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Survey paper

Non-Terrestrial UAV Clients for Beyond 5G Networks: A Comprehensive Survey

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ABSTRACT

The rapid proliferation of consumer UAVs, or drones, is reshaping the wireless communication landscape. These agile, autonomous devices find new life as UE in cellular networks. This paper explores their integration, emphasizing the myriad applications, standardization efforts, challenges, and research community solutions. Key areas of investigation include the complexities of 3D deployment, channel modelling, and energy efficiency. Moreover, we highlight the open questions and research opportunities these flying UEs present. The evolving landscape of UAV integration into cellular networks promises transformative enhancements for next-generation communications, addressing challenges while fostering innovation across industries. The paper encapsulates the essential aspects of UAV integration within the cellular ecosystem, offering a concise yet comprehensive overview of this dynamic field, where UAVs as UEs redefine wireless communication with promise and complexity.

1. Introduction

1.1. Motivation

Unmanned Aerial Vehicles (UAVs), also known as Unmanned Aerial Systems (UASs) or Drones, have received significant attention due to their versatility in both civilian and military applications. Leveraging controlled mobility, autonomous operation, flexible deployment, and cost-effectiveness, UAVs find applications in trade, medical services, rescue operations, and wireless coverage.

The paramount importance of reliable and low-latency wireless connectivity for UAVs cannot be overstated. This connectivity is the backbone for ensuring secure command-and-control operations, facilitating the flow of sensor data, and supporting applications hosted on UAV compute platforms [1,2].

Whether operating in licensed or unlicensed frequency bands, UAVs encounter challenges related to resource sharing, traffic dynamics, and security issues such as jamming [3]. Addressing these challenges becomes crucial for the seamless integration of UAVs into various domains (see Fig. 1).

Three primary scenarios for the connectivity of UAVs with their controllers include satellite links, UAV-specific communication links, and connectivity to cellular networks [4,5]. Cellular networks, particularly with the evolution of Long-Term Evolution (LTE) and 5G technologies, have emerged as a promising solution. With data rates of up to 300 Mbps and latencies as low as 50 ms, cellular networks meet the requirements for UAV control operations, which typically demand latencies of 50 ms and data rates of up to 100 Kbps [6].

Academic and industrial research communities have extensively explored the integration of UAVs with LTE and 5G networks as clients, highlighting both challenges and opportunities [7–9]. Therefore, there has been a strong uptake of cellular connectivity to connect the UAVs and support beyond line-of-sight (BLoS) operations. Furthermore, exploring UAVs as mobile Aerial Base Stations (ABS) presents an intriguing direction. The fast deployment capabilities, acceptable line-of-sight (LOS) probability with terrestrial components, and adjustable altitude features of UAVs make them versatile for modifying existing applications and developing new ones [10,11].

1.2. Related survey papers

Research efforts in the intersection of UAVs and cellular networks have intensified, addressing the challenges and opportunities presented

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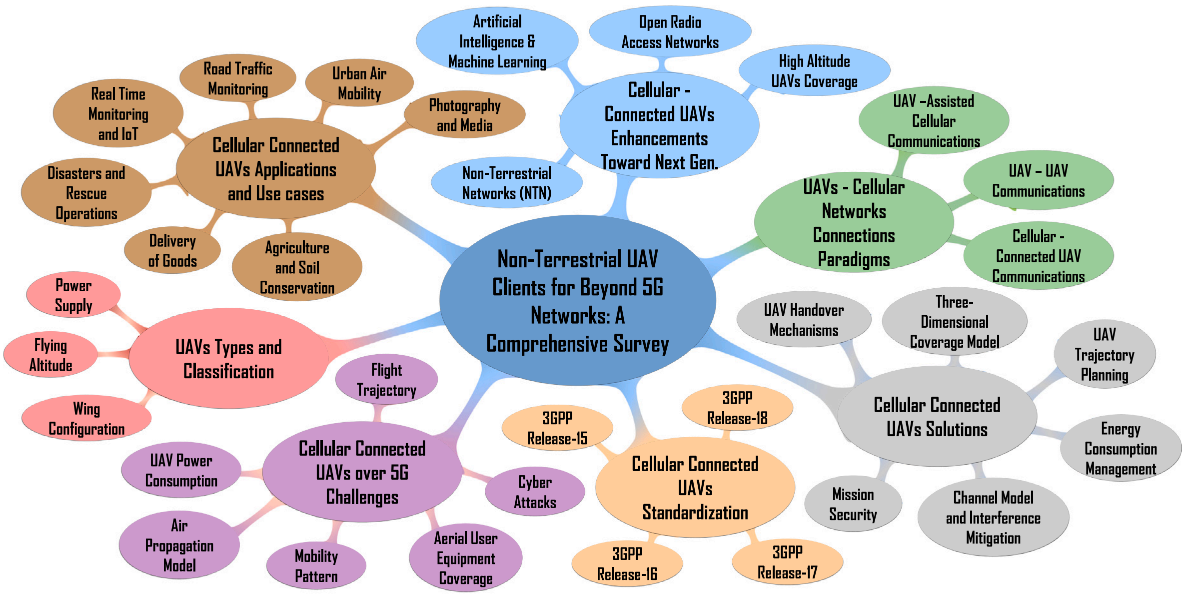

Fig. 1. Diagramatic view of the organization of this survey.

by this integration. Notable contributions have emerged, shedding light on scientific, technical, socio-economic, and security aspects. Many existing surveys and tutorials primarily concentrate on exploring the integration potential of UAVs with 5G/B5G cellular networks, particularly from the standpoint of UAV-assisted cellular communication. They also tend to highlight recent advances, future trends, and challenges within the field of UAV cellular communication. Furthermore, some of these surveys provide detailed analyses and performance studies, addressing specific communication challenges such as channel modelling, physical layer techniques, and security. [2,11–20].

In the context of UAV-assisted relay over 5G networks, standardization, channel modelling, interference mitigation, collision avoidance, optimal trajectory design using deep reinforcement learning, energy harvesting, security, and regulations have been covered in [12]. It explores the role of cognition in the context of UAV-assisted 5G and beyond communications and delves into the challenges, potential applications, and regulations surrounding unmanned aerial vehicles (UAVs) in wireless communications. These topics have been presented as well in [2]. The paper explores design objectives, optimization strategies, and mathematical tools for UAV-assisted communication, relaying, and computing systems. It emphasizes radio and computation resource optimization and presents open problems and potential research directions in the field of UAV-assisted wireless communication.

In [13], the authors discuss the capabilities of 5G in providing reliable low-latency communications, which align with the requirements of AVs for safe and efficient driving. The survey delves into advancements in AV technology, automation levels, enabling technologies, and the specific requirements of 5G for successful integration with AVs. The exploration of UAV placement optimization in UAV-assisted wireless communication networks has garnered substantial attention [11]. The survey reviews recent literature on UAV placement optimization, addressing critical design issues such as objectives, solution techniques, air-to-ground channel models, transmission media, energy constraints, and interference management.

Advancements in cellular technologies and the dense deployment of cellular infrastructure have led to the integration of UAVs into 5G and beyond cellular networks [14]. The emphasis is on achieving safe UAV operation and enabling diverse applications with mission-specific payload data delivery. Key usage scenarios, including enhanced mobile broadband (eMBB), ultra-reliable low-latency communications (URLLC), and massive machine-type communications (mMTC), are considered [14].

The softwarization of UAV networks has become increasingly important in assisting 5G and beyond mobile networks The authors of [15] highlight the increasing importance of UAVs in assisting next-generation mobile networks and identify crucial issues and challenges faced by the UAV assistance paradigm. In particular, the focus is on addressing network management complexities and interoperability issues by adopting Software-Defined Network (SDN) and Network Function Virtualization (NFV) technologies.

The role of unmanned aerial vehicles and millimetre-wave (mmWave) in 5G is explored, emphasizing recent advances and challenges [16]. The article provides a consolidated synthesis of the deployment of 5G services using UAVs and delves into the mmWave potential for radio communication. It also addresses UAV-based cellular communication networks' dynamic and complex nature using artificial intelligence and machine learning techniques [16].

These diverse research contributions provide a foundation for understanding the current landscape of UAV-assisted communication in cellular networks by focusing on utilizing UAVs to service terrestrial UEs as an ABS for many applications, e.g. disaster recovery, ephemeral networks, etc. However, the existing surveys often focus on specific aspects, and a unified work providing a broad picture of all kinds of research developments is still needed. In this survey, we aim to address this gap, specifically focusing on cellular-connected UAVs.

1.3. Contributions

The rare of a systematic and comprehensive review specifically dedicated to cellular-connected UAVs has motivated the undertaking of this study. Our objective is to address the gaps identified in the existing literature by offering a consolidated overview of recent articles focused on the applications and use cases of UAVs within cellular-connected UAV networks. This paper critically analyzes the current state of the art concerning various UAV types and the standardization processes guiding their integration into cellular networks, particularly as orchestrated by the 3rd Generation Partnership Project (3GPP). Furthermore, the survey delves into the challenges associated with incorporating UAVs into cellular networks as clients and presents solutions proposed by the research community to tackle these challenges. The study also outlines some promising technologies and emerging trends that are anticipated to shape the next generations, consequently enhancing the connectivity performance of both UAVs and cellular networks.

Table 1
List of ACRONYMS.

ACRONYMS	Definition	ACRONYMS	Definition
3GPP	The 3rd Generation Partnership Project	MA	Multiple Access
5G	Fifth Generation	MDP	Markov Decision Process
6G	Sixth Generation	MIMO	Multiple-Input-Multiple-Output
A2G	Air-to-Ground	ML	Machine Learning
ABS	Aerial Base-Station	mMIMO	Massive Multiple-Input-Multiple-Output
AI	Artificial Intelligence	mmWave	millimeter-Wave
AoA	Azimuth of Arrival	MPC	Multipath Component
ASA	Azimuth Spread of Arrival	NLoS	Non Line of Sight
AUE	Aerial User Equipment	NOMA	Non-Orthogonal Multiple Access
AWS	Amazon Web Service	NR	New Radio
B5G	Beyond Fifth Generation	NTN	Non-Terrestrial Networks
BLoS	Beyond Line of Sight	OEM	Original Equipment Manufacturer
BS	Base Station	PDF	Probability Density Function
C2	Command and Control	QoS	Quality of Service
CB	Conjugate Beamforming	RB	Resource Block
CNPC	Control and Non-Payload Communication	RL	Reinforcement Learning
D2D	Device to Device Communications	Rma	Macro-Cell in Rural Areas
DDQN	Double Deep Q Network	RMS-DS	Root Mean Square Delay Spread
DRL	Deep Reinforcement Learning	RSMA	Rate-Splitting Multiple Access
DSRC	Dedicated Short Range Communications	RSRP	Referenced Signal Referenced Power
DQN	Deep Q Network	RSS	Received Signal Strength
EoA	Elevation of Arrival	SCDP	Successful Content Delivery Probability
ESA	Elevation Spread of Arrival	SI	Study Item
FAA	Federal Aviation Administration	SINR	Signal-to-Interference-Plus-Noise-Ratio
GEO	Geosynchronous Earth-Orbiting	SNR	Signal-to-Noise-Ratio
GPM	Generalized Poisson Multinomial	TIN	Treating Interference as Noise
GUE	Ground User Equipment	TR	Technical Report
HAP	High Altitude Platforms	U2U	UAV – UAV Communications
IC	Interference Cancellation	UAM	Urban Air Mobility
ICIC	Inter-Cell Interference Coordination	UAS	Unmanned Aerial System
ID	Identity Document	UAV	Unmanned Aerial Vehicle
IoT	Internet of Things	UE	User Equipment
ISP	Internet Service Provider	ULA	Uniform Linear Array
KPI	Key Performance Indicator	UTM	Uav Traffic Management
LA	Lattice Approximation	VLoS	Virtual Line of Sight
LAP	Low Altitude Platforms	VR	Virtual Reality
LEO	Low Earth-Orbiting	VTOL	Vertical Takeoff and Landing
LSM	Liquid State Machines	WI	Work Item
LOS	Line of Sight	XR	Extended Reality

1.4. Structure of paper

This paper explores the landscape of cellular-connected UAV networks, organized into distinct sections as shown in Fig. 1. Section 2 outlines UAV types and categories, providing detailed classifications. Section 3 introduces UAV cellular network paradigms, clarifying their roles within this context. In Section 4, diverse applications and use cases of UAVs as user equipment are examined. Section 5 search into standardization efforts, notably by the 3rd Generation Partnership Project (3GPP). Challenges faced by cellular-connected UAVs with 5G integration are discussed comprehensively in Section 6. Recent solutions and improvements are presented in Section 7. Finally, Section 8 anticipates the implementation of UAVs and their applications in the next generation of mobile communications (6G).

2. UAVs types and classification

The surging demand for versatile UAVs, intended to serve a myriad of purposes for both military and civilian applications, has spurred industry and academia to collaborate on developing innovative UAV models. These models are designed to align more closely with contemporary and anticipated use cases, encompassing considerations related to shape, weight, size, and functionality. It is essential to note that the choice of UAV type plays a pivotal role in determining its communication capabilities with the terrestrial operator and its overall efficacy in fulfilling its designated missions. Currently, UAVs are commonly classified using three fundamental schemes based on their wing type, operational altitude, and power source. In Table 1, we present an overview of some of the most popular UAV models along with their specifications for Ref. [21]".

2.1. Wing configuration

UAVs can be categorized into three primary groups based on their wing configuration: fixed-wing, rotary-wing, and hybrid-wing UAVs. Fixed-wing UAVs, which resemble traditional aeroplanes, utilize their wings for lift, resulting in enhanced energy efficiency, payload capacity, and speed. However, they require a runway for takeoff and landing, limiting their operational flexibility [22,23].

Rotary-wing UAVs, on the other hand, offer distinct advantages such as the ability to hover at a fixed point, vertical takeoff and landing, and increased manoeuvrability. These UAVs typically feature four or more rotors, allowing them to hover steadily at varying altitudes and low speeds, making them suitable for various civilian applications [24]. However, they are not well-suited for extended flight durations and high payloads, relying primarily on their rotors for propulsion rather than the air, unlike fixed-wing UAVs [25,26].

In response to the limitations of both rotary and fixed-wing UAVs, a new hybrid UAV category emerged, combining the benefits of fixed-wing lift for efficient airborne operation and rotors for vertical takeoff and landing [27]. In terms of communication support, each UAV type offers distinct applications and capabilities. Rotary-wing UAVs can serve as base station elements to extend coverage to specific areas, while fixed-wing UAVs excel at connecting different regions, especially in the context of satellite communications [28].

2.2. Flying altitude

UAV's operational altitude and range are crucial considerations for its intended applications. Some UAVs are limited to low altitudes, typically flying only a few hundred feet above the ground. In contrast, High Altitude Platforms (HAPs) are capable of flying at significantly higher altitudes, reaching up to approximately 20 km [29]. HAPs come in various forms, including balloons and aeroplanes, and have specific use cases and limitations. They are costly to deploy and require regulatory authorization, making them suitable for use by Internet Service Providers (ISPs) to provide service in remote areas. However, they are rarely employed in cellular networks due to their substantial interference with other network nodes and their high altitudes [25,29].

Another category of UAVs in terms of altitude is Low Altitude Platforms (LAPs), which can be quickly deployed, maintained, and replaced compared to HAPs. LAPs are well-suited for a wide range of applications, including collecting ground-based sensor data, backscattering technology applications, and serving as mobile base stations to provide connectivity to terrestrial users [30–32].

2.3. Power supply

The choice of energy source significantly impacts a UAV's design, operational duration, and potential applications. Most common UAVs rely on lightweight rechargeable batteries, aiming to maximize flight time while maintaining a lightweight profile to accommodate a significant payload. These UAVs are typically used for short-duration missions that require specific operations [33,34].

Larger UAVs, on the other hand, often utilize fuel cells as their primary power source, generating substantial power for extended flights and increased payload capacities while extending the UAV's operational lifespan [35,36].

In some cases, UAVs are equipped with solar cells, particularly if they feature large wings for solar cell placement. These solar-powered UAVs require daytime operation, are more environmentally friendly, offer lower operating and maintenance costs, and boast an extended operational lifespan [37,38].

3. UAV - cellular network connections paradigms

There are several approaches for providing connectivity to UAVs or using them to aid cellular networks in improving their coverage. These are all outlined below.

3.1. UAV – assisted cellular communications

Employing UAVs as a mobile infrastructure to lay backbone connectivity is attractive due to inherent control over mobility, simplicity of deployment and favourable propagation conditions between UAVs and UEs. This has, therefore, motivated network operators to employ UAVs for the extension of network coverage. The UAVs connect to the wireless cellular system as an ABS to present coverage to terrestrial UEs, as shown in Fig. 2 [39,40]. The significant LoS connectivity, especially for short distances where the LoS probability reaches up to 90% in suburban areas, with both terrestrial cellular deployment, i.e. gNB, as well as UEs, allows UAVs to serve as efficient relays [41]. The ABSs can further collaborate among themselves to serve as distributed relays, enhancing the quality-of-service (QoS), bandwidth and spectral efficiency [42,43].

Fixed infrastructure cellular networks may have unusual traffic and coverage needs augmentation on certain occasions, such as major sporting competitions may require extra connectivity at stadiums, festivals, and other seasonal events may require extra connectivity in remote or less popular areas [44]. Moreover, in the case of unforeseen calamities like floods and earthquakes [45], the terrestrial network may be fully or partially deployed, and UAVs can form a sub-network which augments the main network. In order to provide cellular coverage in all of these situations, quick solutions are required. One such option is the installation of ABS using UAVs. The traditional wireless networks would otherwise be unable to provide coverage in several terrains, such as mountains, oceans, and deserts, where the flying base stations could ensure that and assist the service users. [28].

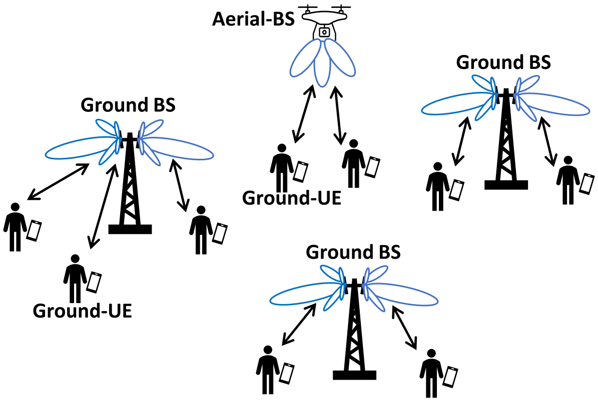

Fig. 2. UAV - assisted cellular communications [17].

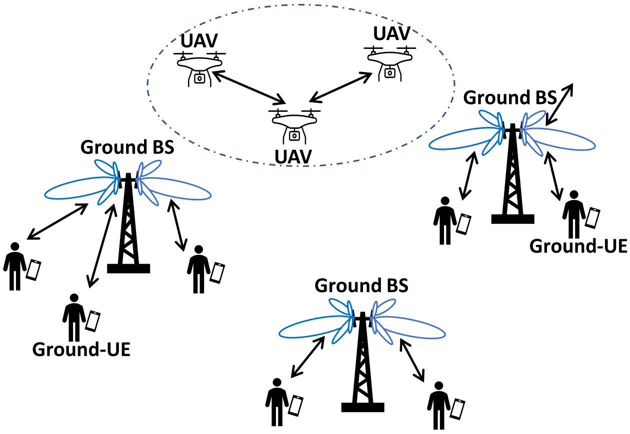

Fig. 3. UAV - UAV communications [17].

3.2. UAV to UAV communications

While UAVs offer several advantageous attributes, they do have inherent limitations, such as interference and restricted connectivity range. UAVs, by themselves, may be insufficient to cover extensive areas or serve a large number of users effectively. Consequently, they often rely on intra-UAV communications for data and control signal exchange, as depicted in Fig. 3 [46].

These UAV-to-UAV communications, commonly referred to as U2U, play a pivotal role in enabling UAV swarms to collaborate and autonomously perform tasks. Such swarms demand a high degree of coordination and orchestration to accomplish activities like real-time monitoring, comprehensive rescue operations, aviation systems, and the expansion of wireless coverage. Synchronization through direct links between UAVs is essential to avert collisions with objects or other UAVs. Moreover, these connections are instrumental for transmitting messages and data from the UAVs to the central controller or server for payload information transfer [47].

U2U communication serves a multifaceted purpose, contributing to spectral sharing, optimizing energy consumption, expanding cellular system wireless coverage, and diminishing the demands on the backhaul network [48,49]. Creating standards and regulations for U2U communications, whether through Wi-Fi, Bluetooth, or other Dedicated Short Range Communications (DSRC) mechanisms, could be envisioned as an extension of existing Device-to-Device (D2D) communication standards [50,51].

Table 2
The specification of the most popular UAVs in 2023.

Model	Wing type	Main application	Max. flight period	Weight	Max payload	Speed	Power supply	Ref.
DJI MATRICE 300 RTK	Rotary	Public Safety	55 min	3.6 kg	0.93 kg	23 m/s	5000 mAh	[58]
FLYABILITY ELIOS 3	Rotary	Indoor Inspection	12 min	0.5 kg	N/A	2 m/s	6700 mAh	[59]
DJI MAVIC 3	Rotary	Photography	46 min	0.895 kg	N/A	19 m/s	5000 mAh	[60]
FREEFLY ALTA 8	Rotary	Photography	12 min	6.2 kg	9.1 kg	15.6 m/s	10 Ah–16 Ah	[61]
XAG V40	Rotary	Agriculture	13.5 min	29.8 kg	N/A	8 m/s	20 Ah	[62]
PARROT ANAFI	Rotary	Public Safety	32 min	0.501 kg	N/A	14.7 m/s	3400 mAh	[63]
WINGTRAONE GEN II	Hybrid	Mapping & Surveying	59 min	3.7 kg	0.8 kg	18 m/s	2 X 99 Wh	[64]

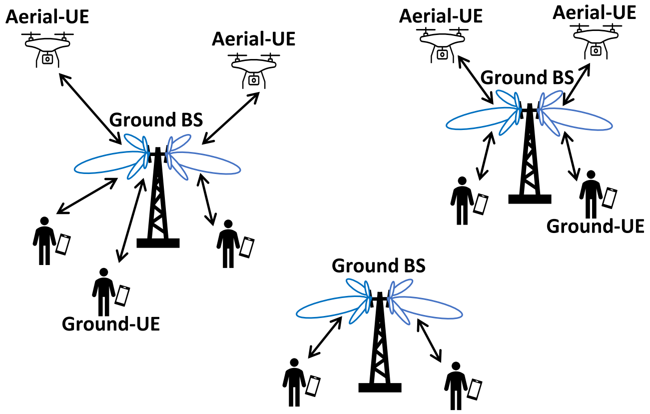

Fig. 4. Cellular - Connected UAV Communications [17].

3.3. Cellular - connected UAV communications

Over the past decade, a significant portion of UAV manufacturers have tailored their drone designs to operate within the confines of a ground controller's Visual Line-of-Sight (VLoS) range. This deployment method, while effective for various applications, does exhibit constraints related to the link between the ground controller and the UAV. These constraints include limited spectrum frequencies and relatively low data rates, as discussed in previous studies [8,52]. Both civil and military sectors have increasingly demanded the establishment of a robust, reliable, and wide-reaching wireless network to control the UAV, and here the cellular-connected UAV networks, sometimes known as "Cellular Assisted UAVs", come, as depicted in Fig. 4 [53,54].

The incorporation of cellular connectivity into UAVs offers several advantages, including reliable, low-latency communication frequency bands for precise UAV control and high data rate payload capabilities. These capabilities are instrumental for a wide range of applications, such as real-time video streaming and monitoring [55]. However, the connection between the AUE and the terrestrial base stations, as well as the connection between terrestrial base stations and terrestrial user equipment, introduces a host of additional challenges. These challenges encompass issues like interference, a notable likelihood of LoS conditions, high mobility, and other complexities, which we will delve into in subsequent sections of this paper [56,57] (see Table 2).

4. Cellular - connected UAVs applications and use cases

Cellular-connected UAVs have emerged as versatile assets with a pivotal role in a diverse array of applications, driven by their attributes of easy deployment, cost-effectiveness in manufacturing and operations, and inherent mobility. The rapid proliferation of UAV usage has led to the continuous development of innovative applications across various domains. Agriculture, search and rescue operations, and goods delivery represent just a few examples of these burgeoning applications. This paper aims to provide a comprehensive taxonomy of cellular-connected UAV applications and use cases, shedding light on the diverse domains benefiting from this transformative technology. As detailed in Table 2, the specifications of the most popular UAVs in 2023 showcase the diverse capabilities and applications of these platforms.

4.1. Agriculture and soil conservation

UAVs have brought transformative advancements to the field of agriculture, introducing novel farming practices and techniques. The integration of UAVs in agricultural processes has proven to be a cost-effective and time-efficient strategy, resulting in enhanced crop yields and increased farm productivity [65]. These technological innovations are leveraged for various agricultural operations, including crop planting, monitoring, weed control, and tracking insect damage [66,67]. UAVs are well-equipped to execute tasks such as soil analysis, precision crop spraying, crop monitoring, and micro-irrigation systems [68]. Moreover, they contribute to protecting crops from disease and decay, ultimately leading to increased agricultural yields [69].

Furthermore, cellular-connected UAV networks play a key role in applications related to soil conservation. They are instrumental in generating precise land maps and monitoring soil decay patterns, enabling targeted interventions for soil conservation and enhancing overall land management practices. These innovative technologies are reshaping the agricultural landscape, making it more efficient, cost-effective, and sustainable, thus revolutionizing the approach to agriculture and soil conservation.

4.2. Delivery of goods

The adoption of UAVs for package delivery has gained momentum in the past decade, with numerous businesses and suppliers harnessing the potential of UAVs to transport food, mail, and various deliveries to customers [70].

This application extends its significance to healthcare, offering the prospect of delivering vital medical supplies, including prescriptions and blood samples. It proves especially valuable in remote or hard-to-access areas where time is of the essence, and swift delivery can be a matter of life and death [71,72]. Notably, in 2015, the Federal Aviation Administration (FAA) authorized the use of UAVs for delivering medical prescriptions and providing real-time assistance to individuals [73].

The logistics sector also reaps the benefits of UAV deployment, aligning with the surge in postal services and the growth of e-commerce. UAVs enable swift and secure deliveries to consumers, enhancing efficiency and providing a reliable means to reach remote or challenging-to-access locations. The incorporation of cellular-connected UAV networks further amplifies their potential efficiently in transporting commercial goods. This technology not only saves time and resources but also offers a cost-effective alternative to traditional delivery methods. UAVs are poised to improve delivery timelines and ensure the safe and rapid delivery of goods, even in challenging terrains. This transformation holds the potential to revolutionize the delivery industry, affording customers faster and more convenient services while reducing delivery costs for businesses. Prominent initiatives embracing this use case of UAVs include Google's Wing project and Amazon's Prime Air [74,75].

4.3. Disasters and rescue operations

UAVs have become invaluable assets in both public and civilian spheres, especially in the realm of public safety and rescue. These aircraft offer a cost-effective and resource-efficient alternative to traditional planes and helicopters, minimizing human risk, particularly in scenarios where human involvement may be hindered by factors like pollution, distance, or altitude [76].

In the event of disasters or challenging conditions, UAVs offer several vital roles in alerting residents and aiding in rescue operations: (i) Providing Wireless Coverage: UAVs can swiftly establish wireless coverage in areas affected by infrastructure breakdowns, ensuring that both citizens and rescue personnel remain connected in critical situations; (ii) Real-time Monitoring and Person Location: UAVs leverage real-time video monitoring and image processing tools to locate missing individuals, significantly expediting search and rescue efforts; (iii) Aid Delivery: UAVs are instrumental in delivering medical supplies and food packages to those trapped or affected by disasters, offering crucial assistance to affected populations [77]. Furthermore, cellular-connected UAV networks play a crucial role in enhancing the responsiveness and efficiency of disaster relief operations. The integration of cellular networks enables real-time monitoring and control of UAVs, ensuring that supplies and assistance swiftly reach their intended destinations. This, in return, mitigates the impact of natural disasters, preserving lives and property. UAV deployment in disaster response and relief efforts proves instrumental in surmounting logistical challenges, such as limited access to affected areas and provides vital support to those in distress. With their versatility and capacity to navigate challenging terrains, cellular-connected UAVs have evolved into indispensable tools in disaster management and relief operations [72].

4.4. Real time monitoring and IoT

Automation and the Internet of Things (IoT) represent promising technologies with significant implications for industry and manufacturing. The integration of these elements is instrumental in enhancing the economics and quality of production across multiple levels. Notably, UAVs have emerged as key enablers of the Industry 4.0 revolution, particularly within Industrial IoT platforms [78]. UAVs assume a vital role in industrial processes by overseeing manufacturing stages and monitoring high-risk areas on-site. These tasks can be executed more efficiently than by human personnel, with a heightened degree of safety and precision. UAVs equipped with sensors and transmission/reception tools enable them and their operators to respond to specific circumstances and steer production remotely or autonomously [79].

Furthermore, the ability of UAVs to provide a comprehensive aerial view of operations not only optimizes logistics and monitoring but also opens doors for predictive maintenance and enhanced security within industrial facilities. As UAV technology continues to evolve, it is poised to revolutionize the industrial landscape further, offering innovative solutions to age-old challenges while concurrently ensuring a more sustainable, data-driven, and interconnected future for Industry 4.0. The convergence of IoT, automation, and UAVs embodies a transformative force with far-reaching implications that are only beginning to be fully realized [80,81].

4.5. Road traffic monitoring

In recent years, UAVs have emerged as a unique technology for traffic monitoring, offering valuable support for various vehicular applications such as traffic surveillance and road condition data collection [82].

UAVs present a cost-effective alternative to conventional monitoring systems, including loop detectors, security cameras, and microwave sensors. They possess the capability to monitor extended stretches of roads continuously or focus on specific road sections, offering versatile solutions for traffic management [83].

UAVs introduce new dimensions of flexibility to aerial traffic monitoring, road safety enhancement, and incident reporting, leveraging their mature technology and three-dimensional mobility. Their ability to traverse vast areas without being constrained by road networks or heavy traffic is particularly advantageous [84]. In traffic surveillance missions, UAVs are anticipated to detect, classify, and identify incidents and objects on the road. These aircraft collect a diverse range of data, often in the form of aerial photography, including images and videos. They process and transmit this data to the nearest vehicular network in real-time while also retaining the data onboard for future Ref. [85].

4.6. Urban air mobility

Urban Air Mobility (UAM) technology has garnered significant attention from both industry and academia, harnessing the capabilities of small aircraft for Vertical TakeOff and Landing (VTOL) [86,87]. However, the design and architecture of UAM systems face a multitude of constraints and challenges, encompassing safety, speed, deployment mechanisms, collision avoidance, and more. To enable the reliable control of autonomous taxis and flying vehicles, effective communication capabilities, such as high data rates and low latency, must be harnessed [88].

Commercial enterprises are actively developing UAM services, with imminent launches on the horizon, particularly capitalizing on the advanced wireless network capabilities of the forthcoming cellular generation [89,90]. The integration of UAM into the sixth cellular generation, 6G, is poised to address these challenges, leveraging planned frequency bands and expected network performance improvements, particularly in data rates and latency. This integration holds the promise of opening doors to other transformative technologies, including eXtended Reality (XR), brain-computer interfaces, and various other innovative directions [91,92].

4.7. Photography and media

In industry, research groups are exploring diverse applications for adaptable, autonomous, and lightweight UAVs as these technologies continue to advance. The multimedia landscape, driven by the need for exceptional mobility in capturing live or recorded scenarios, has given rise to the deployment of UAVs equipped with flying cameras. This trend towards adaptable and autonomous UAVs is significantly impacting various sectors, and it is likely that we will witness a continued expansion of their applications as technology evolves. [93].

Certain areas that are inaccessible to humans demand substantial time, heavy equipment, and machinery to conduct surveys or generate video reports. Examples include remote regions and hazardous environments like quarries, where continuous monitoring and photography are essential for safety and data collection [94]. Researchers have developed UAV-based digital aerial photography systems, incorporating high-resolution cameras, control systems, and UAVs equipped with a multitude of sensors. These systems are designed to determine flight routes, select recording locations, process and manage scene data, and execute various features related to filming and photography [95].

UAVs equipped with cameras have the capability to establish connections with their controllers or operators using cellular networks. This capability extends their filming range and greatly facilitates the transmission of high-definition photographs and videos. It ensures that the data rate requirements necessary for delivering superior media quality are met, as supported by recent research findings [96].

5. Cellular - connected UAVs standardization

The rapid expansion of UAVs in recent years and connecting them with cellular networks have underscored the need for the establishment of new operational guidelines, data-sharing protocols, and standardized procedures. These measures are essential to mitigate issues such as interference, collisions, and other airspace challenges. Leading the charge in this endeavour is the 3GPP, which administers numerous research initiatives and releases aimed at optimizing UAV performance within cellular networks. This commitment to enhancement extends from the LTE era to the 5G/B5G generations and beyond.

5.1. 3GPP Release-15

Within the framework of 3GPP Release-15, research efforts delved into the integration of UAVs with LTE networks for control and connectivity purposes. These efforts assessed how the attachment of a limited number of UAVs to an existing network architecture influenced the QoS provided to terrestrial User Equipment. Additionally, it examined the network's capability to deliver coverage and services to low-altitude UAVs. Notably, the technical report TR 36.777 [97] in Release-15 demonstrated that the LTE network could indeed cater to the needs of low-altitude UAVs without substantially impacting terrestrial users. However, the rise in the number of UAVs did have implications for network performance, particularly concerning uplink and downlink interference [98].

5.2. 3GPP Release-16

3GPP Release-16, authorized in 2019, placed a significant emphasis on system and application layer elements. A technical paper titled "Remote Identification of Unmanned Aerial Systems" was explored in technical report TR 22.829 [99]. This work aimed to establish ethical standards for UAV users, government regulators, and Original Equipment Manufacturers (OEMs) globally. The study was focused on identifying UAVs using control data transmitted over the 3GPP connection between UAVs or UAV controllers and a centralized network-based UAV Traffic Management (UTM) function. Release-16 also evaluated the potential inclusion of UAV-to-UAV communication and communication links between UAVs and terrestrial governmental agencies within the 3GPP standard [100].

5.3. 3GPP Release-17

In 3GPP Release-17, several studies examined the operation of UAVs in 5G cellular networks [101]. One of these studies identified specific Key Performance Indicators (KPIs) pertinent to UAVs and their services for both control and payload communications. Another study considered the service requirements for UAVs and their controllers from the application layer's perspective. The third study focused on UAS connection, identification, and tracking. This release formalized the interplay between 3GPP nodes and the UTM, streamlining the coordination for the safe and orderly operation of UAVs [102].

5.4. 3GPP release-18

In December 2021, 3GPP made the decision to incorporate a set of Study Items (SI) and Work Items (WI) into the research conducted by the organization's workgroups to develop the next generation of 5G, known as 5G advanced, as part of Release-18 [103]. Notably, one of the work items under RP-213600 focuses on the support of New Radio (NR) for UAVs. This work item aims to enhance UAV identification broadcasts and reporting measures established in previous releases. It covers various aspects such as height, flight route, position, speed, and UAV-triggered reports and also delves into the use of directional antennas on UAVs for beamforming. Additionally, this work item calls for research into subscription-based UAV identification within cellular networks [104,105].

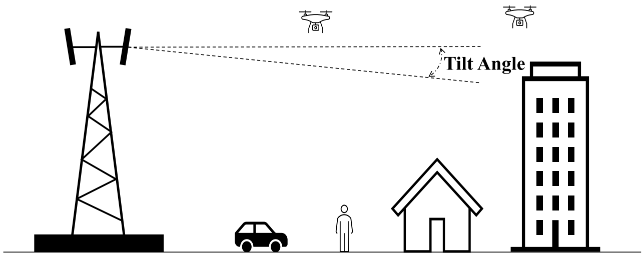

Fig. 5. Cellular base-station antenna tilt configuration.

6. Cellular - connected UAVs over 5G challenges

The integration of UAVs with cellular networks presents a range of significant challenges that necessitate in-depth research and analysis. A paramount concern in cellular network-UAV integration is establishing reliable communication via low-latency wireless frequency bands. The existing architecture of cellular networks is inherently designed to deliver services and coverage to terrestrial-based users whose altitude and mobility are confined to specific limits. These operational characteristics diverge from the behaviour of UAVs when operating as user equipment.

Addressing this divergence requires novel developments in the cellular network system and the UAVs themselves to harmonize their connections and provide satisfactory services to users. The variations in the operational profiles of terrestrial and aerial users, their diverse applications, and the interaction of terrestrial and aerial networks with different terrains and geographical features necessitate tailored solutions. The following delve into the key challenges faced by 5G cellular-connected UAVs in particular.

6.1. Aerial user equipment coverage

The existing cellular infrastructure is primarily designed to cater to the needs of terrestrial users, revealing noticeable disparities when it comes to serving flying objects. 5G base stations (gNodeB) are equipped with antenna configurations optimized for terrestrial user equipment and the base station itself, facilitating optimal coverage and connectivity. This often involves the downward tilting of antennas at specific angles to better align with terrestrial user equipment. However, this orientation can be less than ideal for the aerial user equipment, given their elevated altitudes during flight [106].

Fig. 5 illustrates the typical configuration of down-tilted antennas on a base station.

The challenge here lies in establishing reliable and secure communication links between terrestrial-based base stations and UAVs for both uplink and downlink connections while meeting Signal-to-Noise Ratio (SNR) requirements. Each base station sets a predefined threshold value for SNR to determine whether the incoming messages received via these links are associated with it and should be processed. Failing to meet this threshold may lead the base station to terminate the connection, potentially disrupting UAV operations [107].

In certain applications, such as high-definition photography and filming, UAVs serve as data sinks, necessitating a high data-rate uplink communication link with strong SNR to communicate effectively with terrestrial base stations. Conversely, ensuring high reliability in the downlink messages is crucial for facilitating Control and Non-Payload Communication (CNPC) between base stations and UAVs. This reliability is paramount for maintaining the safety of UAV operations over the cellular link [108].

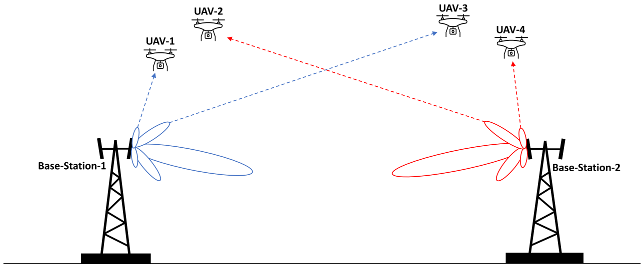

Fig. 6. UAVs connection with base-station side lobes [114].

6.2. Mobility pattern

Traditional cellular networks are purpose-built to provide connectivity to terrestrial users, taking into account well-established locative, speed, and mobility patterns. In contrast, UAVs exhibit distinct three-dimensional movement patterns that deviate from those of conventional terrestrial users [109]. In certain scenarios, unavoidable side lobe signals can extend the coverage for UAVs, making it feasible for low-altitude UAVs to establish connections with terrestrial base stations. Handover processes and cell servicing for users are determined by the received power strength at each point, and this power influences the link between the standard user equipment and the serving base station cell [110].

Various factors, such as user height, speed, environmental obstacles, and weather conditions, play a role in shaping the preferred wireless communication link. For instance, changes in a user's height can alter the potential for LOS communication, affecting the handover process. Moreover, high interference rates or reaching a predefined maximum number of retransmissions can result in connection failures between the UAV and the cell [111,112].

Fig. 6 illustrates the existing connectivity process between the UAV and the base stations. The handover decision relies on the received Referenced Signal Referenced Power (RSRP) and distinguishes between LoS and Non-Line-of-Sight (NLoS) states using base station side lobes. Given the increased uplink message transmission from UAV antennas compared to terrestrial user equipment, non-serving base stations may experience elevated interference levels. Conversely, if a UAV does not establish a downlink connection with a particular base station, it may still receive unwanted signals from the neighbouring cells via their side lobes. These behaviours can have repercussions for the entire cellular network, the quality of service for terrestrial users, and the connectivity between UAVs and base stations [113].

6.3. Air propagation model

The development of a robust cellular-connected UAV network encounters numerous challenges, with one of the primary hurdles being the utilization and modelling of the communication link between terrestrial and aerial components [54]. The interference characteristics between base stations and terrestrial users differ from those between aerial users and base stations. Aerial users, especially as their altitude increases, can introduce increased interference to uplink and downlink, creating high LOS probabilities. This situation can complicate the implementation of existing Inter-Cell Interference Coordination (ICIC) methods, prompting the need for alternative solutions to be developed and optimized by both academic and industrial research teams [115].

The propagation models used in current cellular networks have been developed and tested based on specific characteristics of terrestrial user equipment and channel utilization in both uplink and downlink communication between the UE and the base station. The uplink communication, representing the communication direction from the UAV to the base station, is traditionally designed to carry control and low-data-rate messages. However, cellular-connected UAVs may require high-capacity and high data-rate uplink links to accommodate the payload data of certain UAV applications and missions [116].

The downlink communication, which connects the base station to the UAV, exhibits differences between terrestrial and aerial user equipment in cellular networks. In the context of UAVs, this connection is primarily used for Command and Control (C2), also referred to as CNPC messages. It ensures continuous communication between the UAV and the network and operator, although strong communication capabilities are not necessarily required for this operation. On the other hand, the downlink link places a high premium on the standard terrestrial network, and the nature of the communications transmitted over it differs [116,117].

The strong likelihood of LoS communication between the UAV and the base station antennas influences both large-scale and small-scale fading estimations. As a result, it becomes necessary to develop new propagation models or modify and enhance existing models and relying solely on existing propagation models can lead to inaccuracies in predicting actual or approximate signal intensities [118].

6.4. Flight trajectory

Understanding and addressing the unique characteristics and behaviours of each UAV is crucial, particularly with regard to the UAV's flight trajectory. The flight trajectory of a UAV represents the path it follows from its initial takeoff point to its final destination, which includes various waypoints along the way [70]. Planning the flight path for any UAV mission necessitates careful consideration of several critical factors: (1) the type of UAV and its speed, (2) the specific mission application and services required, (3) power consumption considerations, and (4) the geographical coverage and interference conditions along the path [119].

For UAVs connected to cellular networks, trajectory planning is inherently tied to infrastructure topology and the placement of base stations. Optimization algorithms are primarily focused on minimizing the flight duration while ensuring continuous connectivity with the cellular network for control and payload message transmission [120].

The autonomous nature of UAV operations, distinct from conventional terrestrial user equipment, underscores the critical importance of maintaining a stable connection throughout a UAV's mission. This stability is vital not only for ensuring QoS but also for enhancing the safety of the UAV. Given the multitude of design options for cellular networks and the wide variety of UAV types and mission profiles, establishing a universal trajectory model for all cellular-connected UAVs proves challenging [121].

Fig. 7 illustrates a cellular network scenario where a UAV needs to travel from point S to point F. The connectivity requirements dictate that the UAV must traverse multiple base stations along this path, irrespective of whether it represents the most direct or shortest route. Another consideration is the presence of connection failure zones, occurring when the UAV exits one base station's coverage area but has not yet entered the next one. Therefore, it is essential to thoroughly evaluate tolerance limits and devise solutions to address this issue [17].

6.5. UAV power consumption

UAVs are versatile tools with a wide range of applications, but they are subject to certain limitations and constraints, including power consumption. Understanding the power requirements of UAVs during their missions, their flight duration and their operational capabilities is essential. Battery capacity for UAVs is typically constrained by factors like weight and size limitations. However, it is important to note that the power consumption of the UAVs is generally higher than that of their terrestrial counterparts [122].

Efficient energy management in UAV operations, especially over reliable, low-latency wireless communications while connecting to base

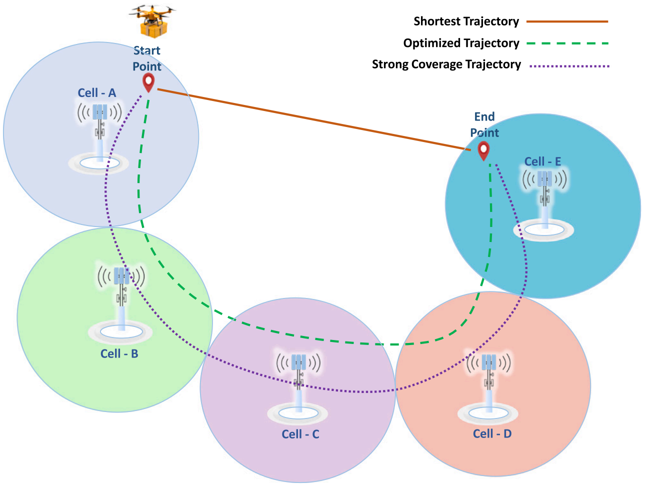

Fig. 7. Cellular connected UAV's trajectory planning [17].

stations, is a complex challenge. While reducing flight duration and increasing UAV speed may seem like ways to reduce power consumption, this approach can lead to higher battery consumption and affect the UAV's communication with cellular network base stations and handover procedures [123]. Conversely, equipping UAVs with larger-capacity batteries may increase payload capacity but limit overall capabilities.

Efficient power utilization is heavily influenced by aspects such as antenna handshaking signals and their quality. Moreover, considerations regarding the connection between the UAV and the serving base station, as well as non-serving base stations, are crucial due to LoS opportunities and the handover process [124].

Designing an energy-efficient system for UAVs must take into account all these factors to establish a robust system that caters to the needs of various applications while maintaining the cellular-connected UAV connectivity parameters within acceptable bounds.

6.6. Cyber attacks

Operating UAVs remotely exposes them to potential loss of control, either intentionally or unintentionally. UAVs often carry sensors and cameras that collect data for various applications, making this data a potential target for theft or manipulation by cyber attackers [125,126]. For instance, in delivery applications, attackers might attempt to hack a UAV to alter its delivery destination, change its course, or even cause its destruction if they fail to steal it. In swarm UAV applications, attackers could exploit stolen authentication data to send false payload messages to the control side and manipulate synchronization messages, which are critical for swarm collision avoidance and data sharing [127].

Threat methods and tools in cellular networks are continually evolving, especially with open-source software platforms, making it increasingly challenging to defend against them. Cellular systems, due to their extensive connectivity and the transmission of critical information, are frequent targets for attackers [128]. However, when a UAV connects to cellular networks as a flying UE, the standard authentication and security procedures used in terrestrial cellular networks may not sufficiently ensure the UAV's security and safety. As a result, one of the significant challenges is integrating new security frameworks that do not negatively impact networking parameters or performance metrics [129]. Ensuring the security and safety of UAVs in the face of cyber threats should be an ongoing and evolving process to thwart or mitigate these attack attempts.

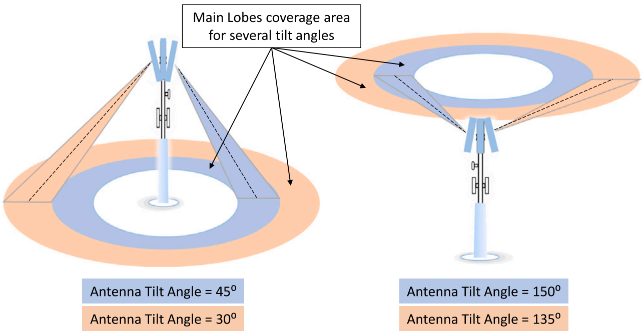

Fig. 8. Terrestrial base-station antenna patterns for different antenna tilts [131].

7. Cellular - connected UAVs proposed research solutions

7.1. Three-dimensional coverage model

To provide suitable coverage for flying UAVs across a range of altitudes, a Three-Dimensional (3D) coverage model is essential [130]. This model can use down-tilted antennas to ensure reliable cellular coverage for terrestrial and aerial user equipment [106]. One pivotal aspect of achieving suitable coverage for flying UAVs in cellular networks involves the consideration of base station service provisioning schemes, focusing on the antenna tilt angle. In this context, the study presented in [131] provides valuable insights into Non-Terrestrial Networks (NTN) and their implications for UAV communications. The paper suggests two distinct service provisioning schemes: the inclusive-service base station (IS-BS) scheme, where BSs simultaneously serve both ground users and aerial users such as UAVs, and the exclusive-service base station (ES-BS) scheme, which segregates base stations for ground users and aerial users as shown in Fig. 8. The analysis considers the antenna tilt angle-based channel gain, deriving the network outage probability for both schemes. Remarkably, the study reveals the existence of an optimal tilt angle that minimizes network outage probability, considering the potential conflict impact of the antenna tilt angle.

Additionally, massive Multiple-Input Multiple-Output (mMIMO) implementations for terrestrial base stations that support both terrestrial and aerial UEs can improve connectivity for UAVs at various altitudes. Conjugate Beamforming (CB) can be employed to achieve a Successful Content Delivery Probability (SCDP) for UAVs. The study suggests that when UAV altitudes are below the height of the base station antennas, the tilted MIMO antennas can provide connectivity for both UAVs and terrestrial UEs. However, when UAV altitudes surpass the antenna height, there can be improvements in the connectivity of both types of UEs [132].

Furthermore, a novel base-station cell association technique for AUEs was employed in [133] to develop spectrum planning. The technique involves spatial cross-validation parameters estimation and the deployment of AUEs using kernel density estimation. Unlike traditional cell association methods, this approach aims to minimize various UAV characteristics, including latency, transmission power, processing capacity, and backhaul consumption, to optimize the connection quality for UAVs.

7.2. UAV handover mechanisms

Efforts are underway to minimize the impact of UAVs as AUEs on the current cellular network's handover process between base station cells.

A study by Fakhreddine et al. in [114] examined the relationship between UAV movement and the LTE-A network's handover mechanism for cellular-connected UAVs. The research conducted in a suburban environment analyzes the number of handovers between UAVs at various altitudes and conventional terrestrial users. The findings show that when a UAV is flying at 150 m, it experiences approximately five cell handovers per minute. In contrast, a terrestrial user moving at the same speed as the UAV experiences just one cell handover, and this rate varies as the UAV's altitude increases.

To enhance the quality of the received signal at UAVs while maintaining the signal's allowed limitations for terrestrial users, a unique handover technique is proposed in [134]. This technique employs Reinforcement Learning (RL) model-free methods to adjust the downtilt angles of terrestrial base station antennas. The aim is to reduce the frequency of handovers for UAVs during their flights while meeting the cellular system's performance targets.

In optimizing the handover mechanism, the analysis and evaluation of UAV mobility factors are crucial because the 3D movement of UAVs affects the handover iterations. Additionally, handover incidents can be used to estimate UAV characteristics, which can help address network performance issues. For example, the velocity of UAVs is a critical parameter that impacts handovers, and a novel method is introduced in [135] to allow the network to estimate the connected UAVs' velocity at various stages of flight. This method involves creating probability mass functions for handover frequency under different UAV velocities and terrestrial base station deployments.

Furthermore, a study proposing a 3D boundary model to analyse handover performance in two-tier HetNets is presented in [136]. This model incorporates trigger conditions and considers the shadow-fading effect. The 3D handover trigger and failure boundary are structured as hemispherical shells with a typical small base station. This model quantifies the effect of 3D mobility and handover parameters in various HetNets deployments, showcasing substantial drops in failure and ping-pong handover probabilities under specific scenarios, emphasizing the consideration of HetNets deployment in choosing appropriate handover parameters.

7.3. Channel model and interference mitigation

Research into the influence of small-scale fading, large-scale fading, path loss, and shadowing is crucial for comprehending and optimizing the performance of cellular-connected UAVs, aiming to refine propagation models and interference mitigation techniques.

Various studies, such as those by Cai et al. [137], Khawaja et al. [138], Amorim et al. [139] and Sun et al. [140] have delved into path loss and shadowing in diverse environments (urban, suburban, and open areas) and at different altitudes for UAVs, providing invaluable insights into signal propagation characteristics essential for optimizing UAV connectivity.

Several small-scale fading models, including the Loo Model [141], Rayleigh Model [142], and Rician Model [143], have been explored to enhance the modelling of the channel for cellular-connected UAVs.

Wang et al. [144] developed a 3D multipath channel sounder to scrutinize the uplink channel for UAVs at 3.5 GHz in Rural Macro-cell areas (RMa). Their research focused on parameters like the Elevation/Azimuth of Arrival (EoA/AoA) of MultiPath Components (MPCs) and the Elevation/Azimuth root mean square Spread of Arrival (ESA/ASA), assessing how these parameters change with UAV altitude through experimental calculations using lognormal Probability Density Functions (PDFs).

In another study, Li et al. [145] proposed a dynamic Interference Cancellation (IC) mechanism that treats interference as noise (TIN) to minimize interference to the co-channel of base stations. This approach enhances UAV communication throughput while ensuring the desired service quality for terrestrial users.

Furthermore, Mei and Zhang [146] introduced an interference mitigation/cancellation technique utilizing UAV communication capabilities and their Line-of-Sight (LoS) connections with neighbouring base stations. This technique involves modifying Resource Block (RB) assignment and broadcasting methods with both serving and non-serving base stations to optimize spectrum utilization in cellular-connected UAVs.

Adding to this discourse, the authors of [45] leverage 3D radio maps and machine learning methods to detect and mitigate GPS spoofing attacks for cellular-connected UAVs. The edge UAV flight controller employs ray tracing tools, deterministic channel models, and Kriging methods to construct a theoretical 3D radio map. Machine learning methods are employed to detect GPS spoofing by analysing the UAV/base station reported Received Signal Strength (RSS) values and the theoretical radio map RSS values. Once spoofing is detected, the particle filter is applied to relocate the UAV and mitigate GPS deviation, achieving precise relocation.

Additionally, the paper [147] proposes a new channel model that simultaneously considers the effects of mobility and shadowing in a UAV-based communication system. The model is generic, accommodating various fading/shadowing conditions through easy-to-evaluate mathematical functions. The introduced low-complexity UAV selection policy exploits shadowing-related information, offering reduced signal processing complexity without significant degradation in performance compared to alternative approaches.

7.4. UAV trajectory planning

In an effort to enhance flight trajectories and reduce flight duration, Yang. in [148] have proposed a sophisticated and dynamically computed algorithm based on the geometric deployment of cellular-connected UAVs. The first stage of this algorithm involves gaining an understanding of the cellular network topology and the spatial distribution of terrestrial base stations. Subsequently, handover location design is utilized to identify the shortest flight path, enabling the comparison of computed trajectories and selection of the optimal one.

Over recent years, Deep Reinforcement Learning (DRL) has emerged as a valuable approach for optimizing UAV trajectories. Gao et al. employed a duelling Double Deep Q Network (duelling DDQN) with a DRL algorithm in [149]. They introduced variations in anticipated periods of coverage outage and considered varying UAV battery levels to evaluate the proposed technique. Another study by Li et al. in [150] presented a flight trajectory optimization technique that combines a Markov Decision Process (MDP) with DRL. This approach aims to simultaneously create the optimal path from the source to the destination. It employs a Quantum-inspired Experience Eeplay (QER) framework to strike a balance between the sampling primacy and variety, which relates the importance of an experienced transition to its associated quantum bit (qubit) and utilizes a Grover iteration based on amplitude amplification methodology.

In [151], S. Zhang and R. Zhang have described an optimal path planning method for cellular-connected UAVs that takes a three-dimensional approach to reduce UAV flight duration. This approach considers the Signal-to-Interference-plus-Noise Ratio (SINR) for UAV uplinks and downlinks with all nearby base stations. It introduces a new radio map for locations, accounting for spatially variable channels and channel interference. The channel gain map of each base station is employed to provide large-scale channel gains with sampled UAV 3D locations, accounting for surrounding buildings and other assumed time-invariant obstacles. In a follow-up study in [152], the authors extended their work by examining two additional attributes: total and maximum outage durations. This information aids in constructing a conventional outage cost function for flight trajectory planning, along with a mathematical tool to minimize mission duration while still fulfilling the necessary connectivity requirements.

These methods and algorithms have significantly contributed to the optimization of UAV trajectories in cellular-connected networks, leading to improved performance and efficiency.

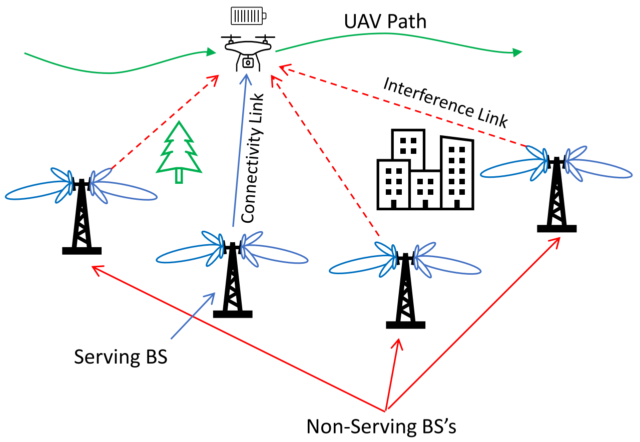

Fig. 9. Cellular connected UAVs associated connections [154].

7.5. Energy consumption management

In an effort to explore and optimize the communication energy demands of cellular-connected UAVs, Rahmati et al. [153] propose a novel approach utilizing Rate-Splitting Multiple Access (RSMA) techniques. These techniques aim to reduce the power consumption of UAVs during base station-to-UAV communications. The study also considers Non-Orthogonal Multiple Access (NOMA) as another Multiple Access (MA) technique for comparison. Evaluation is conducted in millimeter-Wave (mmWave) bands within a 5G cellular network context, adhering to 3GPP antenna design specifications.

Zhan and Zeng [154] address the tradeoff between power consumption and the flight time of cellular-connected UAVs. They employ Deep Reinforcement Learning (DRL) to create an optimization model utilizing multi-step and double Q-learning within a dual Deep Q-Network (DQN) architecture. The study investigates various communication scenarios and barriers, utilizing flight trajectory planning and interference mitigation tools to reduce mission duration and UAV energy consumption effectively. Fig. 9 illustrates the associated connections of cellular-connected UAVs.

Shi et al. [155] present a decoupled access technique complemented by a talent mechanism. This technique is designed for uplink and downlink communications between UAV antennas and nearby base stations, with the primary goal of minimizing battery usage. The approach focuses on enhancing energy efficiency in hybrid cellular-connected UAV cells, ensuring coverage for both terrestrial UEs and UAVs. It utilizes linear-fractional programming and successive convex optimization methods to achieve improved energy efficiency. These research efforts contribute to more energy-efficient operations of cellular-connected UAVs, thereby extending their mission durations and operational capabilities.

Additionally, Yang et al. [156] address a UAV-based patrol inspection scenario, aiming to minimize the sum of total energy consumption by jointly optimizing task completion time, communication scheduling, computation resource allocation, and UAV trajectory. The proposed solution outperforms other benchmark schemes in various scenarios. On the other hand, Su et al. [157] proposes a two-phase command and control transmission scheme in a cellular-connected UAV swarm network, utilizing a decentralized constrained graph attention multi-agent DQN algorithm. This scheme maximizes the number of UAVs successfully receiving the common control messages under energy constraints.

7.6. Mission security

Ensuring the security of UAV missions is of paramount importance, considering the vulnerability of communication links. Several approaches and technologies are being employed to enhance mission security for cellular-connected UAVs.

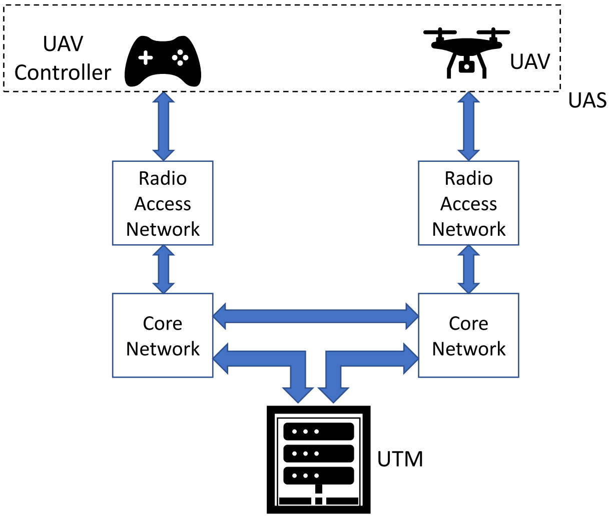

Fig. 10. UTM connectivity with UAS in 3GPP Model [124].

Security Measures in UAV Communications: In [158], the paper introduces physical layer security mechanisms through two case studies, flying base stations and flying users, demonstrating superior performance gains. This comprehensive approach sheds light on new opportunities within emerging network architectures, providing valuable insights for future research directions.

mMIMO Authentication and Security: In [159], a mechanism for authenticating UAVs connected to cellular networks is introduced. The authors explore the advantages of mMIMO technology in UAV communication, emphasizing its potential to enhance coverage and security. They seek to establish ergodic rates for this architecture, further maintaining UAV communication security. The incorporation of a fingerprint access technique is proposed to reduce the risk of unauthorized access or impersonation of UAVs.

Machine Learning for Data Evaluation: Machine learning plays a pivotal role in evaluating exchanged information within cellular networks, distinguishing between genuine data and potential threats. Shrestha et al. in [160] conducted experiments employing multiple machine learning algorithms, including logistic regression, K-Nearest Neighbour, Gaussian Naive, and others. These tests were carried out on CSE-CIC-IDS2018 datasets gathered from Amazon Web Service (AWS). The datasets were tested over a 5G software-defined security system with a UAV acting as an AUE. The results demonstrate that various machine learning algorithms can be employed effectively to achieve the desired levels of data security.

3GPP Standards for UAV Security: In response to the proliferation of UAVs connected to cellular networks, the 3GPP has standardized a synchronization strategy. This strategy involves various 3GPP nodes and a central authorization entity known as UTM, as illustrated in Fig. 10. The UTM plays a crucial role in ensuring the authentication and management of UAV-related data, including UAV Remote ID, flight information, and mission details. By providing this information to cellular network operators, the UTM contributes to the safety and security of data exchanged between UAS terminals, UAVs, and UAV controllers [101,161].

8. Cellular - Connected UAVs enhancements towards next generations

The advent of the next generation of mobile communications, such as 6G, holds the promise of significantly enhancing connectivity performance. It is expected to bring improvements in various aspects,

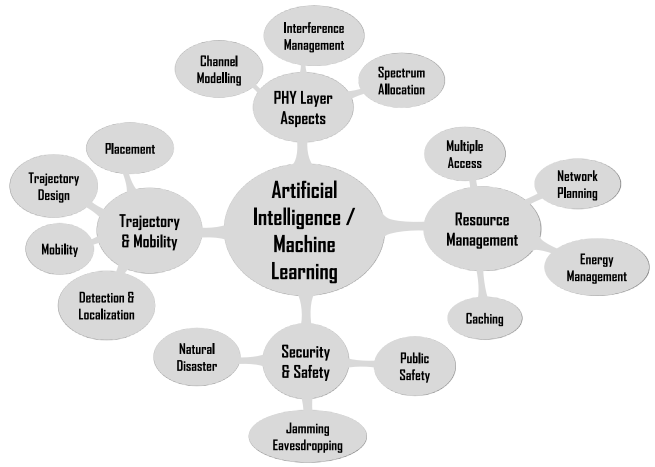

Fig. 11. AI/ML solution classification for UAV wireless communications. [162].

including data rates, response times, mobility management, flexibility, and more, enabling the implementation of a wide range of applications and use cases. However, realizing these improvements comes with its set of challenges and limitations, particularly in hardware and software design. To overcome these challenges and expand the capabilities of current cellular network architectures, the research community is actively exploring various innovative ideas and technologies. These endeavours aim to harness the full potential of the next generation and ensure that it can deliver on its promises, ultimately revolutionizing the way we connect and communicate in the future.

8.1. Non-terrestrial networks (NTN)

Non-Terrestrial Networks (NTN) is a term used by the 3GPP to describe communication networks that operate above the Earth's surface. This category encompasses various types of networks, including low-altitude UAVs, HAPs, and communication satellites. Satellites, in particular, have played a crucial role in recent years in delivering data and communication services, especially to remote and challenging to reach areas. Satellites can be broadly categorized into Geosynchronous Earth-Orbiting (GEO) satellites and Low Earth-Orbiting (LEO) satellites.

HAPs are aerial platforms located in the stratosphere, typically around 20 km above ground level. They serve as a means to connect terrestrial components to the internet wirelessly or act as intermediaries between satellites and terrestrial-based communication systems. In its latest releases, the 3GPP has initiated research efforts to establish connectivity between these different airborne communication networks and create a backbone system that can support terrestrial networks or provide wireless coverage for aircraft.

NTN platforms and the elevations of their components aim to create a seamless and efficient communication infrastructure that spans terrestrial and non-terrestrial networks, enhancing connectivity and coverage for a wide range of applications and users.

Integrating NTNs with cellular networks holds great promise in ensuring connectivity for previously unserved or underserved areas, especially in scenarios such as disasters or remote regions like oceans and deserts where terrestrial cellular networks struggle to provide coverage. An evident advantage of combining cellular networks with NTNs is the enhanced reliability of coverage for IoT devices and other monitoring equipment, as highlighted in a study by Azari et al. [163].

Using low-altitude UAVs in conjunction with NTNs is a particularly promising area of exploration. These UAVs offer extensive mobility and often maintain a clear LoS with terrestrial platforms and satellites. When a UAV offloads its traffic to the nearest LEO satellite through the NTNs, the downlink outage for the UAV can be minimized to nearly 0% in terrestrial cellular networks, as discussed by Benzaghta et al. in [164]. Furthermore, this approach can ensure uplink coverage, and conversely, terrestrial UE can enhance uplink efficiency by reducing the outage rate. This symbiotic relationship between UAVs and NTNs holds the potential to significantly improve network performance and extend connectivity to a broader range of applications and use cases.

8.2. Artificial intelligence and machine learning

Artificial Intelligence (AI) encompasses the study of enabling robots to perform tasks that are human-like in nature. AI finds application in various domains, including autonomous vehicles, voice recognition, translation software, and, more recently, wireless communications. A specialized branch of AI, known as Machine Learning (ML), focuses on teaching computers how to learn and adapt. ML offers solutions in scenarios where numerous devices need to efficiently utilize network resources simultaneously, especially in dynamic and diverse contexts like IoT communications. ML comprises various areas, including RL, unsupervised learning, and supervised learning.

In the context of cellular-connected UAVs, implementing ML is a versatile tool with applications spanning various critical aspects. ML techniques contribute significantly to handover and resource management [136], interference mitigation [134], security [160], energy efficiency [154], trajectory planning optimization [70], and many other applications. The adaptability of ML allows it to address dynamic and complex scenarios inherent in cellular-connected UAVs, making it an essential component for achieving optimal network performance. As UAVs operate in dynamic environments, ML-based solutions offer adaptive and intelligent responses, ensuring efficient resource utilization and robust performance. The integration of ML in cellular-connected UAVs addresses current challenges and opens avenues for innovative applications and advancements.

The application of DRL algorithms such as DQN and Liquid State Machines (LSM) has been explored extensively, as discussed in [165]. This research delves into various network and communication aspects, encompassing radio access networks, security, data rates, uplink and downlink transmission, and more.

Additionally, [162] provides an extensive examination of the diverse applications of UAV wireless networks where ML approaches offer performance improvements compared to traditional optimization strategies. These enhancements span multiple dimensions, including the physical layer, security, trajectory and mobility planning, as well as network and UAV resource management, as illustrated in Fig. 11. The fusion of AI and ML with cellular-connected UAVs opens up new avenues for optimizing and enhancing network performance and enabling advanced applications.

8.3. High altitude UAVs coverage

The topic of supplying connectivity to high-altitude UAVs and aircraft, in addition to low-altitude ones, holds significant promise. Several research endeavours have contributed to achieving this objective, either by adapting existing cellular networks or by developing alternative infrastructure. Unlike satellite communications, Air-to-Ground (A2G) communications that leverage cellular network infrastructure offer high-altitude platforms, stable links, high data throughput, and low-latency connectivity [166].

In a bid to develop and optimize a direct A2G link between the current 5G cellular network and the sky, Chen et al. propose an innovative deep learning-based technique in [167]. They employ two DNN algorithms to optimize throughput, antenna tilt angles, and inter-cell distances. The simulation encompasses various scenarios involving antenna tilting and inter-cell spacing distributions. As depicted in Fig. 12, the results highlight a tradeoff between these two parameters, aiming to achieve the optimal configuration and parameters for the best possible connection performance between base stations and UAVs.

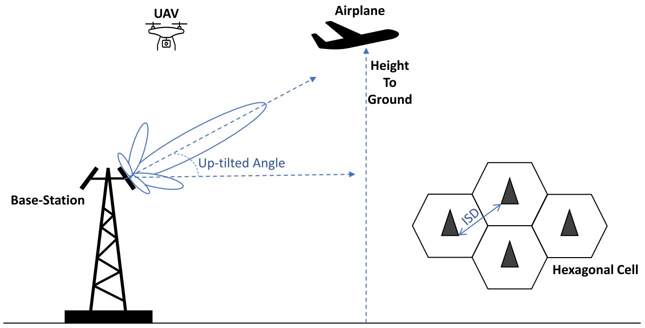

Fig. 12. High altitude A2G communication model. [167].

Expanding on the coverage analysis of aerial communication networks, a recent contribution by [168] utilizes stochastic geometry to analyse network coverage of an integrated High Altitude Platform (HAP) and Low Altitude Platform (LAP) system. The LAPs aim to provide services for ground user equipment in the malfunction area, and the HAP is designed to provide backhaul connectivity for LAPs. The analytical framework of the integrated HAP and LAP (IHL) system coverage is derived through stochastic geometry theory. The analysis also explores the impact of key parameters, such as aerial platform altitudes and LAP densities, providing valuable insights for the backhaul design of LAP aerial base stations, as revealed in the numerical analyses part.

8.4. Open Radio Access Networks

Open Radio Access Networks (O-RAN) have emerged as a prominent area of research in contemporary cellular network development. In contrast to the current RAN technology provided by traditional telecom vendors, characterized as a "black box" with integrated software and hardware, O-RAN aims to create an open framework with open interfaces and support for multi-supplier technologies, enabling virtualization and the decoupling of software and hardware components [169]. O-RAN's open and interoperable architecture aligns perfectly with the dynamic nature of UAV deployments, facilitating flexible integrations and accelerated innovation [170].

To integrate O-RAN with a flexible multi-UAV system, the authors of [171] propose a novel architecture called U-ORAN. They argue that O-RAN's open and disaggregated nature aligns perfectly with the dynamic deployment of UAVs, enabling customized network slicing, on-demand network extension, and seamless multi-vendor interoperability. This opens up exciting possibilities for tailoring network resources to specific UAV missions, dynamically expanding coverage, and fostering innovation in UAV-connected networks.

Focusing on resource management within UAV-assisted WSNs for smart agriculture, Wang et al. [172] propose a joint UAV task scheduling, trajectory planning, and resource-sharing framework. This framework leverages O-RAN's flexibility to optimize UAV movements, data collection schedules, and energy sharing with sensor nodes. By employing multi-agent deep reinforcement learning, they aim to minimize UAV energy consumption and network latency while ensuring efficient data collection within a specific timeframe.

9. Conclusion

In conclusion, this paper has provided an extensive review of cellular-connected UAVs, where UAVs are integrated into existing cellular systems and operate as aerial user equipment. We have introduced various classification schemes for a detailed categorization of UAVs and created a comprehensive taxonomy of cellular-connected UAV applications, highlighting new use cases across various domains and recent technical standards established by the 3GPP. Furthermore, we have discussed the current state-of-the-art regarding the technical challenges encountered by cellular-connected UAVs, particularly in the context of 5G, and explored potential solutions proposed by the research community to tackle or alleviate these challenges. Lastly, we have outlined innovative tools and technologies that can be harnessed to establish and enhance the connectivity between UAVs and the upcoming generation of mobile communications, 6G.

CRediT authorship contribution statement

Mohammed M.H. Qazzaz: Writing – original draft, Resources, Methodology, Investigation. **Syed A.R. Zaidi:** Writing – original draft, Supervision, Project administration. **Desmond C. McLernon:** Writing – review & editing, Supervision. **Ali M. Hayajneh:** Writing – review & editing. **Abdelaziz Salama:** Writing – review & editing. **Sami A. Aldalahmeh:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.adhoc.2024.103440.

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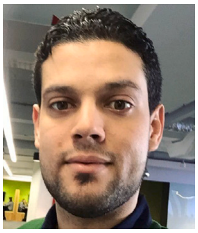

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