs and discuss the main technological hurdles that stand in the way. All along, we distil our numerous findings into essential takeaways, and we identify key open problems worthy of further study.**

***Index Terms*—UAV, drones, cellular communications, mobile networks, massive MIMO, mmWave, UAV-to-UAV, non-terrestrial networks, cell-free, artificial intelligence, reconfigurable intelligent surfaces, THz communications, 3GPP, 5G, 6G.**

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I. Introduction

WHAT would our beloved grandmothers have thought if they had received a bunch of roses delivered by a UAV?[1] Their initial disbelief and skepticism would have soon made room for sheer gratitude, acknowledging the fond gesture. Likewise, even the most tech-reluctant of us will eventually come to terms with UAVs. Barely seen in action movies until a decade ago, their progressive blending into our daily lives will enhance safety and greatly impact labor and leisure activities alike.

A. Motivation and Background

Most stakeholders regard reliable connectivity as a must-have for the UAV ecosystem to thrive. Exciting and socially impactful use cases, including automated crowd, weather, and traffic monitoring and live virtual reality experiences, mandate handling UAV-originated high-resolution video. Venture capitalists, willing to invest in advanced aerial mobility, and also governments, are betting on the wireless industry to address the unmet needs of critical UAV command and control (C2) links [1]. A breakthrough in reliability could persuade legislators to ease regulations on civilian pilotless flights, giving the green light to new vertical markets.

As a result, cellular communications involving UAVs have witnessed a surge of interest, following two philosophies epitomized as *what can UAVs do for networks* and *what can*

[1]Unmanned aerial vehicle, also commonly referred to as drone.

networks do for UAVs, respectively [2]. The former, pioneered by academia, advocates enhancing cellular networks with UAV-mounted base stations (BSs), wirelessly backhauled to the ground. For disaster assistance, border surveillance, or hotspot events, UAVs carrying a radio access node could be promptly dispatched, cheaply maintained, and easily manoeuvred. The latter, at first predominant in the standardization fora, triggered a parallel stream of research that aims at supporting UAV end-devices through cellular networks [3].

Whether featuring UAVs as data beneficiaries or suppliers, the fly-and-connect dream faces showstoppers. As ground cellular BSs are typically downtilted, UAVs are only reached by their upper antenna sidelobes and experience sharp signal fluctuations. Flying above buildings, UAVs receive/create line-of-sight (LoS) interfering signals from/to a plurality of cells, respectively hindering correct decoding of latency-sensitive C2 and overwhelming the weaker signals of ground users (GUEs). The pronounced signal strength fluctuations experienced by UAVs, combined with their high speeds and rapid veering, create unique mobility management challenges, causing frequent and sometimes unnecessary handovers. Technical solutions to these problems, among others, have been introduced in 4G Long-term Evolution (LTE) to deal with a handful of connected UAVs, but as they proliferate, UAV cellular communications will struggle to 'take off' by solely relying on a network built for the ground. Aware of these hurdles, and acknowledging the importance of aerial communications, the wireless research community has been rolling up its sleeves to drive a native and long-lasting support for UAVs in 5G New Radio (NR) and beyond [4], [5].

B. Contribution

UAV cellular communications have been all the rage and the present one is far from the first tutorial on the topic. However, this one-of-a-kind article is arguably the first merging industrial and academic views to forecast, through supporting evidence, the future of UAV cellular communications. This is the most appropriate time to do so, given the significant UAV-related updates in the third-generation partnership project (3GPP), e.g., the recent definition of new UAV applications for NR Rel. 17 and a RAN work item for UAV support within NR Rel. 18 [6], [7]. Moreover, the time is ripe to quantify the benefits and limitations of key 5G NR features such as massive MIMO (mMIMO) and millimeter wave (mmWave), among others. Lastly, the societal role to be played by UAVs in the coming decades, as well as the corresponding 6G empowering technologies, have become clearer than ever.

In this article, it is by showcasing our own recent research findings that we navigate the broad readership from 5G to 6G UAV use cases, requirements, and enablers. Our novel results—abundantly supplied, carefully selected, and accessibly presented—have been obtained in compliance with the assumptions specified by the 3GPP in [3], [8]. Through these results, we share numerous lessons learnt and provide essential guidelines, defining a complete picture of the upcoming UAV cellular landscape and, we hope, acting as a catalyst for much-needed new research.

At a high level, our main contributions can be summarized as follows:

- We review the extensive ongoing activity in the standardization fora, presenting fresh and accessible updates to the broad readership.
- We discuss how the upcoming decades will see a proliferation of network-connected UAVs with stringent control and payload requirements. We also provide concrete UAV use cases demanding extreme data transfer capacity and link reliability, and thus requiring one (or multiple) 6G paradigm shift(s).
- We introduce UAV cellular support through multi-antenna enhancements, namely massive MIMO and cell-free architectures. We discuss the benefits in terms of initial access and cell selection, interference management, and enhanced reliability. We point out the main caveats in terms of sounding reference signal design, scalability, and optimization.
- We illustrate the UAV capacity boost achievable through mmWave and THz communications, studying both urban and suburban scenarios, and considering both conventional street-level BSs and dedicated rooftop-mounted cells.
- We review the main findings on UAV-to-UAV cellular communications, with a special focus on the coexistence with underlayed ground uplink communications. We identify the main tradeoffs achievable through fractional power control and resource allocation.
- We propose technological and architectural enhancements to endow UAV cellular communications with intelligence and resilience. We provide two concrete examples where artificial intelligence (AI) can assist through generative channel modeling and mobility management. We vouch for a future integrated ground-air-space wireless network, where satellite beams can fill coverage gaps and aim for zero UAV outage. We also describe the potential synergies between reconfigurable intelligent surfaces and UAVs.
- We supply a large selection of original results to make the reader familiar with the most compelling features of UAV cellular communications. Having been obtained through extensive system-simulation campaigns, these results can be relied upon both from qualitative and quantitative standpoints.
- For each of the main 5G and 6G technological enablers, we share the key takeaways, point out numerous open problems, and make well-grounded suggestions on potential future work, all along focusing on UAV-specific opportunities and challenges.

C. Outline

The rest of this article is organized as follows. Section II reviews other relevant contributions on similar topics. Section III overviews the status quo on UAV communications in 5G NR, distilling fresh updates from the 3GPP and detailing new 5G NR features that come—directly or indirectly—in support of UAVs. In this section, we also take a first peek beyond 5G, reviewing the most likely use cases envisioned for the next decade. Section IV focuses on UAV cellular support through multi-antenna enhancements: how massive MIMO can

TABLE I
LIST OF ACRONYMS USED THROUGHOUT THIS ARTICLE

Acronym	Definition
3GPP	Third-generation partnership project
AI	Artificial intelligence
BS	Base station
BVLoS	Beyond visual line of sight
C2	Command and control
CDF	Cumulative distribution function
CSI	Channel state information
D2D	Device-to-device communications
DL	Downlink
DVB	Digital video broadcasting
eVTOL	Electric vertical takeoff and landing vehicle
GEO	Geostationary equatorial orbit
GUE	Ground user equipment
HAP	High-altitude platform
HARQ	Hybrid automatic repeat request
HD	High definition
IoT	Internet of Things
ISD	Intersite distance
LEO	Low Earth orbit
LoS	Line of sight
LTE	Long-term Evolution
MF	Matched filter
mMIMO	Massive MIMO
MMSE	Minimum mean-square error
mmWave	Millimeter wave
NLoS	Non line of sight
NN	Neural network
NTN	Non-terrestrial network
NR	New Radio
PRB	Physical resource block
RAN	Radio access network
RIS	Reconfigurable intelligent surface
RSRP	Reference signal received power
SINR	Signal-to-interference-plus-noise ratio
SNR	Signal-to-noise ratio
SRS	Sounding reference signal
SSB	Synchronization signal block
SU	Single user
TDD	Time division duplexing
U2U	UAV to UAV
UAV	Unmanned aerial vehicle
UL	Uplink
UMa	Urban Macro
UMi	Urban Micro
URA	Uniform rectangular array
UTM	UAV traffic management
UxNB	Radio access node on-board UAV
VLoS	Visual line of sight

TABLE II
OTHER RELEVANT WORKS ON UAV COMMUNICATIONS AND NETWORKING, LISTED AND CLASSIFIED AS IN SECTION II

UAV communications	**Selected references**
UAV-assisted wireless communications	[9], [10]
Applications of UAV communications	[11]–[16]
UAV-to-everything communications	[17]–[19]
UAV cellular systems	**Selected references**
UAV cellular communications	[4], [5], [20], [21]
Integration and emerging technologies	[22]–[26]
mmWave and THz UAV communications	[27]–[29]
UAV network architecture	**Selected references**
Internet of drones	[30]–[32]
Space-air-ground networks	[33]–[36]
Standard-related articles	**Selected references**
3GPP-based studies	[37]–[40]
5G-connected UAVs	[41] [42]
Channel measurements and modeling	**Selected references**
Surveys on channel modeling	[43], [44]
UAV channel measurements	[45], [46]
Other relevant overview articles	**Selected references**
Shorter overview articles	[47]–[51]
Other surveys or tutorials	[52]–[63]
Special issues	[34], [64]–[66]
Introduction to 5G and 6G	**Selected references**
5G NR and the 6G vision	[67]–[75]

successfully tackle the cell selection and interference challenges and the gains promised by cell-free architectures. In Section V, we move to higher frequencies and evaluate the mmWave coverage in both urban and suburban/rural settings. We also introduce communications in the THz band, quantifying their potential benefits for UAVs, and discussing the main technological hurdles yet to be overcome. In Section VI, which treats intelligence and resilience, we discuss the role of AI, non-terrestrial networks (NTN), and reconfigurable intelligent surfaces (RIS) in future UAV cellular communications. Section VII is devoted to device-to-device links in the sky, that is, direct UAV-to-UAV cellular communications. We wrap up the article in Section VIII and, all along, we extract our broad vision into takeaways, also highlighting open research questions for the interested reader. The acronyms employed throughout the text are listed and described in Table I.

II. RELATED WORK

In this section, we review other relevant works on UAV communications and networking. For convenience, these works are also listed and classified in Table II.

A. UAV Communications

The article [9] is one of the earliest giving a comprehensive overview on UAV-assisted wireless communications. It first provides a vision for the three typical use cases of UAV-assisted communications, followed by a discussion on the basic networking architecture, main channel characteristics, key design considerations, as well as the new opportunities to be explored. The authors of [10] introduce drone assisted vehicular networks to provide ubiquitous connections for vehicles by efficiently integrating the communication and networking technologies of drones and connected vehicles.

The tutorials [11]–[13] review several UAV applications and their corresponding communication designs, including the UAV placement and trajectory optimization. Instead, [14] focuses on aspects such as cognitive networking, mobile edge computing, and energy harvesting for aerial BSs. UAV quality-of-service requirements and network-relevant mission parameters are quantified in [15], also elaborating on connectivity, adaptability, safety, privacy, security, and scalability. The authors of [16] further elaborate on the application of machine learning to UAV communications, focusing on resource management, path planning, and autonomous flight.

A comprehensive survey on UAV-based IoT services is [17], which presents the relevant key challenges and requirements, comprising not only technical issues, such as physical collision and communications, but also regulatory matters. Furthermore, [18] pinpoints the most fundamental and important design challenges of multi-UAV systems for cyber-physical systems, while [19] focuses on UAV-to-everything communications and presents a variety of communication modes, trajectory design algorithms, and radio resource management techniques.

B. UAV Cellular Systems

An overview on the integration of UAV communications with cellular networks is provided in [4]. This book covers the fundamentals of UAV communications and explores the integration of UAVs acting as both UEs and BSs. Wireless communications and networking with UAVs is also dealt with in [5]. The topics treated include fundamental physical layer aspects, standardization efforts, and channel modeling, among others. Another book focusing on the communications and networking aspects of UAVs is [20], which aims to provide the fundamental knowledge needed to pursue research in the field. Complementarily, this book discusses the regulations, policies, and procedures for deployment, along with test-beds and practical real-world applications. Furthermore, [21] elaborates on practical UAV systems, including swarms and field demonstrations, and their applications in cellular and Wi-Fi networks.

The article [22] provides a detailed overview on the use of UAVs as BSs and UEs in wireless networks. It identifies key challenges, opportunities, and open problems associated with various use cases. In addition, it presents an overview of mathematical tools and frameworks needed for analyzing and optimizing UAV-based wireless communication systems. UAV integration into 5G and beyond is also discussed in [23], [24], touching upon several emerging technologies including: short packet communications, non-orthogonal multiple access, joint sensing and communication, RISs, and machine learning for UAV trajectory design. The challenges and potential solutions for serving UAVs using ground massive MIMO BSs are also explored in [25], while [26] applies cooperation techniques to improve the Quality-of-Service (QoS) of the cellular link between the UAV and the BS in the cellular Internet of UAVs.

A comprehensive survey on mmWave beamforming-enabled UAV communications and networking is provided in [27], which presents the technical potential and challenges and the relevant mmWave antenna structures and channel modeling. The integration of 5G mmWave and 6G THz communications into UAV-assisted wireless networks are also discussed in [28] and [29], respectively.

C. UAV Network Architectures

The article [30] embraces many facets of the Internet of Drones, including privacy and security considerations as well as the potential economic impact. Software defined networking-enabled UAV-assisted systems are discussed in [31] along with several case studies and issues, such as the involvement of UAVs in cellular communications, monitoring, and routing. The survey [32] discusses the architecture of multi-UAV networks, proposing software defined networking for flexible deployment and management of new services, and presenting dynamic routing and handover aspects.

Space-air-ground networks as an integration of satellite systems, aerial networks, and terrestrial communications are introduced in [33]. Their specific characteristics are overviewed, such as heterogeneity, self-organization, and time-variability, also discussing network design, resource allocation, performance analysis, and optimization. The article [34] covers low- and high-altitude-platform-based communication networks, addressing their particular design mechanisms and protocols. More recently, [35] and [36] offer an overview of the architecture and features of an aerial RAN including UAVs and satellites. The articles also discuss 6G application scenarios, propagation-related aspects, energy consumption, communication latency, and network mobility.

D. Standard-Related Articles

The survey [37] is a comprehensive review of various studies on UAV communications in academia, industry, and standardization bodies. Moreover, the deployment and operation of UAVs in cellular networks are investigated from regulatory and cyber-security perspectives. In [38], the authors shed light on the feasibility of providing connectivity for UAVs and presents several ideas to improve LTE connectivity. To enable the coexistence of both aerial and terrestrial users, [39] analyzes two interference mitigation solutions in current LTE networks: interference cancellation and antenna beam selection. In [40], LTE is utilized for scenarios in which UAVs act as BS transmitting in the downlink (DL) or UEs transmitting in the uplink (UL). The paper highlights that current LTE networks require significant modifications for a smooth integration of LTE-enabled UAVs.

Unlike the aforementioned articles, [41] analyzes DL UAV cellular communications by comparing the performance of old-fashioned cellular networks against that of 5G massive MIMO systems. Furthermore, [42] studies how UAV BSs and drone UEs can be integrated into 5G systems. The authors highlight important open issues in the standardization process, either via application of current standards or by providing modifications toward further enhancements that can realize the vision of 5G-enabled UAVs.

E. Channel Measurements and Modeling

An extensive survey of channel measurement methods for UAV communications can be found in [43]. This article also discusses various UAV channel characteristics and outlines future research challenges in this domain. Similarly, [44] provides a comprehensive survey on available air-to-ground channel measurement campaigns, large- and small-scale fading channel models, and their limitations.

The radio propagation characteristics of ground-to-air channels are investigated in [45]. Field measurements are conducted in live LTE networks in the 800 MHz frequency band with a commercial UAV. Measurements of air-to-ground MIMO channels at 915 MHz are reported in [46]. The analysis shows that spatial diversity is significant due to the near-field scattering by the airframe of the UAV, despite the sparse multipath environment.

F. Other Relevant Overview Articles, Surveys, and Tutorials

Shorter overview articles can be found in [47]–[51], whereas [52]–[63] comprise other surveys or tutorials on UAV communications. A further selection of contributions that are relevant to the present article is collected in the special issues [34], [64]–[66].

G. Introduction to 5G and 6G

The reader interested in learning more about 5G NR and the 6G vision is referred to [67]–[75], which include relevant books, vision articles, and white papers.

III. UAV Cellular Communications in 5G NR and Beyond

The current decade will see an unprecedented growth in the number of UAVs employed for public and industrial purposes and, likewise, in the amount of data they generate and transfer in real-time to and from ground control stations. Among other examples, this will be the case for high-resolution aerial mapping, for UAVs inspecting and monitoring tens of thousands of kilometers of pipelines or railway networks [78], and even for UAVs serving as aerial radio access nodes (i.e., BSs) and demanding high-speed wireless backhaul [79]. For some of these applications, sufficiently low latency may only be achieved by skipping the video compression/decompression stages, for which hyper-high bit rates will be instrumental. Besides exchanging the copious captured data with ground stations in real time, these UAVs will have to be controlled with nearly unlimited flight range. In what follows, we provide concrete industrial UAV applications that are likely to require strong wireless cellular empowerment, and then detail how the 3GPP is targeting support for these and other upcoming use cases.

A. UAV Use Cases, Systems, and Requirements in 5G NR

The retail industry—already undergoing a transformation from face-to-face stores to online shopping—is expected to go fully autonomous with upcoming 3D aerial highways. The survival and prosperity of online businesses and retailers, overwhelmed by an exponentially increasing number of online orders, relies on efficiently addressing the last-mile delivery bottleneck. To this end, the number of cargo-UAVs is expected to skyrocket, replacing delivery trucks and leading to less congested roads and more densely crowded skies [80].

Such vision is already embodied by projects of e-commerce giants that aim at safely delivering packages of up to five pounds in under 30 minutes via small UAVs equipped with sense-and-avoid technology [81]. To this end, courier companies are to work with regulators to design an air traffic management system that will recognize who is flying, what, and where. Once provided with appropriate and enforced regulatory support, UAV carriers are expected to enhance current shipment services to millions of customers while increasing the overall safety and efficiency of the transportation system.

Ensuring safe operations of cargo UAVs entails continuously collecting a massive amount of data on speed and location, battery levels, and environmental conditions. Such information can be used to trigger control commands to prevent failures, aerial traffic congestion, and collisions. The corresponding communication key performance indicators include end-to-end latencies on the order of tens of milliseconds and a minimal tolerable lack of connectivity along the itinerary. Unlike present-day deployments, where UAV users are yet to become commonplace, 5G NR networks might have to meet the above requirements for a large number of connected UAVs.

In response to these and other new industrial UAV applications, the traditionally ground-focused wireless cellular ecosystem is increasingly concerned with accommodating flying users. Table III summarizes the most demanding UAV use cases identified by the 3GPP that could be enabled by 5G cellular support. These can be broadly classified into (*i*) C2 links, and (*ii*) payload data links. Table III also quantifies the respective associated requirements in terms of bit rate, latency, reliability, UAV speed and altitude to be supported, as well as positioning accuracy. In the following, we describe different types of UAV communication systems where a need for each of these link types might arise.

1) UAV UEs With Command and Control Links: Owners of commercial UAVs will start using them to deliver mail-ordered goods to their customers' doorsteps. A controller can be employed to communicate with the UAV, where both the UAV and the controller are 5G-compliant devices. Once the owners receive clearance from the UAV traffic management (UTM) to fly their UAV, this comes along with a series of *waypoints* that the UAV can follow while cruising from the warehouse to the recipient. At times, a UAV owner might also be requested to take *direct steering control* of the UAV. This might occur before climbing to cruise altitude, for dropping a package at destination, or to observe an accident that has occurred along the way. During direct steering control, the manoeuvring requires UL video feedback from the UAV. The specifications for such feedback depend on whether the controller is in visual line-of-sight (VLoS), or beyond VLoS (BVLoS). Autonomous flight is also possible via the UTM, which then provides predefined trajectories in the form of four-dimensional polygons while the UAV feeds back periodic position reports for tracking purposes [54].

2) UAV UEs With Data Payloads: UAVs are expected to enable users to experience virtual reality by means of panoramic *8K video live broadcast*, e.g., through a 360° spherical view camera on board the UAV that captures and uploads 8K video in real time to a cloud server. Such video stream will be received live by users through remote VR glasses. Besides high bit rates and low latency, this use case demands

TABLE III
REQUIREMENTS FOR SELECTED 5G UAV USE CASES [76], [77]. LESS DEMANDING USE CASES HAVE BEEN OMITTED FOR BREVITY

Command and control	**Message interval**	**E2E latency**	**UAV speed**	**Message size**	**Reliability**	**Remarks**
Waypoints control (cruising altitude)	1 s	1 s	300 km/h	DL: 100 B UL: 84–140 B	99.9%	—
Direct steering control (takeoff, landing, danger)	40 ms	40 ms	60 km/h	DL: 24 B UL: 84–140 B	99.9%	Video feedback required (see first entry under payload data*)
Autonomous flight via traffic management system	1 s	5 s	300 km/h	DL: 10 kB UL: 1500 B	99.9%	Nominal mission. Unusual events require extra DL.
Payload data	**Bit rate**	**E2E latency**	**Altitude**	**Service region**	**Positioning**	**Remarks**
*Video feedback (UL) for direct steering control	VLoS: 2 Mbps BVLoS: 4 Mbps	VLoS: 1 s BVLoS: 140 ms	—	All	—	VLoS reliability 99.9% BVLoS reliability 99.99%
8K video live broadcast	UL: 100 Mbps DL: 600 kbps	UL: 200 ms DL: 20 ms	<100 m	Urban, scenic	0.5 m	—
Laser mapping/ HD patrol	UL: 120 Mbps DL: 300 kbps	UL: 200 ms DL: 20 ms	30–300 m	Urban, rural, scenic	0.5 m	Average speed 60 km/h
4×4K AI surveillance	UL: 120 Mbps DL: 50 Mbps	UL: 20 ms DL: 20 ms	<200 m	Urban, rural	0.1 m	—
Remote UAV controller through HD video	UL: 25 Mbps DL: 300 kbps	UL: 100 ms DL: 20 ms	<300 m	Urban, rural	0.5 m	Maximum speed 160 km/h

accurate positioning to avoid damage to life or property in densely populated regions. In building-intensive areas, where traditional satellite methods may lack accuracy, an excessive positioning offset might set off an anti-collision system, thus slowing down the UAV. As a countermeasure, UAVs are envisioned to employ *4×4K AI surveillance*, sending four-way 4K full-angle camera data to an AI controller that follows up by issuing timely control instructions. Other applications with similar requirements identified by the 3GPP are laser mapping, high-definition (HD) patrol, and remote UAV controller through HD video.

3) UAV UEs With Direct Device-to-Device (D2D) Capabilities: In D2D, devices in close proximity communicate directly with each other bypassing ground BSs. The establishment of direct communication links might be essential when cellular coverage is not available. In the case of UAVs, D2D capabilities may be particularly useful in swarm deployments, where UAVs need to continuously coordinate their tasks and exchange the information collected. Moreover, UAVs operating autonomously in the presence of other UAVs require D2D communications to self-control the aerial traffic and avoid collisions.

4) UAV BSs With Relaying Capabilities: In scenarios such as disaster monitoring, border surveillance, and emergency assistance, UAVs carrying a BS—denoted UxNB—can be quickly deployed. The same might hold for coverage of hot-spot events, where broadband demand experiences a sudden surge. Although the exact specifications for this use case have not yet been defined by 3GPP, one can expect a combination of stringent C2 as well as payload data requirements. Indeed, these UxNBs will be autonomously controlled and dispatched as the network sees fit, and their required backhaul bit rates could be up to several Gbps depending on the traffic load that each UAV radio access node has to handle.

B. NR Features in Support of UAVs

While not explicitly focused on cellular-connected UAVs, 3GPP Rel. 15 implements a number of features that go in the direction of satisfying the foregoing UAV connectivity requirements.[2] Among these features, the most relevant are:

1) Massive MIMO and mmWave: The integration of a large number of antennas within sub-6 GHz BSs—a.k.a. massive MIMO—and the wideband transmissions above 24.25 GHz—a.k.a. mmWave—are widely deemed as key features of NR. In massive MIMO, cellular BSs are equipped with large antenna arrays and avail of beamforming and spatial multiplexing capabilities, thus serving multiple users on each time-frequency resource [83]. In such multiuser mode, the network operates in a TDD fashion, where channels are estimated at the BS via UL pilots, sent by the users under the assumption of channel reciprocity. Moving up to mmWave frequencies provides an opportunity to meet the demands of more high-data-rate hungry applications. These frequencies offer massive bandwidths and, due to directionality, are more immune to interference than their sub-6-GHz counterparts [84]. Due to their relevance and depth, the significant impact of massive MIMO and mmWave on cellular-connected UAVs is thoroughly treated in Section IV and Section V, respectively.

2) LTE/NR Dual Connectivity: LTE and NR are bound to coexist in the same geographical areas. Indeed, the first release of NR focused on non-standalone deployments, where at least

[2]At the time of writing this article, a new work item on NR support for UAV was introduced [7]. Besides improving connectivity, the NR specification also targets sustainability, as it provides tools to significantly decrease energy consumption and greenhouse emissions [82].

one secondary NR BS complements the user plane of LTE through dual connectivity. In networks where both terrestrial and aerial devices coexist, LTE/NR dual connectivity provides the following benefits:

- *C2 traffic redundancy:* Thanks to information redundancy over LTE and NR links, dual-connected UAVs can enjoy more reliable communication than their single-connected counterparts [85]. For instance, a more reliable sub-6 GHz NR link can be used to compensate for the errors that occur on the less reliable LTE interface. Conversely, an LTE link operating at lower frequencies could compensate for the link failures that typically occur when NR operates at mmWave frequencies, e.g., due to sudden blockages.
- *UAV broadband UL traffic offloading:* Most LTE network resources serving GUEs are generally dedicated to the DL, given the higher amount of data traffic flowing in such direction. For example, typical LTE time-division duplexing (TDD) networks implement subframe configurations with a larger number of OFDM symbols for DL than for UL. A standalone LTE network would likely have to change this configuration to accommodate the large UL traffic requirements of UAVs. As a result, the incumbent LTE-connected GUEs would experience an immediate performance degradation, further exacerbated by the additional UAV-generated interference. This disruption could be alleviated when UAVs are dual-connected, since the UAV broadband UL transmissions could be offloaded to NR BSs.
- *Aerial UL power control:* LTE/NR dual-connectivity is particularly appealing for UAVs because they are immune to one of the typical issues faced by GUEs: insufficient UL transmit power. In practice, this power limitation occurs because the LTE UL must always comply to power specified by its corresponding power control, with the NR UL only availing of the remaining power budget. This issue is unlikely to affect UAVs, which tend to use a much lower UL power than their GUE counterparts thanks to the generally satisfactory LoS propagation conditions they experience with their serving cell.

3) Ultra-Lean Design: One of the NR design criteria was to reduce the number of always-on transmissions, which generate interference and occupy precious time/frequency resources regardless of the network load. A prime example of this philosophy is the removal of the LTE cell-specific reference signals for channel estimation, transmitted by all LTE BSs in every DL subframe and unavoidably causing intercell interference. This simplified design is a stepping stone for the implementation of network-wide coordination techniques for efficient aerial communications. An illustrative example is the one where only a subset of NR BSs transmit towards UAVs in a dedicated part of the spectrum, while the remaining stay quiet; another instance is the cell-free architecture described in Section IV-C.

Takeaway 1: The decade of the 2020s is likely to see a proliferation of network-connected UAVs, whose stringent control and payload data requirements are to be satisfied through NR enhancements such as massive MIMO, mmWave, and dual connectivity.

While the focus of this article is on the wireless communication links in support of cellular-connected UAVs, another key hurdle in pursuing the aforementioned use cases is the power consumption incurred by UAVs. In this regard, the total power consumption of a UAV includes two components: the communication-related power and the propulsion power. The latter is required to ensure that the UAV remains aloft as well as for supporting its mobility. Whether a UAV operates in hovering or in forward-flight mode, three main sources of propulsion power consumption can be identified:

- Blade profile, i.e., the power required to turn the rotors' blade.
- Parasitic power, to overcome the drag force caused by the UAV moving through air. This component can be negligible when hovering, but very large at high speeds.
- Induced power, to overcome the drag force that occurs as the UAV redirects the incoming airflow to generate lift. This component is larger when hovering, since all the airflow must be generated through the main rotors, and smaller in the presence of forward speed, thanks to the increased downward airflow.

As for the communication power—amounting to a few watts in most scenarios—, it is negligible when compared to the hundreds of watts required for propulsion [86]. We refer the reader to [87] and [88, Fig. 2] for more details on UAV power consumption modeling.

C. The 6G Vision

Are you thrilled by the idea of massive MIMO- and/or mmWave-connected UAVs soon delivering groceries to your doorstep? Brace yourself: in the next decade you might become the very passenger, taking the reliability requirements for the underpinning network to an extreme.

Autonomous cars-as-a-service and air taxis will redefine how we commute—and, in turn, where we live and work—with remarkable societal implications and emerging entrepreneurial opportunities. The decade of the 2020s might finally witness fully driverless cars hit the road, shifting mainstream production from Level 2—partial automation: humans monitoring all tasks and taking control when needed—to Level 5—full automation: vehicles going anywhere and anytime without human intervention [89]. Sometimes in the 2030s, we might find ourselves above traffic in flying cars or levitating pods, all autonomous and empowered by widespread 6G connectivity [90]. Electric vertical takeoff and landing vehicles (eVTOLs), projected to be displacing some of the helicopters in operation today, may be the solution to reduce congestion in megalopolis and curb energy consumption [91]. Though hurdles like safety regulations [92], noise concerns, and infrastructure needs could prolong projected launch dates, over 100 cities are already targeting urban air mobility solutions, with several companies planning to lift air taxis and a market of $1.5 trillion by 2040 [93]–[99].

Chinese drone company EHang recently had its two-seater passenger-grade autonomous UAV flying over a densely populated downtown area in Korea, in what the Mayor of Seoul defined as "a dream of mankind for the future transportation [100]. Meanwhile, Uber Elevate seeks to build and scale Uber Air, a multimodal transportation product that seamlessly integrates time-saving first- and last-mile ground transportation, e.g., between city centers and airports, in a holistically sustainable way. Three target launch cities have been announced: Los Angeles, Dallas, and Melbourne, with interest spreading globally. Though initial operations will be limited to a handful of eVTOLs, this number might be scaling to possibly hundreds over a period of 5–10 years, as community acceptance and interest dictate [101]. In its quest, Uber is teaming up with AT&T, at first to keep piloted aircrafts connected to 5G networks at low altitudes, to determine existing boundaries. The joint venture might then target 6G features to provide eVTOL safe and pilotless operations by 2030 [102], [103].

While autonomous air taxis could eventually become one of the defining killer apps of the 6G era, they exhibit unprecedented C2 as well as connectivity requirements all around a 3D environment. Safety-wise, accurate cm-grade 3D localization and navigation will also be essential at heights ranging from tens to hundreds of meters. In this regard, 6G development towards even higher frequency ranges, wider bandwidths, and massive antenna arrays, will enable sensing solutions with very fine range, Doppler, and angular resolutions [104]. Improved positioning may also be achieved by using new reference nodes, such as the rooftop-mounted BSs (introduced in Section V-A) and satellites or high-altitude platforms (HAPs), which may serve as aerial radio access nodes in 6G cellular networks as detailed in Section VI-B [105].

Besides supporting autonomous eVTOLs, future networks are meant to provide reliable, seamless, robust, and high-speed data connectivity for eVTOL passengers, enhancing their flight experience. Mobile operator Ooredoo recently connected a two-passenger, driverless air taxi to its 5G network. The test was conducted at The Pearl-Qatar, for about 20 minutes and at speeds of up to 130 km/h, with passengers reportedly achieving rates up to 2.6 Gbps [106]. While such experiment is indeed auspicious, many more air taxis with a plurality of flying passengers are expected to travel at hundreds of meters above ground, and next-generation mobile networks must be designed and planned appropriately.

D. 6G Candidate Technologies

In a quest for enabling the above bold ambitions—and many more non-UAV-related ones—the wireless community has already rolled up its sleeves in (re)search for candidate beyond-5G features. These enhancements will inevitably include more infrastructure, more bandwidth, and higher spectral efficiency via network intelligence. In the following sections, the spotlight is placed on the five main disruptive innovations being discussed in industrial fora and academia that are likely to be integrated in next-generation mobile systems:

- *Non-terrestrial networks* comprised of satellites and high-altitude platforms providing cellular service to fill the coverage gaps of the ground networks. Accordingly, NTNs are potentially capable of handling the most mobile users across their large footprint, and backhauling radio access nodes in un(der)served areas [34], [61], [107]–[109].
- *Cell-free architectures*, where a multitude of ground BSs deployed at high densities jointly communicate with all UEs simultaneously. Cell-free networks provide macro-diversity and turn interference into useful signal, thus improving worst-case performance and overall reliability when compared against typical cellular deployments [110]–[112].
- The pervasive application of *artificial intelligence* across different parts of the cellular system design to optimize the overall operation [70], [73].
- The deployment of *reconfigurable intelligent surfaces* capable of reflecting and/or refracting signals in a controlled manner. Essentially, RISs provide a way of smartly manipulating the wireless propagation environment to one's advantage, enhancing the link efficiency and reliability [113]–[121].
- Communication at *THz frequencies*, putting in play truly enormous bandwidths, allowing for MIMO transmissions even in strict LoS conditions, and further opening the door to a synergistic integration of communication, positioning, and even imaging [122]–[125].

In the remainder of the article, besides introducing these five paradigms, we focus specifically on how they are envisioned to benefit UAV communications and what hurdles stand on the way of this vision.

Takeaway 2: When compared to 5G, 6G will need to simultaneously provide ultra-reliable C2 and high-speed aerial passenger connectivity to a much larger number of UAVs, which will also have to be 3D localized with a cm-grade resolution.

IV. UAV Cellular Support Through Sub-6 GHz Multi-Antenna Enhancements

In this section, we discuss how sub-6 GHz multi-antenna enhancements can be instrumental to tackle the otherwise severe initial access, cell selection, and interference challenges experienced by UAVs.

A. 5G NR Massive MIMO for Initial Access and Cell Selection

Prior to the reception and transmission of payload data, cellular-connected UAVs must access the network. For this purpose, cellular BSs regularly transmit synchronization signal blocks (SSBs) that facilitate their discovery. Up to LTE Advanced Pro networks, the radiation of SSB signals was determined exclusively by the BS antenna pattern [40], [41], [126]. For the typical cellular network with downtilted BSs, this means that devices flying higher than BSs could only perceive SSB signals through antenna sidelobes. This phenomenon is illustrated in Fig. 1, which represents the antenna gain perceived by UAVs flying at (from top to bottom) $\{150, 75, 50, 1.5\}$ m and moving away from a BS with a height of 25 m. The BS is equipped with an 8×1 vertical array downtilted by 12° [8]. Fig. 1 shows how, while cellular

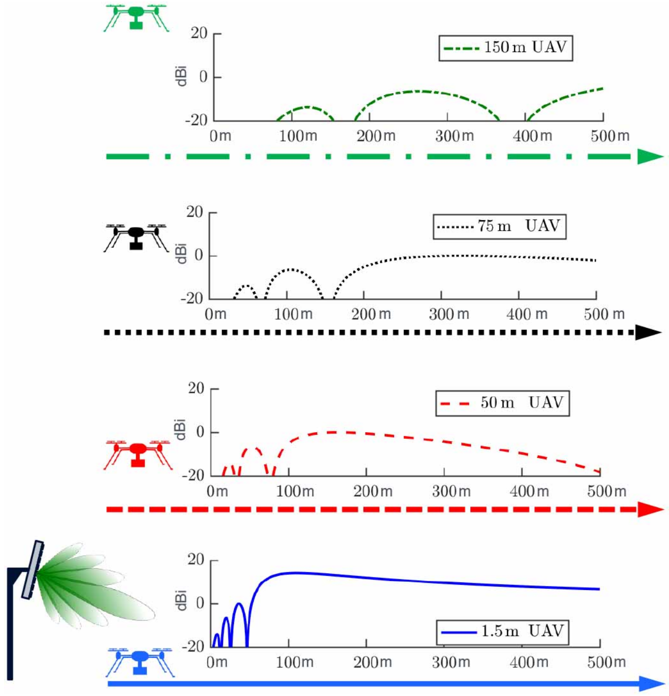

Fig. 1. Antenna gain [dBi] vs. 2D BS-to-UAV distance [m] for a BS deployed at 25 m and UAVs of various heights, aligned to the BS's horizontal bearing.

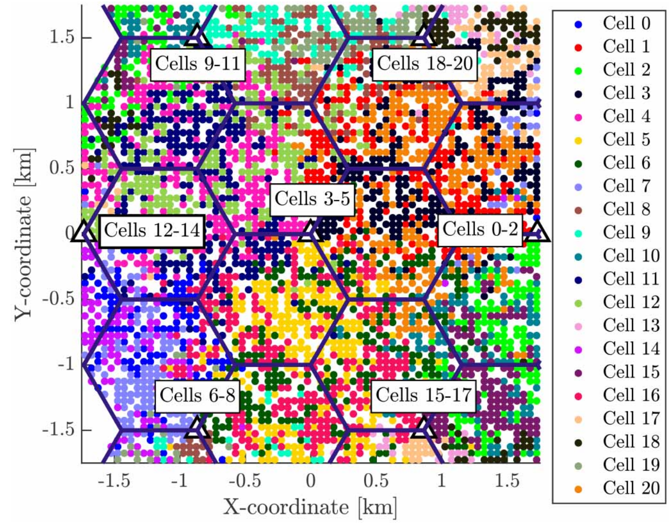

Fig. 2. Serving cell selection map based on RSRP for a UAV flying at 50 m. White spots correspond to grid points where no UAVs were present.

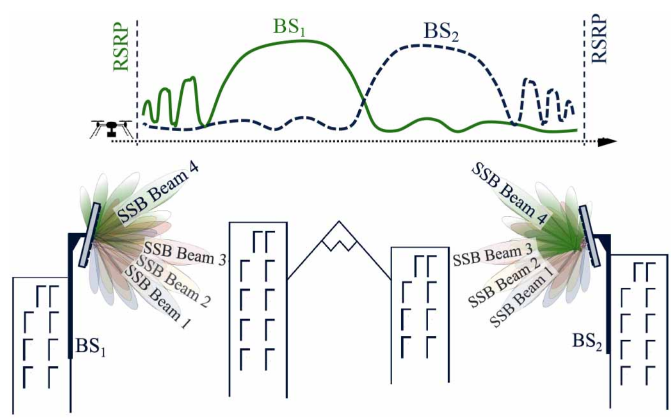

Fig. 3. Illustration of a SSB beam design optimized for serving UAVs.

devices near the ground generally experience reasonable and smooth antenna gain variations as they move away from the BS, this is not the case for UAVs, whose antenna gains are dramatically reduced and become highly irregular as the altitude increases and only BS antenna sidelobes can be perceived.

Not only does the foregoing behavior pose a great challenge when UAVs attempt to initially access the network, but also when they fly at reasonable speeds and need to (re-)select their serving cell. To illustrate this, Fig. 2 represents a typical Urban Macro (UMa) network comprised of three-sector[3] BSs with an intersite distance (ISD) of 1.5 km and indicates, in grids of 50 m $\times$ 50 m, the best serving cell, i.e., the one providing the strongest reference signal received power (RSRP), for UAVs flying at an altitude of 50 m [127]. The map in Fig. 2 demonstrates that UAVs do not tend to associate to their physically closest cells, which is typically the case for GUEs. Moreover, the figure shows that UAVs will execute a large number of handovers due to the changes in the best-serving cell they experience when moving from a given grid point to an adjacent one.

In contrast to LTE Advanced Pro and preceding networks, the SSB signals originated by NR BSs can be transmitted towards multiple directions through time-multiplexed beam sweeping, denoted as an SS burst set [67]. This capability is illustrated in Fig. 3, where it can be observed that BSs operating between 3 GHz and 6 GHz can transmit up to four different SSB beams.

The possibility of focusing beamformed SSBs towards the sky opens up a new way of mitigating the sidelobe-related issues previously described. Indeed, mobile network operators aiming at reliably serving UAVs may opt to perform a network-wide design of the beamformed SSBs to uniformly cover the sky, similarly to what is done for the ground. This concept is also exemplified in Fig. 3, where the UAV flying above the BSs now perceives a smooth RSRP transition that facilitates the initial cell selection and subsequent handovers.

Takeaway 3: The beamformed SSBs introduced in NR can greatly facilitate initial cell selection and subsequent handovers for UAV users, overcoming the power fluctuation issues associated with sidelobe-based UAV-BS association.

B. 5G NR Massive MIMO for Interference Management

Once UAVs connect to the network, the latter needs to guarantee a pervasive and sufficient signal quality to enable reliable C2 and data transmissions. The NR massive MIMO capabilities are critical to achieve this objective [128]. This observation is supported by the system-level simulation results provided in the remainder of this Section [129]. Fig. 4 shows the 5%-worst DL signal-to-interference-plus-noise ratios (SINRs) per time/frequency physical resource block (PRB) of 7 OFDM symbols and 12 subcarriers. This

[3]In cellular networks, a deployment site is traditionally divided into three sectors, each covered by a different BS and considered as a different cell.

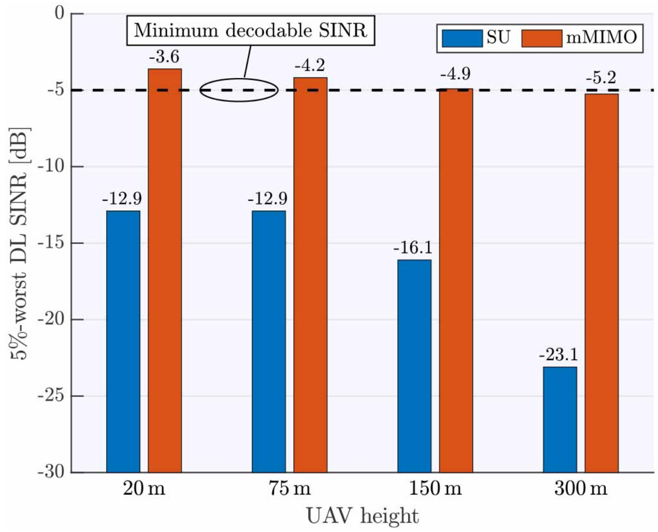

Fig. 4. 5%-worst DL SINRs per time/frequency block experienced by UAVs flying at different heights in single-user and massive MIMO networks with perfect CSI.

figure assumes single-antenna UAVs flying at different heights and two typical fully loaded Urban Macro networks with an ISD of 500 m [41], [130]:

- A single-user (SU) network comprised of BSs downtilted by 12° and equipped with one RF antenna port connected to 8 vertically stacked cross-polarized antenna elements.
- A massive MIMO (mMIMO) network with BSs also downtilted by 12°, but equipped with 128 RF chains connected to an 8×8 planar array of cross-polarized antenna elements. These BSs are capable both of focusing their transmissions (i.e., beamforming) and of spatially multiplexing up to eight devices[4] through—for the time being—zero-forcing precoding with perfect channel state information (CSI).

In both networks, 14 GUEs and one UAV are deployed per cellular sector, as per 3GPP Case 3 [3]. The results of Fig. 4 demonstrate how NR massive MIMO capabilities are essential to reliably serve the worst-performing UAVs in loaded cellular networks. This is mostly because UAVs receiving DL transmissions experience LoS propagation conditions with an increasing number of interfering BSs as their altitude increases [131]. Cellular BSs with NR massive MIMO capabilities can simultaneously increase the useful signal power (thanks to the boost provided by their beamforming gains) and reduce the intercell interference (thanks to the higher directionality of their transmissions).

The CSI needed by massive MIMO BSs to beamform and spatially separate UEs in TDD networks is acquired by observing UL sounding reference signals (SRSs) and leveraging UL-DL channel reciprocity [67]. In practice, these estimates are imperfect since the finite number of SRSs have to be reused across multiple cells and they interfere with each other, a phenomenon commonly known as pilot contamination [132], [133]. Fig. 5 considers a realistic CSI acquisition situation where eight SRSs are reutilized every three sectors and illustrates the percentage of UAVs flying at 150 m that achieve DL C2 rates higher than 100 kbps (the minimum requirement originally defined by 3GPP [3]). The figure considers both UMa and Urban Micro (UMi) deployments. In the latter, BSs are deployed at a height of 10 m with an ISD of 200 m. The performance is shown for UAVs and networks with the following enhanced capabilities [129]:

- *aaUAV.* UAVs with 2×2 antenna arrays and a single RF chain capable of beamforming their UL/DL signals towards/from their serving BSs.
- *mMIMOnulls.* Massive MIMO BSs capable of placing up to 16 radiation nulls towards the most interfering UAVs both during the UL SRS stage—therefore partially suppressing the harmful UAV-generated interference—and the data transmission stage—therefore mitigating the harmful intercell interference [134]–[136]. Massive MIMO BSs can perform such null steering relying only on statistical CSI, i.e., by leveraging the strong directionality of the LoS channels towards the most harmful UAVs (in the UL) or the most interfered ones (in the DL) [129].

The following key observations can be made based on the results of Fig. 5:

- While equipping UAVs with multiple antennas does not suffice to guarantee a satisfactory DL performance in SU networks—only 33% of the UAVs in UMi SU networks experience rates larger than 100 kbps—, substantial benefits can be found in networks with NR massive MIMO BSs, where the number of UAVs reaching 100 kbps in UMi networks doubles from 42% to 85%.
- The best-performing solution is the one where massive MIMO BSs implement null steering capabilities, with almost all UAVs reaching the desired 100 kbps in fully loaded UMa networks. This solution seems particularly attractive for mobile operators, since it does not rely on the features implemented by UAV manufacturers.
- For all four systems considered, the performance of UAVs served in UMi networks is worse than that attained by UAVs flying through UMa networks. This can be explained as follows: the higher the network density, the more BSs will generate/receive interference to/from the LoS UAVs served by neighboring BSs, resulting in performance degradation [137].

For completeness, the interested reader can find in Table IV the DL C2 performance for UAVs flying over UMa deployments at other heights. Such performance can be directly compared to the C2 reliability requirements reported in Table III, although it should be noted that the results in Table IV have been obtained under the worst-case scenario of a fully loaded network.

Takeaway 4: At sub-6 GHz, the higher the network density, the more BSs that generate/receive interference to/from neighboring LoS UAVs. Enhancing NR massive MIMO with UAV-aware intercell interference suppression capabilities can nearly double the UL rates of coexisting aerial and ground devices, even when availing of just statistical intercell CSI.

[4]Multiplexing a larger number of devices might yield a higher cell spectral efficiency. However, it might prevent achieving a minimum guaranteed rate for all devices, which is the primary goal for supporting the UAV C2 link.

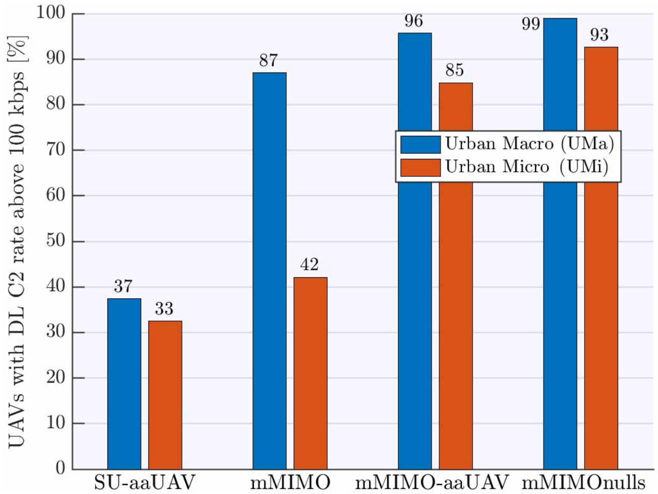

Fig. 5. Percentage of UAVs with DL C2 channel rates larger than 100 kbps when flying at 150 m above UMa and UMi cells.

TABLE IV
PERCENTAGE OF UAVS WITH DL C2 CHANNEL RATES LARGER THAN 100 KBPS AS A FUNCTION OF THEIR HEIGHT, FOR AN UMA DEPLOYMENT

	SU-aaUAV	mMIMO	mMIMO-aaUAV	mMIMOnulls
15 m	87%	97%	97%	99%
75 m	79%	96%	98%	99%
150 m	37%	87%	96%	99%
300 m	3%	33%	83%	98%

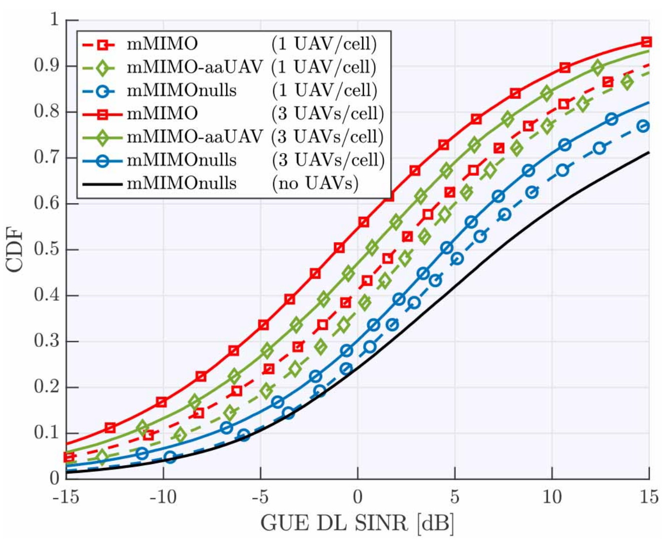

Fig. 6. CDF of the GUE DL SINR per time/frequency block under the presence of 1 and 3 UAVs per UMa cell flying at 150 m.

Such approach is more effective than beamforming at the UAV side.

While Figs. 1–5 focus on the performance of the cellular-connected UAVs, one should not forget that these networks will have to satisfactorily continue to serve GUEs. Fig. 6 presents the cumulative distribution function (CDF) of the DL SINRs experienced by GUEs in the presence of 1 and 3 UAVs per cell at 150 m. The GUE DL performance is seen to degrade as more UAVs are served. Somewhat surprisingly, the main reason for this can be found in the UL SRS transmission that

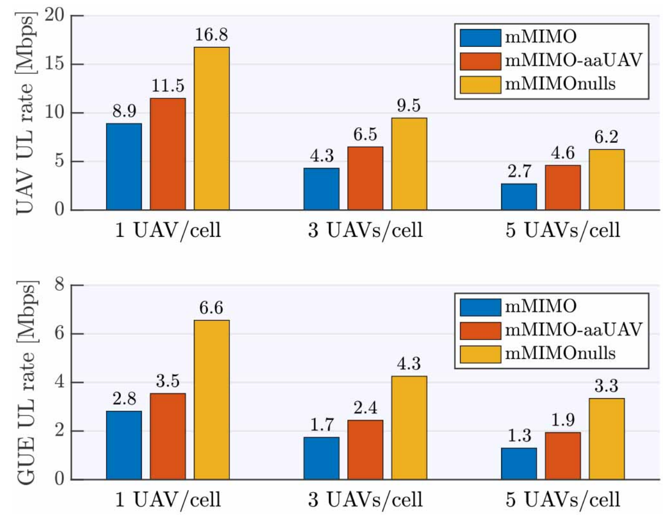

Fig. 7. Mean UL rates for UAVs (top) and GUE (bottom) for UMa cellular networks with 1, 3, or 5 UAVs per cell.

precedes the massive MIMO DL data transmission; the SRSs of high-altitude UAVs generate strong interference towards a large number of BSs that are simultaneously receiving SRSs from GUEs. In simple words, the larger the number of UAVs, the worse the DL channel estimates and the resultant DL beamforming and spatial multiplexing accuracy of the massive MIMO BSs. Regardless of this phenomenon, equipping massive MIMO BSs with null steering capabilities remains the best-performing solution.

Finally, Fig. 7 looks directly into the UL performance of both UAVs and GUEs by showing the mean UL bit rates for UMa networks with 1, 3, and 5 UAVs per cell at altitudes uniformly distributed between 1.5 m and 300 m. The results of Fig. 7 exhibit similar trends to those of Fig. 6, highlighting again the importance of enhancing baseline NR massive MIMO networks with UAV-aware intercell interference suppression capabilities to substantially improve—nearly doubling in most cases—the UL rates of the coexisting aerial and GUEs.

Takeaway 5: The uplink data transmission performance of GUEs can be greatly affected by the presence of UAVs when they share the same time/frequency resources through spatial multiplexing. Furthermore, when operating in TDD networks where downlink CSI is estimated by leveraging UL-DL channel reciprocity, the performance of GUEs is also affected in the downlink due to the additional SRS pilot contamination generated by UAVs.

C. Cell-Free Architectures for UAVs

Looking towards 6G, there is the perception in many quarters that the cellular framework might be exhausted and should be transcended, at least for dense deployments. Underpinning this perception is the recognition that, in the UL, intercell interference is merely a superposition of signals that were intended for other BSs, i.e., signals that happen to have been collected at the wrong place. If these signals could be properly classified and routed, they would in fact cease to be interference and become useful in the detection of the data they bear. A dual observation can be made about the DL, altogether motivating so-called cell-free networks where all BSs joint communicate with all users [110]. Such networks have the potential of providing major benefits in terms of signal enhancement (both macro- and micro-diversity) and interference reduction [111], [112].

For UAV communication, where LoS conditions generally exist to multiple BSs, with the correspondingly severe intercell interference, the appeal of a cell-free operation is reinforced even further [138], [139]. In fact, in terms of interference relief, such dense cell-free networks could be regarded as a competing alternative to macrocellular massive MIMO; spatial degrees of freedom that are spatially distributed in the former versus concentrated in the latter.

To gauge the potential of cell-free architectures for UAV communication, we examine how the SINR distribution in a UMi environment ($\mathsf{ISD} = 200$ m) changes as the network is rendered cell-free. Once more, the focus is on the UL, the most demanding link for UAV communication. We begin with UAV-only service at 2 GHz, detailed as:

- A 20 MHz TDD channel.
- Transmit power, noise figure, antenna gains, LoS probability, pathloss, and Ricean fading, all as per [3].
- BSs and UAVs randomly deployed, with the altitudes of the latter distributed between 25 and 150 m.
- Fractional power control with $\epsilon_{\mathrm{UAV}} = 0.7$ in all cases. (The cell-free extension of this power control technique is formulated in [140], [141].)
- SU per cell and single antenna per BS.

Channel estimation acquires heightened importance for cell-free operation because, as interference is removed, the residual estimation error becomes a limiting impairment. To provide a comprehensive view of the cell-free advantage, we thus quantify such advantage for the two extremes in terms of channel estimation: on one hand, perfect estimation; on the other hand, minimum mean-square error (MMSE) estimation based on an UL SRS occupying one symbol per time-frequency coherence interval [142]. Any operating point is bound to be somewhere in-between these extremes.

Two cell-free variants are entertained, namely a first one where all the BSs jointly form matched-filter (MF) beams towards the users, maximizing the SNRs with no regard for the interference, and a second one where the beams are designed under an MMSE criterion and the SINRs are maximized. The former is computationally less intense and may admit somewhat distributed implementations [143] while the latter, a decided shift towards the C-RAN paradigm, is where the full cell-free potential is unleashed [144]–[146].

Presented in Fig. 8 is the CDF of the SINR, averaged over the small-scale fading, in cellular and cell-free networks having an equal number of BSs and users. The cellular performance, whose lower tail corresponds to the values in Fig. 4, is barely affected by the channel estimation precision: the estimation error is much weaker than interference-plus-noise, even with a single-symbol SRS per coherence interval. The MF cell-free alternative, also not significantly impacted by channel estimation, increases the worst-case SINRs noticeably,

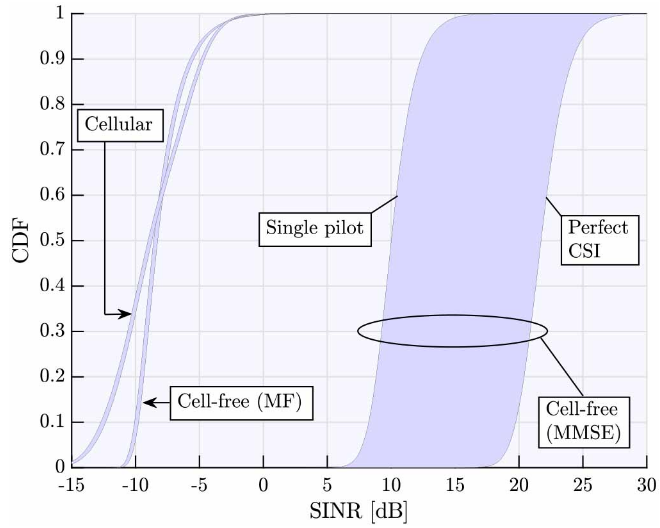

Fig. 8. SINR distribution in a UAV-only UMi cellular network alongside its cell-free counterparts. For each case, the shaded region spans the range between single-symbol SRS and perfect channel estimation.

but does not otherwise improve things. It is in its MMSE incarnation that cell-free operation dramatically improves the performance, with median SINR gains of 20–30 dB depending on the channel estimation accuracy, which takes center stage as anticipated. As this accuracy goes hand in hand with the SRS overhead, to be discounted from the spectral efficiency, some intermediate operating point within the shaded range in the figure is desirable depending on the fading coherence. Regardless of its exact value, the benefit is hefty, and indeed even larger than for terrestrial service because of the increased LoS probability for UAVs.

Next, the exercise is repeated for a network where there are 14 GUEs for every UAV [3]. The LoS probability and pathloss for GUEs are as per [8]. Shown in Fig. 9 is the CDF of the SINR for the UAVs, which, on account of the reduced LoS probability for intercell interferers, shows a somewhat diminished degree of cellular outages. Nevertheless, the potential of the cell-free alternative in its MMSE form remains largely intact.

Research is ongoing on various aspects of cell-free operation that are still not fully resolved, including scalability [147], DL precoding [148]–[150], or DL power allocation [151], [152], and new issues arise with the move to C-RAN structures, where the traditional shared resources of power and bandwidth are augmented by a new shared resource: computation [153]. All of this research is relevant to UAV service, and should be expanded to accommodate UAV specificity, chiefly the dependence on altitude and the strict battery charging schedules.

As anticipated in Section III, UAVs may also act as flying BSs, fashioning networks for disaster relief, emergency services, or special events [154]. These networks would present a host of specific challenges, above all the wireless nature of the backhaul, the fact that the BSs would be battery-operated and themselves mobile, and the need to synchronize over the air. Also for such networks, which in a sense would

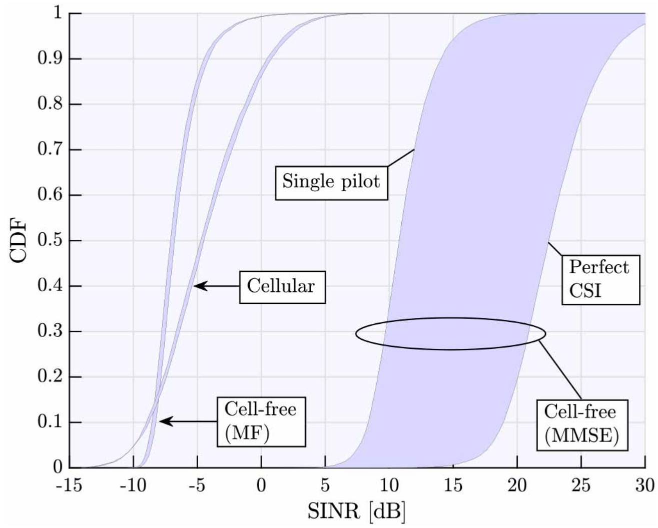

Fig. 9. SINR distribution for UAVs in a UMi cellular network having 7% UAVs and 93% GUEs, alongside its cell-free counterparts. For each case, the shaded region spans the range between single-symbol SRS and perfect channel estimation.

be the dual of terrestrial networks serving UAVs, cell-free operation might be enticing [9].

Takeaway 6: Cell-free architectures can provide macro-diversity and turn interference into useful signal, dramatically improving the worst-case performance scenarios and thus the overall reliability. For UAVs undergoing LoS conditions to multiple BSs, the appeal of cell-free operations is reinforced even further. Unresolved aspects include scalability, DL precoding and power allocation, and the dynamicity of the cluster of serving BSs.

V. UAV Capacity Boost Through mmWave and THz Communications

A relentless trend in the evolution of wireless communications is the hunger for bandwidth, and fresh bandwidth is only to be found at ever higher frequencies. The mmWave spectrum represents the current opportunity, and a formidable one at that, to unlock large swaths of bandwidth and enable the most ambitious 5G aerial use cases listed in Table III. Moreover, in order to cope with the prohibitive isotropic propagation loss at such short wavelengths, mmWave links are highly directional and hence less prone to interference, which reduces the myriad of challenges detailed in Section IV-B and facilitates the coexistence of terrestrial and aerial devices. In what follows, we quantify the achievable performance of mmWave-connected UAVs in both urban and suburban/rural scenarios. We focus on the UL, since this is the power-limited direction and the one typically demanding the highest capacity.

A. 5G NR mmWave UAV Urban Coverage

Aerial coverage depends in an intricate manner on the angular and power distributions of signal paths along with the antenna patterns at the UAV and BS. To capture these distributions accurately in an urban environment, and given the lack of a calibrated mmWave aerial channel model, we conducted ray tracing simulations by means of the Wireless Insite tool by Remcom [155], [156].[5]

Fig. 10. 3D map of a section of London employed, together with Remcom Wireless InSite ray tracer, to generate the propagation paths of 25800 mmWave air-to-ground links.

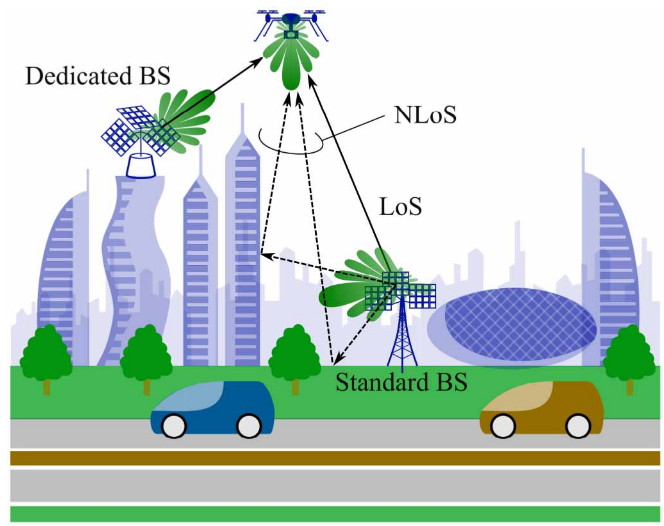

Fig. 11. Urban deployment featuring standard and dedicated BSs.

In particular, our study spanned a 1 km $\times$ 1 km 3D section of London, shown in Fig. 10. As illustrated in Fig. 11, such area features two complementary networks operating at 28 GHz with a bandwidth of 400 MHz. The first network was comprised of street-level *standard* NR mmWave BSs at heights between 2 and 5 m, deployed uniformly at random with average ISD of $\mathsf{ISD_s}$, each spawning three sectors with a 12° downtilt. A second network of *dedicated* mmWave BSs was deployed only on rooftops, also uniformly at random but with average ISD of $\mathsf{ISD_d}$, and with a 45° uptilt angle. The transmitting UAVs were distributed uniformly at specific heights, with their antennas pointed downwards. Each sector features an 8 $\times$ 8 uniform rectangular array (URA) while each UAV is equipped with a single 4 $\times$ 4 URA. In both cases, the antenna element radiation pattern is set according to [8]. The Python-based system-level simulator employed is freely available [157].

1) Coverage With Standard NR mmWave BSs: Let us begin by considering a deployment reliant exclusively on standard

[5]As discussed in Section VI-A, machine learning techniques can be employed to recreate such model, avoiding the computational burden of ray tracing simulations.

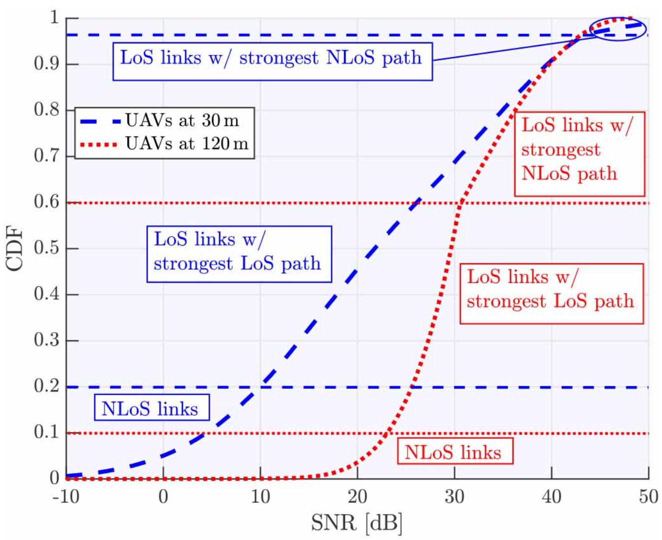

Fig. 12. SNR distribution for UAVs served by standard mmWave cells in an urban environment. Horizontal lines show the breakdown into three regions: NLoS-dominated (bottom), LoS-dominated (middle), and LoS-dominated with strong NLoS paths (top).

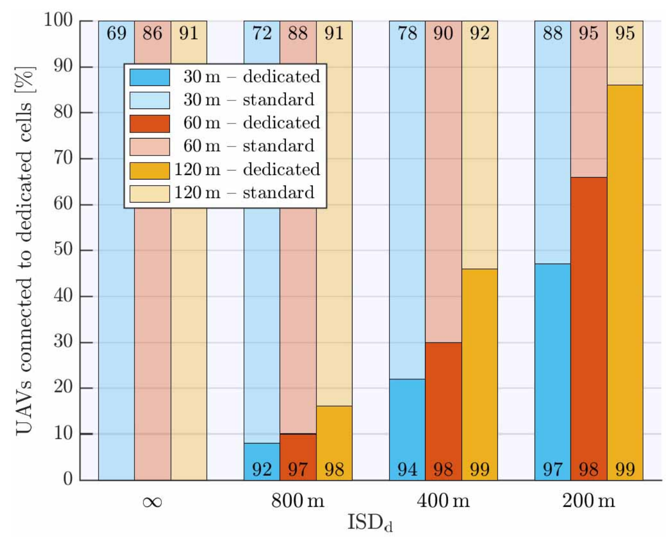

Fig. 13. Fraction of UAVs connected to standard (clear bars) and dedicated (solid bars) mmWave cells in an urban environment. Three UAV heights are considered and, for each case, the percentage of LoS links is indicated by the numbers at the top (for standard BSs) and at the bottom (for dedicated BSs). $\mathsf{ISD_s} = 200$ m is fixed for standard cells, whereas $\mathsf{ISD_d}$ varies to capture scenarios with different dedicated cells densities.

BSs, to assess the extent to which such a deployment can provide satisfactory aerial coverage. With the signal-to-noise ratio (SNR) taken as a proxy for coverage, Fig. 12 presents the distribution of the SNR with $\mathsf{ISD_s} = 200$ m, and UAV altitudes of 30 and 120 m. At least 98% of UAVs at 30 m have an SNR > -5 dB, testifying to an acceptable coverage at low altitudes. Moreover, the coverage improves with altitude. By 120 m, almost all UAVs achieve in excess of 15 dB. This result may seem surprising given the downtilted directional nature of the antennas at the BSs, with a front-to-back ratio of 30 dB [8].

To understand how UAVs still enjoy satisfactory coverage, Fig. 12 identifies three SNR regions with distinct dominant link behaviors.

- The lower tail corresponds predominantly to non-LoS (NLoS) links.
- The middle section is dominated by LoS links whose LoS component is in turn dominant.
- The upper tail is mostly constituted by LoS links, but with a NLoS link being the strongest link after accounting for the antenna gains.

Thus, in the lower tail, which is what determines the coverage, the connectivity rests mostly on NLoS communication, meaning through a conjunction of BS antenna sidelobes and reflected paths. Both these ingredients turn out to play a substantial role, revealing that the BS sometimes leverages NLoS paths that happen to be stronger than the LoS, especially when the UAV is horizontally close as illustrated in Fig. 11.

As the UAV altitude increases, the LoS probability grows, but NLoS paths continue to play an important SNR-enhancing role. Altogether, a standard 5G mmWave deployment suffices for UAV coverage when $\mathsf{ISD_s} = 200$ m. Then, as $\mathsf{ISD_s}$ extends beyond this value, coverage decays for low-altitude UAVs, and a progressively higher minimum altitude is required for service. This suggests that a sub-6 GHz coverage umbrella might be desirable to support some of the use cases in Table III for low-altitude UAVs, e.g., for takeoff and landing operations. Although not shown for brevity, our study reveals that for $\mathsf{ISD_s} = 400$ m, for instance, roughly 10% of UAVs at 30 m turn out to experience negative-dB SNRs, indicating that coverage is no longer guaranteed at this altitude.

Takeaway 7: At typical urban microcellular densities, NR mmWave networks can provide satisfactory coverage to aerial links—in spite of employing highly directional and downtilted antennas—thanks to a favorable combination of antenna sidelobes and strong reflections. In deployments with lower mmWave BS densities, UAV coverage cannot be guaranteed, especially at low altitudes where NLoS links are predominant.

2) Coverage Enhancement With Dedicated mmWave BSs: Having characterized the coverage for a standard deployment, let us now quantify the impact of incorporating dedicated BSs with $\mathsf{ISD_d} \geq \mathsf{ISD_s}$. Fig. 13 provides the following information:

- The fraction of UAVs that choose to connect to dedicated BSs (solid bars) as the density of the latter increases, i.e., as $\mathsf{ISD_d}$ decreases, rather than connect to standard BSs with $\mathsf{ISD_s} = 200$ m (clear bars). This fraction is presented for various UAV altitudes, indicating that it is the UAVs at higher altitudes that exhibit increased preference for the dedicated BSs. This is toned down at lower altitudes, but even then dedicated BSs are generally favored when their density equals that of the standard ones. As one would expect, the relevance of dedicated BSs dwindles as they become sparser.
- The percentage of links that are in LoS (numbers at the top and at the bottom for standard and dedicated BSs, respectively), providing another perspective on the effects of deploying dedicated BSs. The addition of dedicated BSs drastically brings such percentage close to 100% at all the considered UAV altitudes and, with

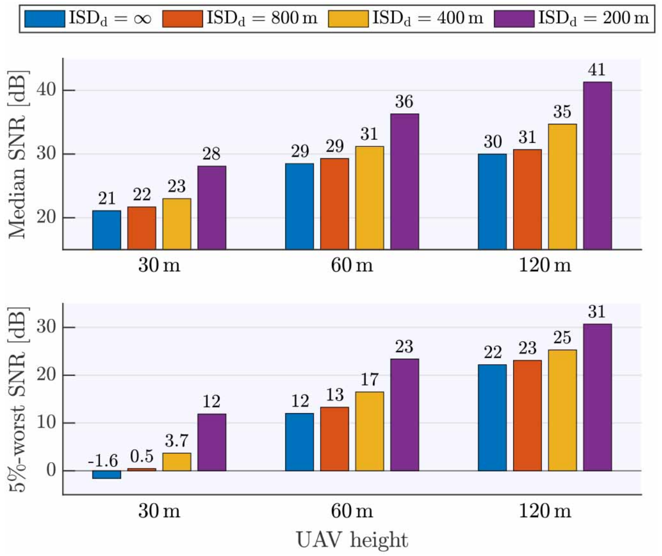

Fig. 14. Median and 5%-worst SNR for UAVs served by both standard and dedicated mmWave cells in an urban environment. $\mathsf{ISD_s} = 200$ m is fixed for standard cells whereas $\mathsf{ISD_d}$ varies for dedicated cells of various deployment densities.

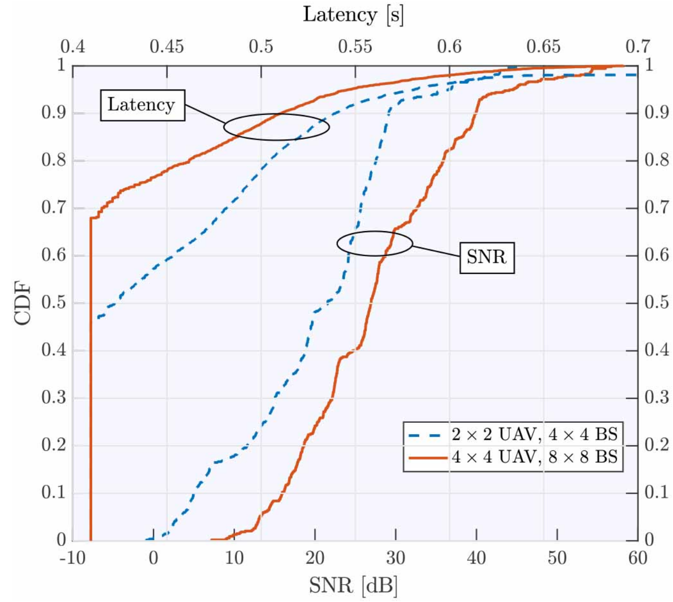

Fig. 15. CDF of the SNR and latency experienced by a UAV in a suburban/rural environment when served by mmWave links with two different antenna array configurations.

$\mathsf{ISD_d} = \mathsf{ISD_s} = 200$ m, a vast majority of UAVs enjoy LoS connectivity to their serving BSs.

The ensuing SNR distributions, with each UAV connecting to its preferred BS, either standard or dedicated, are presented in Fig. 14 for UAV altitudes of 30, 60 and 120 m. The SNR improvement with dedicated BSs is pronounced, especially for the 5%-worst SNR, provided those dedicated BSS are as dense as their standard counterparts. Such improvement can help achieve the most stringent bit rate requirements of the payload data use cases listed in Table III, for the vast majority of UAVs. With sparser dedicated BSs, the improvement weakens, becoming anecdotal for $\mathsf{ISD_d} = 4 \times \mathsf{ISD_s}$.

Takeaway 8: As their density declines, the coverage from standard mmWave BSs becomes progressively less robust. For low-density deployments, dedicated BSs mounted on rooftops and uptilted could substantially enhance coverage. When radiating mmWaves above the horizon, compliance to emission regulations must be ensured.

B. 5G NR mmWave UAV Rural/Suburban Coverage

In contrast to the above, we now consider a UAV employed for a public safety application, taking place in a suburban or rural environment. Specifically, we employed actual drone flight traces from the Austin Fire Department, obtained using inertial measurement unit sensors and including position, velocity and orientation of a UAV that aims at wildfire prevention or behavior monitoring. The UAV motion traces were fed into an end-to-end 5G NR network simulator that updated the optimal beam pair every 5 ms, consistently with the 3GPP beam management guidelines [158], accounted for the Doppler effect due to the UAV motion, and periodically generated a UDP payload of 1500 bytes, for a total traffic source rate ranging from 10 to 1000 Mbps [159]–[161].

Fig. 15 captures the statistical distribution of the SNR and latency when operating at 28 GHz with a bandwidth of 1 GHz.

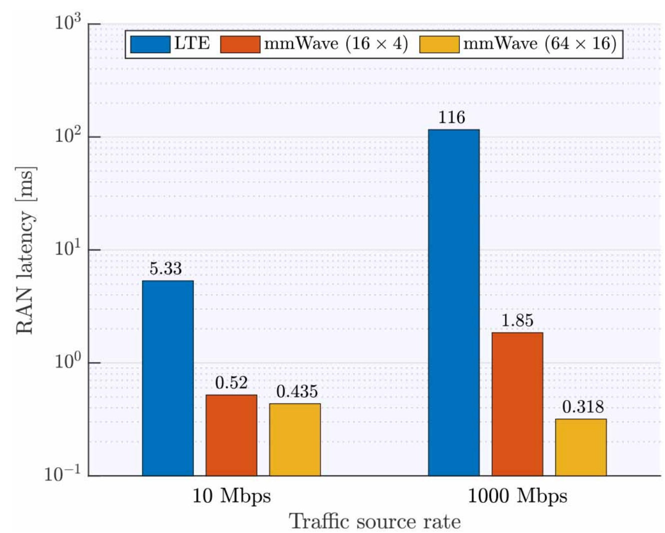

Fig. 16. Mean RAN latency experienced by UAV users served by LTE and mmWave links (two array configurations) under traffic loads of 10 and 1000 Mbps.

The transmitting UAV is equipped with 2×2 and 4×4 antenna arrays whereas the receiving BS incorporates 4×4 and 8×8 arrays. As expected, a higher number of antennas can help sustain a better connection, especially when the UAV and the BS are further away, with direct benefits in both SNR and latency.

Fig. 16 further compares the mmWave setup to a baseline LTE system operating at 2.1 GHz in terms of radio access network (RAN) latency. While incurring a reduced pathloss, the limited LTE bandwidth results in a much lower throughput. Moreover, the frame design in LTE does not support the sub-ms latency that can be achieved with NR mmWave [162]. Consequently, LTE can yield mean latencies below 10 ms when the traffic source rate is low. In contrast, the vast bandwidth availability in the mmWave spectrum enables Gbps connectivity with millisecond-latency even under a high traffic source rate [163].[6]

C. UAV Communication at THz Frequencies

While 5G is seizing the mmWave band, the attention of researchers is shifting already to the THz range, broadly defined as 100 GHz–10 THz [122], [123]. Because of reduced diffraction, THz communication is mostly circumvented to LoS channels, but that is compatible with UAV situations where extremely high bit rates may be required, say wireless fronthaul to UAVs acting as BSs [124]. Furthermore, the THz band opens the door to a synergistic integration of communication with positioning and even imaging [125].

The understanding of THz propagation is still incipient and comprehensive channel models are lacking for terrestrial applications, let alone for aerial settings [164]. On the one hand, behaviors that begin to arise at mmWave frequencies become prominent in the THz realm, including pronounced peaks of molecular absorption [165], angular sparsity, high omnidirectional pathloss, and wavefronts that are nonflat over the span of large arrays [166]. Likewise, the extremely broad bandwidths bring to the fore phenomena that were hitherto muted, including spatial widening over large arrays and the ensuing beam squinting [167]. On the other hand, some of these same behaviors lead to new opportunities. Wavefront curvature over the arrays, for instance, opens up the possibility of MIMO communication in strict LoS conditions: even in the absence of multipath propagation, high-rank channels can then be created based only on the array apertures [168]–[171]. Moreover, because the attributes of such channels hinge on sheer geometry, they can be controlled through the design and disposition of the arrays themselves [172].

The potential of THz communication can be gauged in Fig. 17, which presents the information-theoretic bit rates achievable as a function of the distance on a free-space channel. A comparison is drawn between a 400 MHz transmission at 28 GHz and a 1.6 GHz transmission at 140 GHz. The transmit power, noise figure, and antenna gains, are all as per [8]. At 28 GHz, the transmitter features a 16-antenna planar array with half-wavelength spacing (1.6 cm $\times$ 1.6 cm) and the receiver features a 64-antenna array, also planar and with half-wavelength spacing (3.75 cm $\times$ 3.75 cm); beamforming is applied. At 140 GHz, the noise figure is increased by 3 dB and the same array areas and antenna spacings are used, now accommodating 256 antennas at the transmitter and 1296 antennas at the receiver; beamforming is again applied. The spectral efficiencies are capped at 4.8 bps/Hz per antenna to prevent artifact values corresponding to excessively large constellations [154]; this results in steady bit rates up to 1000 m, with the 140 GHz transmission exhibiting a fourfold advantage by virtue of the combined effects of more bandwidth and more antennas (within the same real estate).

[6]Fig. 16 shows a slightly decreasing latency versus traffic load for a mmWave (64 $\times$ 16) setup. This is simply owed to a numerical error due to the very small values of latency experienced under this setup.

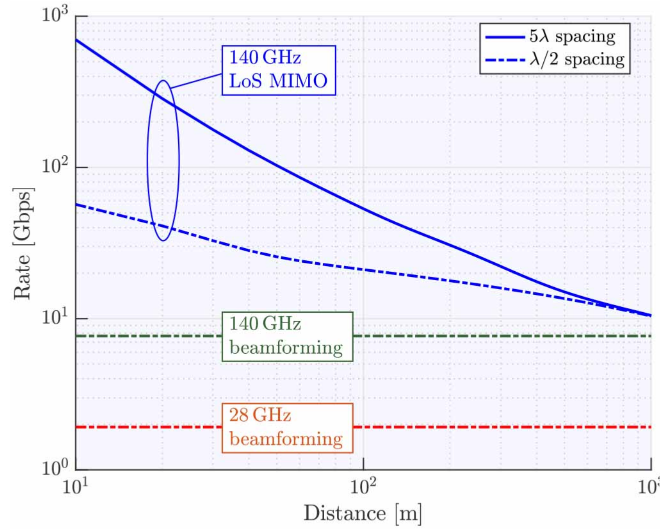

Fig. 17. Information-theoretic bit rate as a function of distance for 28 GHz and 140 GHz LoS transmissions. At 28 GHz: 16 transmit and 64 receive antennas. At 140 GHz: 256 transmit and 1296 receive antennas.

An even more dramatic leap in performance is possible by resorting to LoS MIMO, even if the compact half-wavelength antenna spacings are retained, and let alone with these relaxed to 5λ so the respective arrays occupy 16 cm $\times$ 16 cm and 37.5 cm $\times$ 37.5 cm. Then, truly stupendous bit rates are theoretically feasible at short and intermediate distances and, even if only a fraction of these are realized, the upside is extraordinary.

Enter UAVs, with new challenges in the domain of channel characterization such as the effects of altitude and trajectories, the uncertainties associated with wind [173], the orientation and wobbling of the arrays [174], [175], or possible signal blockages by the body of the UAV [176]. The power consumption aspect also becomes exacerbated, and additional limitations might be imposed because of size and weight considerations. Chief among the power consumption issues at THz frequencies stand the analog-to-digital converters, whose power consumption grows linearly with the bandwidth and exponentially with the resolution [177]. Despite these hurdles, which call for multidisciplinary research efforts, UAV communication at THz frequencies is an exciting proposition with vast potential, if not as a primary means of communication, at least as an enhancing mode with fallback to lower frequencies.

Takeaway 9: UAV communication at THz frequencies has vast potential, putting in play truly enormous bandwidths and—due to the wavefront curvature of the arrays—allowing for MIMO transmissions even in strict LoS conditions. Issues such as power consumption, attenuation, and sensitivity to blockage and vibrations suggest confining THz operations to short-to-intermediate distances and to a non-standalone mode.

VI. Intelligence and Resilience for UAV Communications

A. Artificial Intelligence to Model and Enhance UAV Communications

Arguably, the pervasive application of AI frameworks across different parts of the cellular system design is widely regarded as one of the key constituents of the future 6G networks [70], [73]. Below we present two proven and distinct use cases where UAV cellular communications greatly benefit from the application of AI frameworks.

1) AI for Aerial Channel Modeling: Despite their importance, accessible channel models—not based on computationally intensive ray tracing—for UAV communications that operate in the mmWave spectrum are not yet available. For instance, current 3GPP standard-defined aerial channel models are calibrated only for sub-6 GHz frequencies [3]. Attempts to create the first measurements-based mmWave aerial channel model [176], [178], [179] focus exclusively on LoS links and are still missing a statistical description of the multipath channel, which is essential to enable wireless coverage in a multitude of scenarios, as discussed in Section V. Similarly, several other works such as [180]–[183] fall short of providing a 3D spatial channel model and are therefore not yet fully adequate to conduct a rigorous assessment of the performance that can be achieved by mmWave-connected UAVs.

Since mmWave systems rely on highly directional communication at both transmitter and receiver, channel models must provide statistical descriptions of the full *doubly directional* characteristics of the channel, which include the totality of path components as well as the angles of arrivals, angles of departure, gains and delays. Modern data-driven machine-learning methods become an attractive recourse to tackle this challenge. In particular, neural networks (NNs) have been used in [184]–[188] for indoor mmWave channel modeling, where the NN outputs parameters that represent a regression from the training dataset, similar to what is typically proposed with learning-based planning and prediction tools [189]–[196].

To develop an accessible aerial channel model, we put forward a generative model featuring a novel two-stage NN structure.

- A first NN determines if the link is in a state of LoS, NLoS, or outage.
- A conditional variational autoencoder is employed to generate the path parameters given that link state.

This work is extensively discussed in [197], [198], and a massive ray-tracing-based urban dataset suitable for training purposes as well as the ensuing statistical generation of the 3D spatial channel model is publicly available [199]. The accuracy of the AI-based model is corroborated in Figs. 18 and 19 for the section of London portrayed in Fig. 10. Fig. 18 compares the actual LoS probabilities in the test data, obtained via ray tracing, with the output of the NN-based link-state predictor. Similarly, Fig. 19 contrasts the CDF of the path loss corresponding to the test data with the CDF of the path loss generated by the trained model.

2) AI for UAV Mobility Management: As highlighted in Section IV-A, cellular-connected UAVs require novel and robust solutions for mobility management support, leveraging their knowledge of the network-controlled UAV trajectory [200]–[204]. While new radio resource control signaling has been introduced in LTE for this purpose [205], the intricacy and dynamic nature of the problem calls for AI and machine learning approaches [206]–[211]. In this regard, reinforcement learning appears particularly suitable to optimize

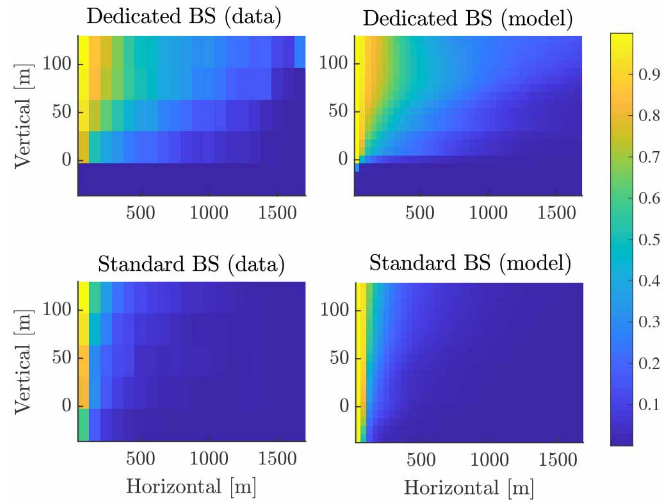

Fig. 18. LoS link probabilities as a function of horizontal and vertical distance to the BS for standard and dedicated BS types (see Section V-A): empirical distribution of the test data (left) versus probability forecast by the trained link-state predictor (right).

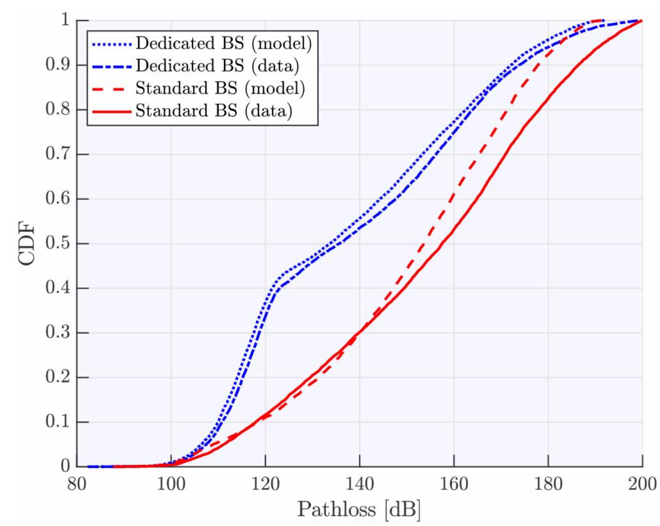

Fig. 19. CDF of the path loss for the test data alongside the one generated by the trained model for the city of London.

handover decisions and therefore reduce the number of unnecessary handovers [127], [212].

Fig. 20 considers the same setup as in Fig. 2, where this time a flexible Q-learning algorithm is employed with the purpose of reaching a trade-off between the number of handovers performed by UAVs (to be minimized) and their observed RSRP values (to be maximized). The Q-learning algorithm essentially decides when a UAV with a given position and travelling trajectory should execute a handover. The figure illustrates the CDF of the number of handovers for different combinations of weights w_{HO} and w_{RSRP}, respectively assigned to the handover cost and to the RSRP value. Note that the case $w_{\mathrm{HO}}/w_{\mathrm{RSRP}} = 0/1$ corresponds to a conventional greedy scheme, where the UAV always connects to the strongest cell. The inset also shows the corresponding handover ratio, defined as the ratio between the number of handover under each weight combination and the one under the greedy approach. Fig. 20 shows how the number of handovers decreases as

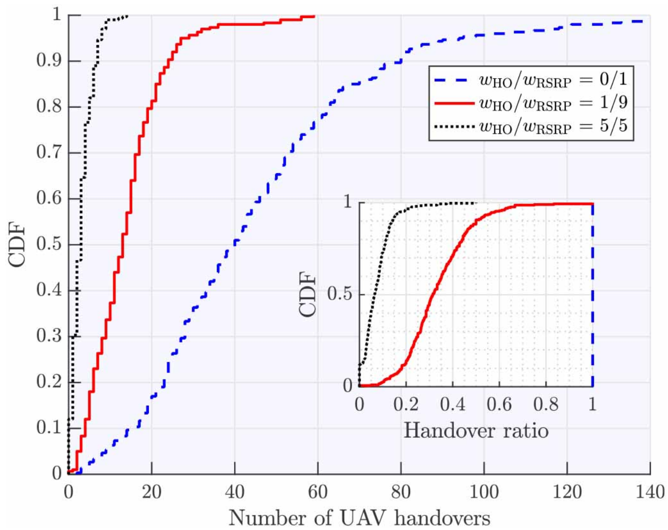

Fig. 20. CDF of the number of handovers for a UAV, with the corresponding handover ratio shown in the inset, under a reinforcement learning approach for various weight combinations.

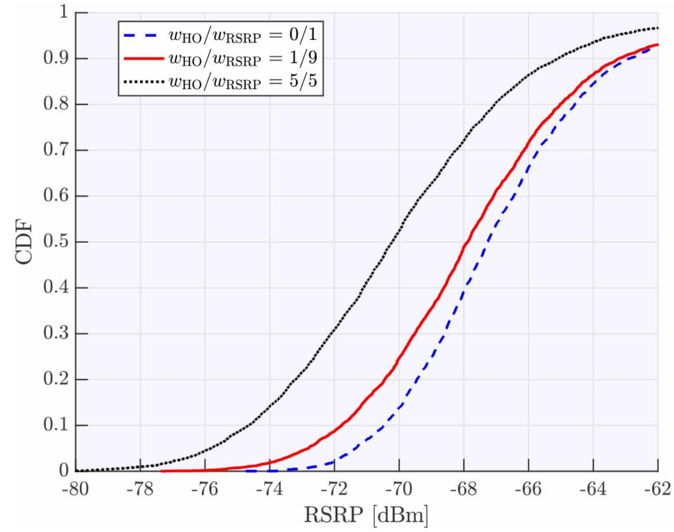

Fig. 21. CDF of the RSRP observed by a UAV under a reinforcement learning approach for various weight combinations.

the ratio $w_{\rm HO}/w_{\rm RSRP}$ increases, and that by properly tuning the weights, such number can be reduced significantly. For instance, for $w_{\rm HO}/w_{\rm RSRP} = 5/5$, where handover cost and RSRP are considered equally important, the highest 10% handover ratio is reduced by 85% with respect to the greedy baseline setup with $w_{\rm HO}/w_{\rm RSRP} = 1/1$. Learning-based techniques thus generalize traditional mobility management schemes and, more broadly, open up new possibilities for optimal UAV-aware network design and operations.

Fig. 21 shows the CDF of the RSRP observed by a UAV for the same three weight combinations, illustrating how the RSRP drops as the ratio $w_{\rm HO}/w_{\rm RSRP}$ increases. For instance, we can observe how the 5%-worst UAVs lose around 4.5 dB when comparing $w_{\rm HO}/w_{\rm RSRP} = 5/5$ with the greedy baseline, whereas setting $w_{\rm HO}/w_{\rm RSRP} = 1/9$ only leads to a 1.8 dB deficit. In all three cases considered, the minimum RSRP is always above -80 dBm, corresponding to a 33 dB SNR over a bandwidth of 1 MHz, and typically sufficient to provide reliable connectivity. Depending on the specific scenario, the weights may be configured to operate at an acceptable RSRP level while minimizing the number of handovers and thus both the associated signaling overhead and failure probability.

Takeaway 10: Data-driven machine-learning methods are an attractive resource to fill the gaps in aerial channel modeling, enabling novel and rigorous performance assessments of UAV communications. Additionally, AI-based approaches can generalize traditional mobility management schemes and, more broadly, open up new possibilities for optimal UAV-aware network design and operations. To this end, field data are needed to drive the models, either gathered through targeted measurement campaigns or directly user-supplied.

B. Resilient UAV Communications in Non-Terrestrial Networks

NTN is a termed coined within the 3GPP context to subsume all connections going through a flying component, i.e., UAV, HAP, or satellite, as illustrated in Fig. 22. Satellite links have been around for over half a century, mostly in the geostationary equatorial orbit (GEO). Among other virtues, satellites are well positioned to reach where cables cannot, they can blanket vast areas with a LoS coverage umbrella, and their links are resilient to natural disasters on Earth [107], [108]. Lying in between us and space, HAPs are typically unmanned and operate in the stratosphere in quasi-stationary position. HAPs could well complement spaceborne platforms since they are cheaper to launch, can act as wireless relays, and achieve acceptable latencies owing to their lower altitudes [34], [109].

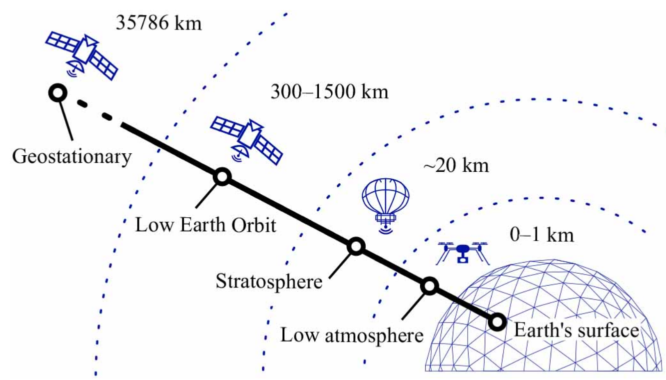

Fig. 22. Illustration of NTN platforms at different altitudes. From the top left: GEO, LEO, HAP, and UAV.

The cellular standardization community has thus far focused on satellite communications for three main reasons: satellites have an established commercial base of manufacturers, operators, and consumers, both private and institutional; the entire sector has been redefining itself due to the recent interest shift from content broadcasting to multibeam data services; the introduction of more affordable insertions into the Low Earth orbit (LEO) is favoring the burgeoning of large nongeostationary constellations [61]. The 3GPP effort has been mainly devoted to the following targets:

- For Rel. 15, a selection of deployment scenarios, key system parameters, and channel models [213].
- For Rel. 16, the definition of the architecture, higher-layer protocols, and physical layer aspects [214].
- For Rel. 17, technical solutions—albeit LTE-focused—concerning timing relationships, UL synchronization, and hybrid automatic repeat request (HARQ) [215].
- For Rel. 18, the agenda is currently being discussed.

1) UAV-to-Satellite Communications: The most promising use cases and technological enablers that combine UAVs and satellites can be identified as follows:

Integrated Terrestrial-NTN for UAV Users: BVLoS control of UAVs entails zero outage in terms of connection availability, as connectivity gaps can jeopardize a UAV mission. The combination of terrestrial and NTN can potentially alleviate this shortcoming by providing blanket coverage over cells ranging from tens to hundreds of kms. Recently, such combination was used in a practical setup for transporting Covid-19 samples and test kits [216]. Unlike a hybrid terrestrial-NTN architecture, an integrated one avails of a common network management architecture [217]. The latter is required in the case of spectrum coexistence between terrestrial and NTN [218]. Fig. 23 illustrates a potential architecture for an integrated ground-air-space network, including from the right gateway-to-air-or-space feeder links and service links. Depending on the carrier frequency, the latter can directly serve a UAV or be relayed through a very-small-aperture terminal (VSAT).

Backhauling to UAV Radio Access Nodes: Satellite broadband backhauling is one of the most rapidly developing areas mainly due to maritime and aeronautical demand. Backhauling to a UAV radio access node is a much more challenging endeavor, owing to the reduced terminal size for a data demand of roughly the same order. Due to the latency requirements, LEO satellites would be preferred for their proximity. Alternatively, GEO could be employed if integrated with the terrestrial network and with traffic classification [219]. An instance of such configuration is content distribution for cache feeding [220], where the traffic is latency-tolerant and mostly DL.

Aggregators for Internet of Things (IoT) Services: IoT data collection from remote areas is a prime example where UAVs can shine as radio access nodes [221]. However, there would still be a need for considerable UL capacity so that the data can be transferred to the main IoT servers for processing. NTN connectivity can facilitate this especially when the task is not latency-sensitive. Since IoT sensors typically have to be low-cost and low-form, direct satellite access does not seem a viable choice, except for LEO [222].

2) Roadblocks to an Integrated Ground-Air-Space Network: Irrespective of the targeted use case, UAV-satellite communications face several challenges:

Hardware: Establishing a bidirectional connection with a satellite requires specialized antennas that might increase the power and weight requirements of the UAV. In this context, the main dilemma is choosing the most suitable satellite orbit. On the one hand, GEO requires a narrower field of view but also more power due to the larger propagation distance. LEO, on the other hand, incur a less severe path loss but their rapid movement requires a wider field of view, quick tracking capabilities, and considerable Doppler compensation. Furthermore, the NTN antenna would be very difficult to reuse for terrestrial connectivity, since it has to be positioned on the top of the UAV to enable LoS connection with the satellite. Despite the recent progress, low-cost production for massive civilian applications is still challenging.[7]

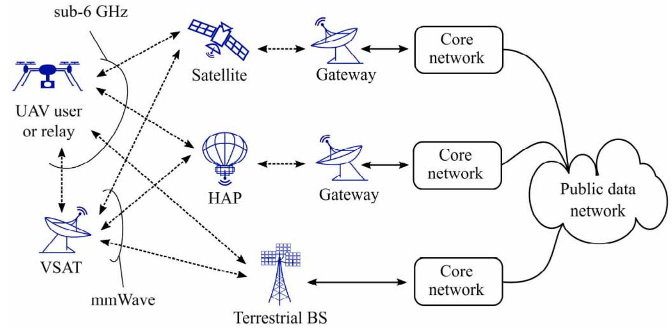

Fig. 23. Potential architecture for an integrated ground-air-space network supporting a UAV, with dashed and solid arrows respectively denoting wireless and wired links.

PHY: In view of the satellite data service renaissance, a number of advanced technologies are actively being developed, such as multiuser precoding, active antennas, carrier aggregation, non-orthogonal multiple access, and beam hopping. Even though these are widely accepted techniques for spectrally efficient communication in terrestrial systems, their application to NTN, UAVs, or both, is often complicated due to the propagation environment and transponder peculiarities:

- *Multiuser precoding* appears to be the frontrunner since it was recently demonstrated over-the-air through a live GEO satellite [224]. However, the applicability over LEO and for UAVs would bring about mobility-induced CSI variations, which also incur a significant latency in being reported back to the Gateway [225].
- *Active antennas*, in the sense of dynamic beamforming through electronically steerable arrays, are next in line, with commercial deployment only a couple of years away. Still, early deployments are expected to have limited capabilities in terms of beam granularity, update rate, and bandwidth.
- *Satellite carrier aggregation*, a well established technology in 3GPP, seems promising when carriers from the same satellite are combined [226]. However, aggregating carriers from different satellites—and even worse from different orbits—still appears to be an elusive target.
- *Non-orthogonal multiple access* was shown to have some applicability in specific configurations, for example when users are at different altitudes, e.g., airplanes and UAVs. When it comes to constructing the superimposed waveform, airplanes could be seen as the strong users and UAVs as the weak ones [227]. The potential gains are however to be verified in practical settings.

[7] In all above cases the assumption is that broadband NTN connectivity is used for both communication and control [223]. If the interest is limited to UAV control, lower-band narrow carriers could be used to simplify the antenna requirements.

- *Beam hopping* is a satellite radio access alternative to frequency reuse, which allows allocating the entire spectrum for each beam by illuminating nonadjacent beams in a time-hopping pattern. Although this is gaining momentum with an experimental payload in the making, UAV applications might be sensitive to its intermittent access, especially if the C2 link is relayed over satellite [228].

Protocols: In satellite communications, the main protocol stack is based on digital video broadcasting - satellite (DVB-S). Even though the DVB consortium originally focused on broadcasting, it quickly became obvious that data services had to be accommodated too, and the relevant standards—e.g., DVB-S2X—have been adapted to support broadband connectivity. More recently, the connectivity convergence within 5G NR and beyond has attracted substantial interest from the satellite community, and there are currently work items focusing on enabling 3GPP standards over satellite. In this direction, there are two parallel integration approaches:

- *At the architecture level*, where the underlying waveforms remain compatible with DVB-compliant equipment;
- *At the waveform level*, where NR is adjusted to overcome the peculiarities of the ground-to-space channel.

The latter is more enticing since it would allow satellite equipment manufacturers to benefit from the 5G economies of scale. However, it is a more challenging one since the massive size of satellite cells poses a series of incompatibilities, e.g., in terms of HARQ timers, timing advances, and Doppler compensation [229]. While the priority of the 3GPP is addressing these issues for satellite-to-ground links, their technical solutions could pave the way for satellite-to-UAV cellular communication too.

Takeaway 11: Satellites could offer continuous, ubiquitous, and scalable service, filling the inevitable ground coverage gaps that can currently jeopardize a UAV mission, and aiming for zero outage. Additionally, spaceborne cells could handle the most mobile UAVs across their large footprint, or backhaul aerial radio access nodes. However, important challenges need to be overcome for UAV-to-satellite communications in terms of hardware, PHY, and protocol design.

C. UAV Cellular Communications With Reconfigurable Intelligent Surfaces

As mentioned, the autonomous UAV cargos and taxis of tomorrow will afford minimal lacks of connectivity along their flights. Unfortunately, UAVs might happen to navigate complex and unpredictable propagation environments, with the air-to-ground links occasionally blocked by trees or high-rise buildings. Besides enhancing the cellular infrastructure—by densifying ground deployments (Section IV, V, IV-C) or reaching for space (Section VI-B)—an alternative means to boost reliability is the one of manipulating the wireless propagation environment itself to one's own advantage. Such smart manipulation can capitalize on an emerging transmission technology known as RISs [113]–[121].

RISs realize programmable and reconfigurable wireless propagation environments through nearly passive and tunable signal transformations. An RIS is a planar structure engineered with properties that enable a dynamic control of the electromagnetic waves. An RIS is usually made of a large number of nearly passive scattering elements whose response to electromagnetic waves can be adaptively configured through simple and low-cost electronic circuits such as PIN diodes or varactors. Conceptually, an RIS can be thought of being made of many sub-wavelength antenna dipoles (or patch antenna elements), which can be controlled by tunable lumped loads [230]. By tuning the load, the scattered field can be optimized and, for instance, a plane wave that impinges upon an RIS from a given direction can be steered towards a direction of reflection, different from that of incidence and corresponding to the location of an intended user [231], [232].

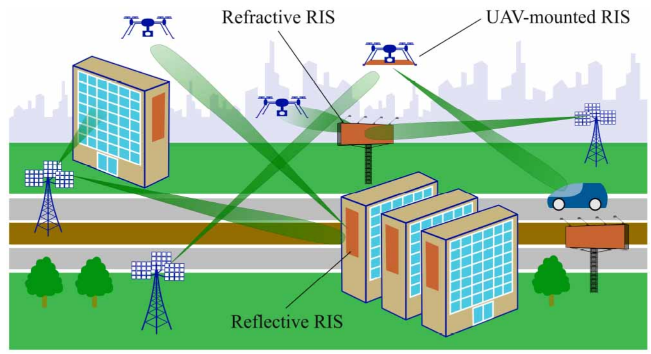

Fig. 24. Examples of RIS-assisted UAV cellular communications.

An RIS can realize sophisticated and exotic signal transformations, which include anomalous refractions, polarization conversion, collimation, and focusing [115]. A remarkable instance of these capabilities is that of dual-function RISs, which can simultaneously reflect and refract signals adaptively to ensure full coverage on both sides of an RIS, depending on the spatial distribution of the users around [233]. Besides making complex wireless environments programmable, RISs can be used to design single-RF but multistream transmitters at a low complexity, power, and cost [234], and they can serve as an ingredient in reconfigurable backscatter communication systems [235].

As exemplified in Fig. 24, RISs could be employed in different ways to overcome some of the limitations of UAV communication networks, making them more efficient and reliable:

- *Smart reflections:* RISs could be deployed on the faÃğades of high-rise buildings and controlled to create signal reflections that enhance the reliability of air-to-ground links when the latter are, e.g., blocked by other buildings.
- *Smart refractions:* RISs could be installed on billboards and optimized to create signal refractions that enhance the link reliability when UAV users transit behind the billboard. In some cases, refractive RISs could also be placed on windows to assist outdoor-to-indoor communications, e.g., between a UAV BS and an in-building user.
- *UAV-carried smart surfaces:* RISs could be mounted on UAVs too, acting as relays to provide a 360°

panoramic view and on-demand coverage through controllable ground-to-air-to-ground signal reflections.

Ongoing studies are focusing on whether and how to exploit the potential synergies between UAVs and RISs [236]–[238]. A large body of research has been concerned with the performance evaluation of RIS-assisted UAV communications, accounting for the UAV heights, the RIS features, and the potential presence of phase errors [239]–[246]. However, a deployment optimization of RIS-assisted UAV cellular communications should be carried out on realistic large-scale networks [247]. The marriage between UAVs and RISs also brings about the unique problem of jointly optimizing the UAV trajectories and the signal transformations applied by the RISs [248]–[253]. In some cases, due to its algorithmic or modeling deficiencies, such optimal design has been approached with machine learning tools, achieving more computationally efficient implementations [254]–[260].

Takeaway 12: RISs—mounted on billboards and building façades, if not directly on UAVs—might enhance the efficiency and reliability of future air-to-ground links through optimally controlled reflections and/or refractions. Nonetheless, major outstanding issues in this domain range from the electromagnetic-consistent modeling of RISs all the way to the performance evaluation and deployment optimization in practical large-scale networks featuring UAVs.

VII. UAV-TO-UAV CELLULAR COMMUNICATIONS

Cellular device-to-device (D2D) communication—*sidelink* in 3GPP terminology—, whereby devices communicate directly with each other bypassing ground BSs, were proposed for GUEs to facilitate the implementation of proximity services such as content sharing, public safety, and multi-hop transmission [261]–[263]. This is because D2D communication can provide higher bit rates and lower latencies than those attained by the typical BS-centric communications when the relevant devices are in close proximity. Moreover, the establishment of a direct communication link might be essential when cellular coverage is not available. Other advantages of D2D communication include lowering the energy consumption, alleviating congestion, offloading cellular traffic, and possibly extending the range of communication via multiple D2D hops [264]–[268]. The 3GPP has been developing standards for D2D operations since LTE. In NR Rel. 16, sidelink solutions were specified for public safety and advanced automotive industry services, allowing vehicle-to-vehicle and vehicle-to-roadside-unit communication. Such operations are being extended to cover new commercial use cases and requirements in NR Rel. 17 [269]. The availability and benefits of D2D communication motivate the use of such technology for UAVs, as discussed in the sequel.

A. Applications and Distinct Features of Aerial D2D

Important use cases exist where a reliable and direct UAV-to-UAV (U2U) communication link can be of great value:

1) UAV Swarms: A single UAV has limited processing capability, payload capacity for carrying various sensing devices, and range of communication. Accordingly, to meet specific goals such as environmental sensing, a group of UAVs may work together as a swarm. U2U communication is essential to deploy such UAV swarms. Indeed, high-throughput U2U links are needed for the distribution of tasks in swarms where one or multiple responsible UAVs control the rest [59].

2) Autonomous Operation: To enable autonomous operation of independent UAVs performing different tasks, U2U communication links can be utilized to guarantee the low latencies required for collision avoidance and an adequate self-control of the aerial traffic.

3) Aerial Relaying: U2U communication also enables aerial relaying for various purposes. For example, the coverage of ground BSs can be extended through multi-UAV hops to serve users in remote or disaster areas. Furthermore, U2U communication can be utilized to guarantee high throughput in areas without a reliable cellular service in the sky, e.g., through a hovering UAV head well connected to the ground.

In all above use cases, D2D communication in the sky exhibits distinct features w.r.t. its ground counterpart. Four different link types can be found in a U2U communication system reutilizing the ground cellular spectrum: 1) UAV-to-UAV, 2) UAV-to-BS, 3) GUE-to-BS, and 4) GUE-to-UAV. Each of these links experience different propagation conditions. For instance, UAV-to-UAV links are mostly in LoS conditions, subject to differences in the UAVs altitudes and building heights. The more favorable propagation conditions for direct UAV communication facilitates the reception of stronger signals, theoretically making U2U networking less dependent on the ground infrastructure for data exchange purposes due to their higher range. However, LoS propagation may also be detrimental owing to the stronger interference to/from other UAVs and ground communications. This suggests that the design of D2D cellular communication must be revisited for aerial devices.

B. U2U Communications: Key Design Parameters

1) Power Control: Power control is a key mechanism for efficient cellular D2D communications. In this context, a common approach known as fractional power control consists in utilizing a power proportional (in logarithmic scale) to the large-scale loss between the transmitter and receiver [270]–[272]. Fractional power control intends to extend the battery life while providing a sufficient received signal quality and maintaining a constrained interference level. Under this scheme, a simplified expression of the transmission power per PRB, $\mathrm{P}_{\{\mathrm{UAV,GUE}\}}$ [W], is given by

$$\mathrm{P}_{\{\mathrm{UAV,GUE}\}} = \min\left\{\mathrm{P}_{\max}/\mathrm{n}_{\{\mathrm{UAV,GUE}\}}, \mathrm{P}_{\mathrm{ref}} \cdot \xi^{\epsilon_{\{UAV,GUE\}}}\right\}, \tag{1}$$

where $\mathrm{n}_{\{\mathrm{UAV,GUE}\}}$ is the number of PRBs utilized for the communication by UAVs or GUEs, $\mathrm{P}_{\max}$ is the maximum transmission power, $\epsilon_{\{\mathrm{UAV,GUE}\}} \in [0,1]$ is a factor controlling what fraction of the overall large-scale loss ξ is compensated, and $\mathrm{P}_{\mathrm{ref}}$ is a device-specific baseline power parameter.

2) Spectrum Sharing Strategy: Two main classes of spectrum sharing strategies can be considered for U2U communication, namely *underlay* and *overlay* [273].

- *Underlay spectrum sharing:* U2U links reuse a portion η_{u} of the GUE spectrum, which spans the entire available bandwidth [274]. Accordingly, the U2U links generate co-channel interference to the GUEs and vice versa. Intuitively, since a larger $\eta_{\mathrm{u}} \in [0, 1]$ results in further interference, both among UAVs and between UAVs and GUEs, $\eta_{\mathrm{u}} = \mathrm{n}_{\mathrm{UAV}}/\mathrm{n}_{\mathrm{GUE}}$ captures the aggressiveness of the underlay approach. In this setup, the U2U links may employ frequency hopping and randomly choose their $\mathrm{n}_{\mathrm{UAV}}$ PRBs from the available $\mathrm{n}_{\mathrm{GUE}}$ PRBs to reduce the UAV-to-UAV interference [275].
- *Overlay spectrum sharing:* The available spectrum is divided in a non-overlapping fashion between ground and U2U communications. As a result, GUEs are not interfered by UAVs at the expense of having access to a shrunk spectrum. Similarly, UAVs are only interfered by other co-channel UAVs.

C. Performance Analysis of U2U Communications

We now illustrate the impact of the key design parameters as well as the spectrum sharing strategy on the performance of coexisting UL GUE and U2U communications. We consider an UMa cellular network operating at 2 GHz, occupying 10 MHz of bandwidth, and with a density of 5 BSs/km^2 (corresponding to an average ISD of 480 m). BSs schedule one GUE per PRB and U2U communication is held within UAV pairs with a density of 1 UAV/km^2. Unless otherwise specified, the receiving UAV is randomly and independently located around its associated transmitter following a truncated Rayleigh distribution with mean distance $\bar{R}_{\mathrm{UAV}} = 100$ m [275].

1) Impact of the UAV Altitude: The impact of the UAV altitudes on the SINR performance of GUEs and UAVs is investigated in Fig. 25, which considers the most aggressive U2U underlayed approach where UAVs can access the whole UL GUE spectrum ($\eta_{\mathrm{u}} = 1$). The results confirm that the UL performance of GUEs degrade in the presence of U2U links due to the co-channel interference generated by aerial devices. In spite of being limited due to the low powers employed by UAVs, such degradation becomes more pronounced when the UAVs fly at higher altitudes due to the increase in the number of ground BSs perceiving UAV-generated LoS interference. The performance of U2U communication links follows the same trend, since more interfering UAV-to-UAV and GUE-to-UAV links become LoS when the U2U pairs fly higher.

2) Impact of UAV Power Control: Fig. 26 captures the impact of the UAV power control factor ϵ_{UAV} for different mean U2U link distances $\bar{R}_{\mathrm{UAV}}$. The following broad-ranging observations can be made from the results of this figure, where the UAV altitude is 100 m:

- *GUE UL performance:* Larger UAV power control factors lead to a lower GUE UL performance, a direct consequence of the higher interfering UAV powers. Such performance reduction is negligible when ϵ_{UAV} adopts extremely low values (where the UAV-generated interference is negligible compared to the ground interference) or extremely high values (where the majority of UAVs transmit at maximum power already). Fig. 26 also shows that increasing the U2U communication link distances leads to a reduced GUE performance, since UAVs need to employ larger transmission powers to compensate for the increased U2U path loss.
- *U2U performance:* Increasing ϵ_{UAV} improves the U2U communication performance on account of the growth in useful U2U signal power. Although this is at the expense of an increase in the interference among UAV pairs, it is worthwhile because the interference perceived by UAVs is mostly produced by the GUEs transmitting at high

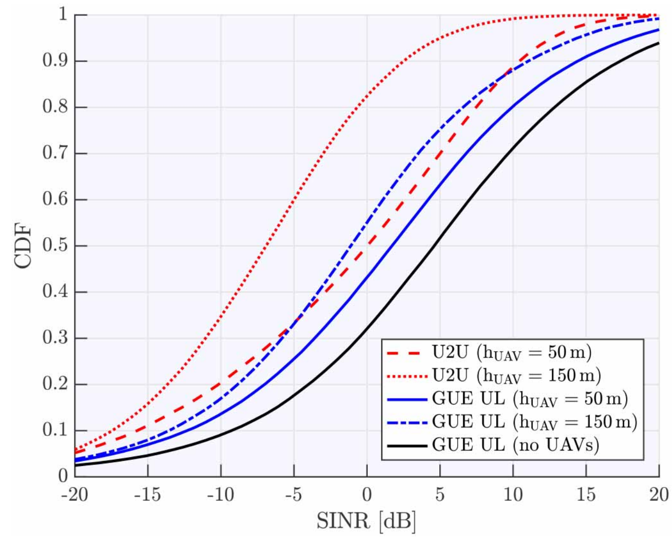

Fig. 25. CDF of the SINR experienced by: the GUE UL without U2U underlayed communications (black); the GUE UL with U2U underlayed communications and UAVs at different heights $\mathrm{h}_{\mathrm{UAV}}$ (blue); and U2U links underlayed with GUEs (red). $\mathrm{P}_{\max} = 24$ dBm, $\epsilon_{\mathrm{UAV}} = \epsilon_{\mathrm{GUE}} = 0.6$, and $\mathrm{P}_{\mathrm{ref}} = -58$ dBm.

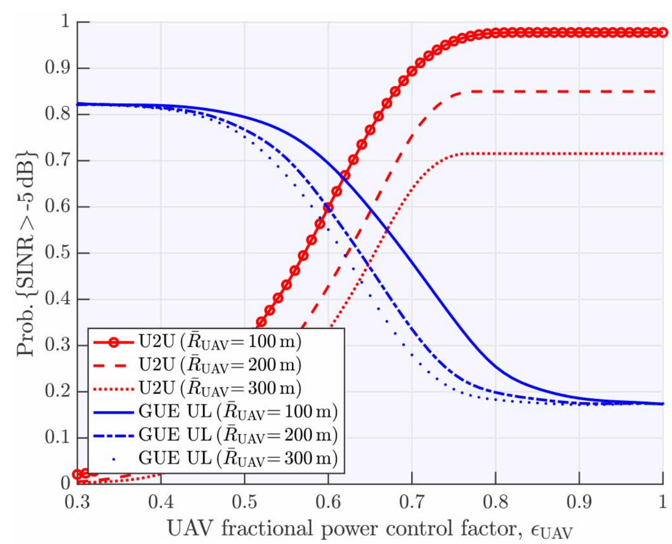

Fig. 26. U2U and GUE underlay coverage probabilities for different UAV power control factors and three values of the mean U2U link distance $\bar{R}_{\mathrm{UAV}}$.

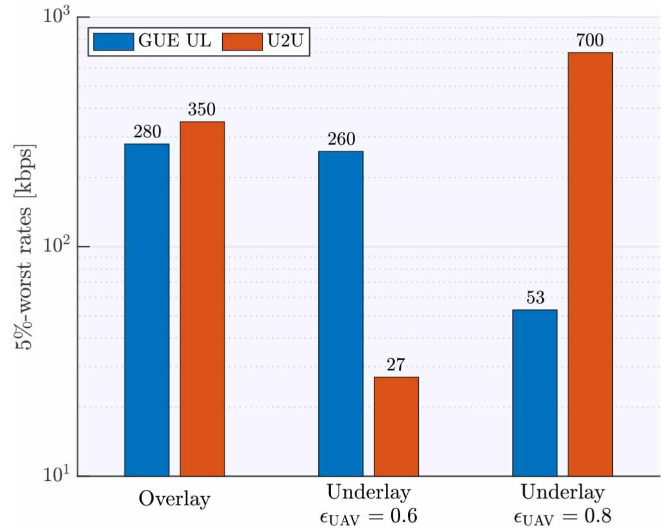

Fig. 27. 5%-worst rates for GUE UL and U2U links in overlay, where UAVs are restricted to access 1 MHz, and underlay, where UAVs can access the entire 10 MHz.

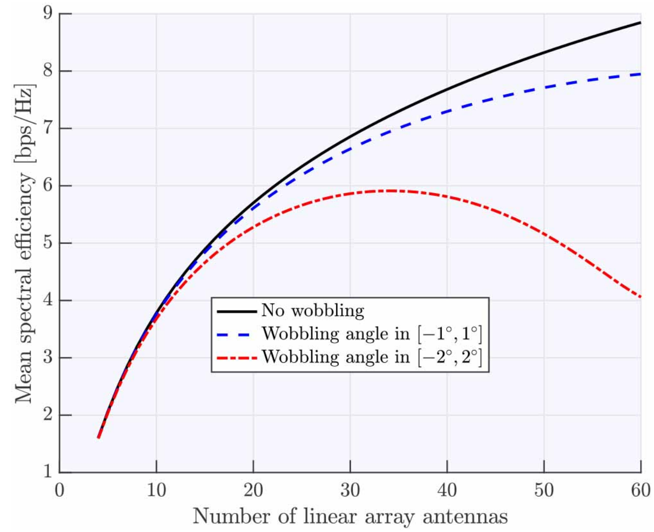

Fig. 28. Mean spectral efficiency versus number of antennas for a 500 m U2U link at 60 GHz, where both UAVs undergo wobbling around the local vertical angle.

powers. Fig. 26 also shows that the longer communication range between UAVs deteriorates the overall U2U performance.

3) Impact of the Spectrum Sharing Strategy: Fig. 27 compares the rate performance of the 5%-worst GUE UL and U2U links in an overlay setup where UAVs are restricted to access 1 MHz and in an underlay setup like the one in Fig. 26 (considering two values of ϵ_{UAV}). We note that the impact of the UAV power control factor is negligible in the overlay, since both the signal power and the overall interference proportionally increase with ϵ_{UAV}. Fig. 27 also reveals that the best guaranteed GUE UL performance is provided by the overlay setup, where the 5%-worst U2U bit rates reach 350 kbps. A similar GUE UL performance can be achieved in the underlay when UAVs utilize a reduced transmission power ($\epsilon_{\text{UAV}} = 0.6$), although this comes at the expense of a 13-fold decrease in the 5%-worst U2U rates. The U2U performance dramatically grows to 700 kbps in the underlay scenario with $\epsilon_{\text{UAV}} = 0.8$, where GUEs suffer due to the increased aerial interference. Overall, the results of Fig. 27 convey that the overlay spectrum sharing approach provides the best performance trade-off between direct aerial communication and legacy GUE communication.

Takeaway 13: Underlaying direct UAV-to-UAV links with the GUE UL incurs limited interference, which however becomes more pronounced when UAVs fly higher and most cross-tier links turn to LoS. UAV-specific fractional power control can trade off the performance of UAV-to-UAV links and GUE UL, whereby higher control factors favor the former at the expense of the latter.

D. mmWave U2U Communications

As detailed in Section V for UAV-to-ground links, the large bandwidths available at mmWave frequencies could be exploited to boost the performance of U2U links too. Once again, highly directional antenna arrays should be employed to compensate for the higher propagation losses incurred at these frequencies. However, the fact that both end devices wobble and travel in U2U links will worsen the fluctuations and beam misalignments, resulting in link quality dips. This phenomenon is illustrated in Fig. 28, which shows the mean spectral efficiency versus the number of antennas for a 500 m U2U link at 60 GHz. Both UAVs are equipped with a vertical uniform linear array and undergo wobbling. The wobbling is characterized through variations in the elevation angles of each UAV array, which follow a uniform random variable with maximum value $1°$ or $2°$. Fig. 28 shows that wobbling at both ends of each link can have a significant impact on the optimal mmWave U2U antenna design. Depending on the extent of the wobbling and on the communication distance, a larger number of antennas could lead to a more frequent and prominent beam misalignment, and hence to a worse overall performance.

VIII. Discussion

In this section, we review the candidate technologies discussed in the article, along with the key lessons learnt and outstanding challenges when applied to UAV cellular communication. A further recap of each technology's potential and caveats is provided in Table V.

A. Key Lessons Learnt and Future Outlook

Through concrete results, we detailed how NR enhancements can greatly help satisfying the stringent control and payload data demands of network-connected UAVs throughout this decade. Among them, beamformed control signals facilitate UAV cell selection and handovers with respect to sidelobe-based association. Massive MIMO paired with UAV-aware nullsteering or UAV-based beamforming is essential to guarantee reliable cellular connectivity in both UMa and denser UMi scenarios. If one is after larger bandwidths and higher capacity, somewhat surprisingly NR mmWave networks too can provide satisfactory coverage of the sky, thanks to

TABLE V
RECAP OF THE CANDIDATE TECHNOLOGIES DISCUSSED IN THIS ARTICLE, ALONG WITH THEIR POTENTIAL AND CAVEATS WHEN APPLIED TO UAV CELLULAR COMMUNICATIONS

Multi-antenna enhancements	**Pros**	**Cons**
Massive MIMO	Beamforming facilitates initial cell selection and handovers. Intercell interference suppression can nearly double the rates of coexisting aerial and ground devices.	The DL performance of GUEs is affected by the presence of UAVs due to the UL SRS pilot contamination. When UAVs fly fast and experience NLoS, CSI acquisition introduces a large overhead.
Cell-free architectures	Provide macro-diversity and eliminate inter-cell interference by turning it into useful signal, which mostly benefits UAVs in downlink and GUEs in uplink.	Unresolved aspects include scalability and dynamicity of the cluster of serving BSs, due to the large number of BSs in LoS and the high UAV mobility, respectively.
Higher frequency bands	**Pros**	**Cons**
mmWave communications	At typical densities, can provide satisfactory coverage to aerial links, thanks to a combination of antenna sidelobes and strong reflections.	As density declines, coverage becomes progressively less robust. While coverage could be enhanced via rooftop-mounted BSs, this solution would require UAV-focused investments.
THz communications	Put in play truly enormous bandwidths and allow for MIMO transmissions even in strict LoS conditions.	Power consumption, attenuation, sensitivity to vibrations, and UAV body blockage. Only for short-to-intermediate distances and non-standalone.
Intelligence and resilience	**Pros**	**Cons**
Artificial intelligence	Fill the gaps in channel modeling, generalize mobility management, and optimize UAV-aware network design and operations.	Field data needed to drive the models, either gathered through targeted measurement campaigns or directly user-supplied.
Non-terrestrial networks	Fill coverage gaps aiming for zero outage. Handle mobile UAVs across a large footprint, or backhaul aerial radio access nodes.	Important challenges need to be overcome in terms of hardware (e.g., equipping UAVs with specialized antennas), PHY (e.g., Doppler compensation), and protocol design (e.g., handovers between satellites and the ground network).
Reconfigurable intelligent surfaces	Enhance the efficiency and reliability of future air-to-ground links through optimally controlled reflections and/or refractions.	Electromagnetic-consistent modeling, performance evaluation, and deployment in practical large-scale networks, which may involve UAV-focused investments for the operators.
Device-to-device communications	**Pros**	**Cons**
Underlayed UAV-to-UAV and cellular communications	UAV-specific fractional power control can trade off the performance of UAV-to-UAV links and the ground UL.	Non-negligible air-to-ground interference when UAVs fly higher and most interfering links turn to LoS.

a favorable combination of antenna sidelobes and strong reflections. Albeit subject to regulations, such coverage could be further enhanced by rooftop-mounted uptilted mmWave cells. For UAV-to-UAV applications, direct links that bypass the network infrastructure might be preferable. Underlaying these with the ground UL operating in the same band incurs limited mutual interference, which however becomes more pronounced when UAVs fly higher. UAV-specific power control can effectively trade off the UAV-to-UAV performance with its ground-link counterpart.

Shifting gears to the next decade, empowering air taxis with sufficient data transfer capacity and a minimal lack of connectivity will require a 6G paradigm shift in 2030. Non-terrestrial networks could offer continuous, ubiquitous, and scalable service, filling the inevitable ground coverage gaps that can currently jeopardize a UAV mission, also handling the more mobile UAVs across their large footprint. In a complementary fashion, cell-free architectures and reconfigurable smart wireless environments could turn interference into useful signal and boost UAV coverage, dramatically improving worst-case performance and thus overall reliability. AI can already enable aerial channel modeling and will also help with optimal UAV-aware network design and operations, e.g., for mobility management, among other endeavors. Finally, THz frequencies could provide enormous bandwidths for UAVs, allowing MIMO even in strict LoS conditions.

B. Challenges

The above optimistic picture shall be complemented by highlighting the main technological hurdles that stand in the way to the fly-and-connect dream.

1) Sub-6 GHz Cellular UAV Support: The benefits of reusing the same spectral resources for coexisting ground and aerial users might be outweighed by the downlink interference ground BSs generate at UAVs when serving GUEs (see Sections IV-A and IV-B). As for the uplink, where UAV links turn from victims to aggressors, traditional fractional power control policies have been shown not to scale well under a heterogeneous population of GUEs and UAVs.

Learning-based power control approaches may be sought for a scenario-specific optimal tradeoff between fairness and cell sum-throughput. Although 5G-and-beyond cellular networks will rely on massive MIMO to boost the rates of aerial and ground devices alike, the performance of GUEs can be still greatly affected in the UL by the presence of UAVs communicating to ground BSs or to each other, and in the DL due to the additional pilot contamination generated by UAVs. Such interference could be predicted and prevented by implementing a coordination aware of the UAV trajectories, eventually enabling aggressive and dynamic sharing of all available resources without sacrificing reliability. Cell-free architectures (see Section IV-C) can turn some of the interference into useful signal, but the large number of BSs in LoS and the high UAV mobility make the cluster scalability and dynamicity non-trivial and worthy of further research.

2) mmWave UAV Communications: To provide Gbps data rates in the air, the use of above-6 GHz frequencies may be necessary due to their unique large available bandwidths. As detailed in Sections V-A and V-B, UAV communications in mmWave bands are less prone to inter-cell interference but incur greater power consumption and sensitivity to blockage and vibrations, and thus may have to be confined to a non-standalone mode, e.g., devising sub-6 GHz-plus-mmWave UAV multi-connectivity solutions. At high frequencies, directionality, and thus precise beam alignment, along with optimal radio resource management are required to achieve a sufficiently high link budget. Nodes operating in the mmWave spectrum to serve high-mobility UAVs may thus require the re-design of PHY/MAC control procedures and higher-layer operations, including beam alignment, user tracking, handover, channel estimation, resource allocation, and radio-link failure recovery—all originally designed for 2D terrestrial networks. The techno-economic feasibility of UAV-dedicated rooftop-mounted mmWave cells should also be accurately studied, accounting for incumbent systems and their behavior in unlicensed bands, e.g., fixed point-to-point services, to guarantee coexistence among different networks.

3) THz UAV Communications: Behaviors that begin to arise at mmWave frequencies become prominent in the THz realm (see Section V-C), including pronounced peaks of molecular absorption, angular sparsity, high omnidirectional pathloss, and wavefronts that are non-flat over the span of large arrays. Likewise, the extremely broad bandwidths bring to the fore new phenomena, including spatial widening over large arrays and the ensuing beam squinting. On the other hand, some of these same behaviors may lead to new opportunities, since at these tiny wavelengths MIMO transmission becomes feasible even in LoS conditions. Because the rank and attributes of such LoS MIMO channels hinge on sheer geometry, they need to be controlled through the design and disposition of the arrays themselves both onboard UAV and on the ground. The understanding of THz communications is still incipient for terrestrial applications, let alone for aerial settings. Moreover, despite the recent progress, accurate propagation models for THz UAV communications are needed to provide statistical descriptions of the full doubly directional characteristics of the channel, which include the totality of path components as well as the angles of arrivals, angles of departure, gains and delays.

4) Artificial Intelligence to Model and Enhance UAV Communications: Besides higher bands with more antennas, future cellular networks are envisioned to bring about new paradigms such as the use of artificial intelligence at the modeling, design, and operation stages (see Section VI-A). As far as UAV communications are concerned, fields worthy of further investigation include the development of:

- Generative networks for spatially consistent air-to-ground channel modeling, due to the current lack of statistical aerial models at high frequencies.
- Machine learning algorithms for time series prediction that minimize the need for the high-frequency CSI acquisition required for UAVs moving at high speeds.
- Learning-based algorithms for mobility management (i.e., handovers) and dynamic radio resource allocation, which are necessary to adequately deal with the high UAV mobility.
- Data-driven optimization of ground network deployments to support hyper-reliable aerial corridors, essential to devise networks tailored to each 3D physical location.

For AI to truly enable UAV-aware network design and operations, plenty of field data are needed. This data may have to be initially gathered through targeted measurement campaigns due to the limited presence of UAVs in current networks.

5) UAV Communications in Non-Terrestrial Networks: While appealing in a quest for a real zero-outage UAV connectivity from space, the integration of terrestrial and non-terrestrial networks brings about important challenges to be overcome (see Section VI-B). In terms of PHY and hardware, Doppler compensation will be essential and fine antennas and circuitry may be necessary so as not to substantially increase the overall UAV weight and power consumption. Dual ground-plus-space connectivity could be exploited for an increased coverage probability. However, meeting the strict and heterogeneous UAV traffic needs will also require optimal dynamic load distribution, e.g., defining slices of radio access network resources to be assigned to each UAV service class, accounting for the diverse link budget, capacity, and delay of the available satellite and terrestrial radio links.

6) UAV Cellular Communications With Reconfigurable Intelligent Surfaces: Another promising means to enhance UAV coverage is by optimally controlling the wireless environment itself through RISs (see Section VI-C). A significant amount of work has dealt with the performance evaluation of RIS-assisted UAV communications, accounting for the UAV heights, the RIS features, and the potential presence of phase errors. However, we are currently lacking techniques for optimizing the deployment of RISs catering for UAV cellular communications in realistic large-scale networks. These techniques should be evaluated through system-level and ray-tracing simulators, which poses a challenge due to the large dimensions of the scenarios that have to be reproduced. The marriage between UAVs and RISs also brings about the complex problem of jointly optimizing the UAV trajectories and the signal transformations applied by the RISs, which may call for learning-based approaches.

7) UAV-to-UAV Cellular Communications: Underlaying direct UAV-to-UAV links with the uplink of the ground network requires careful consideration, since the interference caused may not be tolerable when UAVs fly high and most cross-tier links turn to LoS (see Section VII). mmWave UAV-to-UAV communications may provide advantages in terms of bandwidth and spatial isolation. However, propagation at higher frequencies suffers more rapid attenuation with the distance, requiring a highly directional antenna gain and making the UAV-to-UAV setup very sensitive to beam misalignment. The latter, particularly critical due to the double UAV mobility and the consequently increased channel fluctuation speed, may result in a remarkable degradation of the link quality and reliability, and require novel fast beamforming and tracking procedures. The potential blockages caused by the UAV frames or even other UAVs—especially when flying in swarms—also need to be factored in when assessing the reliability of UAV-to-UAV communications.

IX. CONCLUSION

While the understanding of UAV cellular communications has been advancing over the last few years, many fundamental challenges remain to be addressed. In this article, we blended academic and industrial views, embarking on a journey that took us from 5G to 6G UAV use cases, requirements, and enabling technologies. As tailoring these technologies to UAVs is nothing short of challenging, we also pointed out numerous open problems and made well-grounded suggestions on much-needed future work. We hope this article will foster new research and breakthroughs, bringing the wireless community one step closer to the fly-and-connect era.

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