GTI
Cellular-Connected UAV Technical Requirement White Paper

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1 Executive Summary

With the advancement of digitalization, intelligence and automation technologies, UAVs are being increasingly integrated into diverse applications, ranging from logistics and management to emergency response, agriculture and urban services, as part of the expanding low-altitude industry ecosystem. To meet the demands of large-volume flight operations in low-altitude, building secure, reliable, wide-area connectivity at scale has become a critical foundation for the growth of the low-altitude industry. Cellular networks, with extensive coverage, high capacity, and high reliability, are emerging as a key connectivity solution for UAVs. As 5G networks continue to evolve, cellular networks are increasingly capable of supporting UAV control links and service data transmission, providing a solid foundation for the large-scale development of low-altitude applications.

The cellular-connected UAV industry is now accelerating its development. Across the value chain, ranging from chipsets and modules to terminals, networks, platforms, and applications, innovation is refining the technology system, and accelerating ecosystem maturity. From a global perspective, this white paper examines the current state and evolution of cellular-connected UAVs, providing systematic analysis of industry demands, the ecosystem, key technologies, and standardization progress, while offering a forward-looking view of the low-altitude industry. It is intended to serve as a reference for stakeholders across the value chain in technology innovation, product development, standardization, industry collaboration, and ecosystem building, to jointly promote the prosperous development of the low-altitude economy.

2 Abbreviations

Abbreviation	Explanation
3GPP	3rd Generation Partnership Project
4G	4th Generation
5G	5th Generation
5G-A	5G-Advanced
AT	Attention
BTB	Board-to-Board Connector
C2	Command and Control
CAGR	Compound Annual Growth Rate
Cat 1/1bis	Category 1 / Category 1 bis
Cat 4	Category 4
CCSA	China Communications Standards Association
CHO	Conditional Handover
CNAS	China National Accreditation Service for Conformity Assessment
CNPC	Control and Non-Payload Communication
eMBB	Enhanced Mobile BroadBand
eSIM	Embedded Subscriber Identity Module
FDD	Frequency Division Duplex
GSMA	Global System for Mobile communications Association
IMEI	International Mobile Equipment Identity
IMSI	International Mobile Subscriber Identity

IPEX	Integrated Panel Mount External
ITU	International Telecommunication Union
ITU-R	ITU Radiocommunication Sector
ITU-T	ITU Telecommunication Standardization Sector
LCC	Leadless chip carrier
LGA	Land Grid Array
LTE	Long Term Evolution
Mini PCIe	Mini Peripheral Component Interconnect Express
MMCX	Micro Miniature Coaxial connector
NGFF	Next Generation Form Factor
RedCap	Reduced Capability
RSRP	Reference Signal Received Power
SDIO	Secure Digital Input/Output
SDK	Software Development Kit
SIB2	System Information Block Type 2
SIB4	System Information Block Type 4
SIM	Subscriber Identity Module
SINR	Signal to Interference plus Noise Ratio
SMA	SubMiniature version A
SSB	Synchronization Signal Block
TDD	Time Division Duplex
TSG	Terminal Steering Group
TTL	Transistor-Transistor Logic
UAI	UAV Application Identifier
UAS	Unmanned Aircraft System
UAV	unmanned aerial vehicle
UE	User Equipment
USB	Universal Serial Bus
USB-C	Universal Serial Bus Type-C
WLAN	Wireless Local Area Network

3 Service Analysis

The low-altitude economy is a comprehensive economic ecosystem that revolves around low-altitude flight activities and drives the integrated development of related industries. As the UAV industry grows rapidly and technology continues to advance, the sector is moving toward scaled deployment, exhibiting characteristics such as BVLOS operations, high-frequency flight activities, diverse aircraft types and complex operational environments. To support the real-time communication needs of aircraft operating at various altitudes and distances, cellular connectivity for UAVs has become a prerequisite for realizing this vision.

Traditional UAV connectivity has largely relied on point-to-point proprietary protocols, such as WiFi in the 2.4 GHz or 5.8 GHz bands. While these approaches are simple to implement, they are constrained by limited transmit power and interference in unlicensed spectrum, which typically restricts effective communication to line-of-sight range, significantly limiting their application in BVLOS management, logistics, and other scenarios. This is why cellular connectivity has emerged as a key enabler for UAVs. According to Dataintelo statistics (Cellular Connected Drone Market Report, 2025 edition), the global cellular-connected UAV-related market was approximately USD 7.4 billion in 2025, and is expected to grow to approximately USD 28.6 billion by 2034, with a CAGR of approximately 16.2%. Among them, the 5G connectivity segment has a CAGR of 24.7%, and is expected to account for over 61% by 2034. UAVs have already been deployed in areas such as agricultural services, medical emergency, low-altitude firefighting and logistics, with early-stage commercial trials already underway in urban air mobility and aerial sightseeing. The core characteristics of low-altitude communication are "high uplink throughput + low-latency control", which means services are predominantly uplink data transmission, while imposing stringent requirements on low latency and high reliability of the control link. These requirements vary significantly across scenarios and fall into two main categories, as described below:

- **Flight control services:** These involve flight control commands, requiring stable QoS guarantee and high security assurance, with a data rate of 100 kbps, latency of 100 ms, and metre and sub-metre levels positioning accuracy. This places requirements on low latency, high reliability, and security encryption capabilities of communication terminals/modules.
- **Video and data transmission services:** These cover the transmission of data, images, video, and other service information, with rate requirements up to 25 Mbps (for 4K and above video transmission) and beyond, imposing requirements on the uplink data rate and concurrent service processing capability of communication terminals/modules.

The application scenarios for UAVs can be divided into seven major categories:

UAV-based Management

UAV-based management covers urban and suburban scenarios, including infrastructure management, environmental monitoring, traffic management. Flight altitude is currently mainly below 120 metres, with some scenarios potentially extending to 300 metres. For this scenario, communication and navigation requirements are relatively strong. In terms of information

transmission, UAVs need to send telemetry flight control status information and video streams to the control platform during operations. In terms of flight operations, UAVs are required to have RTK high-precision positioning capability, requiring sub-metre positioning accuracy during take-off and landing phases, and metre-level positioning accuracy during operations.

Low-Altitude Agricultural

Low-altitude agricultural services are primarily deployed in suburban scenarios, with flight altitude currently mainly below 120 metres. Equipped with crop protection sprayers, spectral detectors, and other payloads, UAVs carry out operations to enable precise and large-scale agricultural management. For this scenario, communication and navigation requirements are relatively strong. In terms of information transmission, agricultural UAVs and other real-time operational equipment need to receive control commands in a timely manner, and UAVs need to transmit flight control information to the control platform during operations. In terms of flight operations, UAVs are equipped with RTK high-precision positioning capability, requiring sub-metre high-precision positioning during take-off and landing phases, and metre-level positioning accuracy during operations.

Medical Emergency

Medical emergency involves both urban and suburban areas. Using helicopters, UAVs and other low-altitude aircraft, with flight altitude generally below 120 metres, emergency responders can quickly bypass ground obstacles to reach the scene. For medical emergency scenarios, communication and navigation requirements are relatively strong. During flight, UAVs send telemetry flight control data and video to the control platform. UAVs rely on RTK and vision systems to achieve precise positioning during flight and take-off/landing phases, requiring sub-metre high-precision positioning during take-off and landing, and metre-level positioning accuracy during operations.

Low-Altitude Firefighting

Low-altitude firefighting takes place in both urban and suburban areas, with flight altitude currently mainly below 120 metres. Firefighting helicopters, UAVs, and other aircraft enable responders to arrive quickly on the scenes, improving response efficiency and rescue outcomes. This scenario demands communication and navigation capabilities. During flight, UAVs transmit telemetry flight control data and real-time video back to the control platform. For flight operations, UAVs leverage RTK and vision systems to achieve precise positioning, requiring sub-metre high-precision positioning during take-off and landing, and metre-level positioning accuracy in regular operations.

Low-Altitude Logistics

Low-altitude logistics involves both urban and suburban areas, leveraging UAVs, cargo eVTOL, helicopters, and other vehicles to establish air supply channels, enabling UAV-based food delivery, supply for river vessels, and cross-sea fresh food delivery, significantly saving deliver costs and time. For low-altitude logistics scenarios, communication and navigation requirements are relatively strong. In terms of information transmission, UAVs maintain two types of

communication: data transmission and video transmission. In terms of flight operation accuracy, to ensure precise route navigation, UAVs are required to have metre-level positioning and navigation accuracy when flying in complex urban scenarios (such as areas with dense high-rise buildings).

Low-Altitude Passenger Transport

Low-altitude Passenger Transport involves both urban and suburban areas, covering manned transportation, urban air taxis, and other fixed and non-fixed route transport services. For Passenger Transport scenarios, communication and navigation requirements are relatively strong. In terms of information transmission, eVTOL terminals have communication requirements including flight control data transmission with ground platforms and real-time interactive video transmission. For passengers, the information transmission requirements are similar to those for ground consumer services, covering real-time video interaction with ground platforms as well as onboard communication and entertainment services. These typically require uplink and downlink data rates of approximately 10 Mbps, with room for future growth. In terms of flight operation accuracy, sub-metre high-precision positioning is required during take-off and landing phases, and metre-level positioning accuracy is required during operations.

Aerial Sightseeing

Aerial sightseeing involves both urban and suburban areas, utilizing UAVs, eVTOL, and other low-altitude aircraft to offer bird's-eye views of landscapes, transcending ground-level perspective limitations and effectively enhancing tourists' sightseeing experiences. For aerial sightseeing scenarios, communication and navigation requirements are relatively strong. The service requirement profiles for aerial sightseeing are similar to those of the passenger transport scenario. As these applications further mature, future communication requirements will further expand, and uplink and downlink data rates for video transmission are expected to continue to grow.

4 Ecosystem

4.1 Cellular-Connected UAVs

Over the past decade, the global UAV market has experienced exponential growth, with two mature product segments, consumer- and industry-grade, having taken shape. UAVs have been deployed in applications such as agricultural services, power line management, geospatial mapping, low-altitude logistics, photography and entertainment, with growth across multiple regional markets. According to iiMedia Research (data.iimedia.cn), the global commercial UAV market reached USD 42.85 billion in 2025, with the Asia-Pacific region ranking first at USD 17.89 billion, closely followed by North America at USD 11.82 billion. The Asia-Pacific and North America are the dominant markets for commercial UAVs, accounting for 69.33% of the global total. Europe ranked third, with a market size of USD 9.86 billion, while the Middle East & Africa, Oceania, and South America had relatively smaller market sizes, as shown in Figure 4-1. Driven by technological

advancements and expanding applications, the global commercial UAV market is expected to continue growing in the coming years.

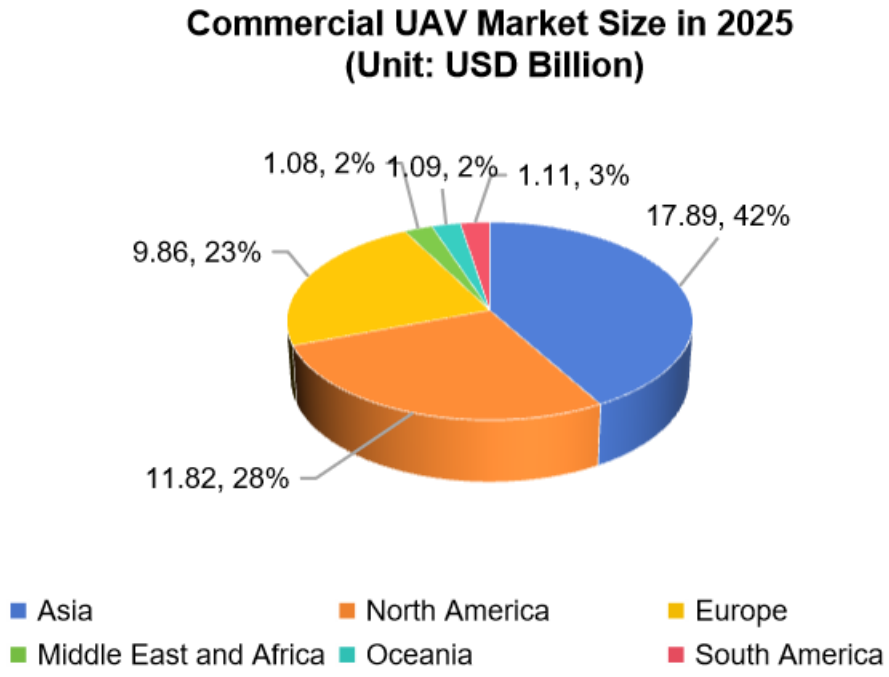

Figure4-1 2025 Commercial UAV Market Size (in USD Billion)

- **Consumer-Grade UAVs**

Consumer-grade UAVs are primarily used for aerial photography and recreational purposes, with DJI being the representative player. Characterized by compact size, ease of use, and affordable pricing, these devices are widely used in personal photography, travel vlogging, family entertainment, and other scenarios, democratizing aerial content creation for consumers. Market penetration is steadily increasing. Consumer-grade UAVs account for approximately 58% of the civil UAV market, with annual shipments exceeding 5 million units and weights ranging from 249 grams to 2 kg, which aligns with regulatory requirements across more than 60 countries and regions. North America accounts for close to 35% of consumer UAV demand, with over 1.7 million registered hobbyist UAVs. Battery capacities typically range from 2,000 mAh to 5,000 mAh, offering up to 30 minutes of flight time per charge; camera resolution typically reaches 4K at 30 fps. Industry insights indicate that over 65% of recreational users employ UAVs for aerial photography, which remains a key growth driver for the civil UAV market.

- **Industry-Grade UAVs**

Industry-grade UAVs address the digitalization needs of verticals, with a focus on high reliability, long endurance, and high payload capacity. These devices have been deployed in areas such as agricultural services, management and mapping, emergency rescue, logistics and transportation. As demand from various industries for UAVs continues to grow, application scenarios are becoming more diverse and sophisticated. These applications range from replacing humans in high-risk tasks to overcoming geographical constraints, tackling critical industry challenges and fundamentally reshaping workflows and productivity. UAVs have become a core tool for improving efficiency, reducing operational risks, and cutting costs across industries, with significant room for

market expansion. Industry-grade UAVs account for approximately 42% of the civil UAV market, with over 3.8 million units deployed worldwide for industrial and enterprise missions. Maximum take-off weight often exceeds 5 kg, with payload capacities ranging from 2 kg to 10 kg. The Asia-Pacific region accounts for about 39% of industry-grade UAV installations, driven by over 500 million hectares of agricultural land requiring aerial monitoring. Flight endurance reaches 55 minutes, and advanced models have a range of over 10 km. Industry forecasts identify more than 300,000 licensed commercial operators worldwide, pointing to growing opportunities in management, mapping, and logistics.

There are two approaches for UAVs to support cellular connectivity: built-in, which uses communication modules, and aftermarket add-on, which uses communication terminals for UAVs. Given the current state of cellular network deployment, UAVs can choose solutions that best fit their application scenarios and cost requirements.

4.2 Communication Modules for UAVs

Industry-grade UAVs currently integrating 4G modules directly into the motherboard, with deep integration across flight contro, navigation, and operational identification system. This approach offers advantages such as high integration, good stability, and strong anti-interference capability, meeting the stringent reliability requirements of industrial applications.

Given the development of 5G/5G-A low-altitude network, UAV connectivity solutions are being built around a combination of 5G eMBB and RedCap. 5G eMBB is positioned for high-performance communications, while 5G RedCap targets cost-effective communications. The two are complementary, together driving 5G modules from being "optional add-ons" to factory-installed standard features, thereby accelerating the adoption of cellular-connected UAVs.

5G eMBB, based on 3GPP Release 15/16 standards, focuses on premium communication capabilities of large bandwidth, low latency and high reliability, supporting 4K/8K ultra-HD video transmission, remote precision control and other high-bandwidth, low-latency services. 5G RedCap, based on 3GPP Release 17 standards, is a lightweight 5G technology customized for medium-to-high data rate IoT scenarios, with lower module costs, capable of 1080p HD video transmission and basic flight control, offering significant cost advantages.

Both 5G eMBB and RedCap are well-supported by a rich portfolio of communication module products readily available for integration into cellular-connected UAVs, giving manufacturers the flexibility to choose the right solution based on their application scenarios and cost considerations. Leading module vendors, including Quectel, Fibocom, China Mobile, Telit, and Semtech (Sierra Wireless), offer comprehensive eMBB and RedCap product lines. For details, refer to Table 4-1.

Table 4-1 Some of the eMBB and RedCap Module Products

Technology	Module vendor	Chip platform
eMBB	Quectel	Qualcomm: X55, X65, X62, X75, X72; UNISOC: V510, V610, V620
	Fibocom	Qualcomm: X55, X65, X62, X75, X72
	Telit	Qualcomm: X62, X72, X82, X85

	Semtech (Sierra Wireless)	Qualcomm: X55, X62, X65
	TD-Tech	HiSilicon: Balong 5910
	China Mobile	HiSilicon: Balong 5910; UNISOC: V510
	MeiG	Qualcomm: X62
	Tozed Kangwei	UNISOC: V620
RedCap	Quectel	UNISOC: V517/V527; ASR: ASR1903; Qualcomm: X35
	Fibocom	UNISOC: V527; MediaTek: T300; Qualcomm: X35
	Telit	Qualcomm: X35
	Semtech (Sierra Wireless)	Qualcomm: X35
	China Mobile IoT	HiSilicon: Balong 5612; ASR: ASR1903; UNISOC: V527; XinSheng: CM9610
	TD-Tech	HiSilicon: Balong 5612
	Lierda	HiSilicon: Balong 5612
	MeiG	Qualcomm: X35
	Tozed Kangwei	HiSilicon: Balong 5612
	Neoway	HiSilicon: Balong 5612

4.3 Communication Terminals for UAVs

Communication terminals for UAVs refer to onboard communication terminals installed on UAVs (mainly for post-installation). Consumer-grade UAVs or third-party platform manufacturers typically adopt this solution to provide cellular connectivity for UAVs to transmit flight control and payload data. Current typical cellular-connected terminals include the following:

- DJI Cellular / Enhanced Video Transmission Series

Take DJI's consumer-grade UAVs as an example. The company offers a 4G module as a standalone accessory that users can purchase and connect to the UAV via the USB-C port. This enables BVLOS flight and remote video transmission, as shown in Figure 4-2.

Figure 4-2 DJI Cellular-Connected Terminal

DJI has currently launched three generations of cellular-connected post-installation products, featuring dual RF units, dual eSIM (no physical SIM card slot), and supporting dual-SIM dual-active,

though still operating over 4G networks.

- **China Mobile Hubble-1 Series**

Hubble-1 is a 5G-connected UAV onboard communication terminal developed by China Mobile. It has formed a comprehensive product portfolio, including general-purpose, pre-installed, smart, and RedCap versions. Featuring a lightweight and compact design, it supports 5G eMBB/5G RedCap (while also compatible with 4G) and offers a rich set of physical interfaces.

Operating within a "cloud-network-terminal" collaborative framework, Hubble-1 enables real-time exchange of flight control and image data with the cloud platform over 5G networks, achieving uplink data transmission and downlink mission dispatch, thereby enhancing flight control as well as data analysis and processing.

Hubble-1 has been adapted to 50 manufacturers and over 200 UAV models, and has been deployed across China as well as in overseas markets.

- **Others**

Elsight Halo is a multi-link aggregation communication platform developed by the Israeli company Elsight. It can aggregate up to four cellular links (each with an independent SIM from different operators), along with satellite links and point-to-point links, into a unified heterogeneous connectivity solution. Through real-time link quality monitoring and seamless traffic switching, it delivers highly reliable connectivity, providing redundant communication assurance for applications such as critical infrastructure management and logistics.

5 Communication Requirements

5.1 Software Requirements

5.1.1 Basic Communication Requirements

Low-altitude UAV flight activities are trending toward BVLOS operations, high-frequency missions and large traffic volumes. As such, wide-area and stable cellular connectivity has become the foundation for ensuring high-reliability flight and large bandwidth video transmission of UAVs.

1. To address the diverse requirements of low-altitude service scenarios, 5G eMBB delivers high-performance communication, while 5G RedCap offers a lightweight, low-cost alternative. Together, these two technologies can help satisfy the communication needs of different market segments for cellular-connected UAVs.

5G eMBB can provide large bandwidth and high data rates, with uplink peak data rate exceeding 100 Mbps on major frequency bands, sufficient for 4K and higher ultra-high-definition (UHD) video transmission. However, eMBB module comes at a higher cost. In contrast, 5G RedCap is a lightweight 5G technology that can effectively support UAV flight control and 1080P video transmission at a comparatively lower module cost. Following a tiered strategy, 5G eMBB would

be recommended for cellular-connected UAVs with high-performance requirements, while 5G RedCap would be a cost-effective choice for lightweight and low-cost requirements. In areas where 5G SA is not yet supported, 4G LTE could serve as a pragmatic fallback.

2. To address low-altitude coverage gaps, the multi-mode and multi-band capabilities of low-altitude terminals/modules can improve the communication reliability of UAVs. Dual-SIM dual-standby (DSDS), dual-SIM dual-active (DSDA), and multi-link convergence help provide more cost-effective low-altitude communication solutions for cellular-connected UAVs.

Existing 4G and 5G networks are primarily designed for ground mobile communications. Today's Low-altitude coverage is mainly provided by the side-lobe radiation of existing base stations, with coverage heights typically limited to around 100 meters. Going forward, to address low-altitude coverage, operators can operators can build upon the inherent advantages of 5G—wide coverage, large capacity, and high reliability—to provide solid support for low-altitude communications. Considering the current network coverage status and future deployment plans, and to enhance the communication reliability of cellular-connected UAVs, low-altitude cellular-connected terminals/modules should be designed to support both 4G and 5G dual-mode operation. In terms of frequency bands, given that UAVs take off from the ground and operate in complex low-altitude cellular environments, band selection should be aligned with coverage conditions in the target operational areas. For the Asia-Pacific market, bands such as n1, n3, n5, n7, n8, n20, n28, n38, n40, n41, n77, n78, and n79 are recommended. From a global perspective, the following band portfolio is suggested: 5G n1, n2, n3, n5, n7, n8, n12, n13, n14, n18, n20, n25, n26, n28, n29, n30, n38, n39, n40, n41, n48, n66, n70, n71, n75, n76, n77, n78, n79.

Low-altitude cellular-connected terminals/modules are also expected to support DSDS (Dual-SIM Dual-Standby) and DSDA (Dual-SIM Dual-Active) capabilities:

- DSDS allows two SIM cards to remain in standby mode simultaneously, allowing concurrent camping on either the 4G and 5G networks of the same operator or on networks of two different operators.
- DSDA enables both SIM cards to conduct data communication concurrently.

This approach would replace the conventional dual module design with a single module, significantly saving internal space and reducing overall equipment cost, thereby enhancing the commercial viability of cellular-connected UAVs.

Furthermore, low-altitude cellular-connected terminals/modules are recommended to support multi-link converged communication, including multi-SIM convergence within cellular networks, as well as intelligent convergence across cellular networks, point-to-point links and private networks deployed by UAV operators. This would ensure highly reliable communication assurance for low-altitude cellular-connected UAVs.

5.1.2 UAV Specific Communication Requirements

To address the challenges in low-altitude communication scenarios, including strong air-to-ground interference, high costs of network optimization, and difficulties in service assurance, 3GPP Releases 16-19 have introduced enhanced communication features for cellular-connected UAVs.

These features improve terminal communication performance through mobility management optimized based on altitude and air-oriented beamforming; facilitate low-altitude network optimization through Minimization of Drive Tests (MDT) integrated with three-dimensional coordinates; and enable efficient service assurance through precise time-based trajectory reporting. The details are as follows:

1. Based on terminal reporting of aerial UE parameters, the base station can identify aerial UEs and their capabilities, thereby enabling differentiated services and assurance for UAV operations.

- **Aerial UE Parameters (R18)**

Aerial UEs report the AerialParameters-r18 field via UE-NR-Capability. The specific parameters are shown in Table 5-1. The base station can use this field to identify Aerial UEs and their corresponding capabilities, thus achieving differentiated services and assurance for UAVs.

Table5-1 Aerial UE Parameters

Parameters	Definitions for parameters
aerialUE-Capability-r18	Indicates whether the UE supports aerial UE communication.
altitudeMeas-r18	Indicates whether the UE supports altitude based measurement reporting. It is mandatory if the UE supports aerialUE-Capability-r18.
altitudeBasedSSB-ToMeasure-r18	Indicates whether the UE supports altitude based ssb-ToMeasure.
condEventAxHy-r19	Indicates whether the UE supports condEvents A3H1, A3H2, A5H1, and A5H2. A UE supporting this feature shall also indicate support of eventAxHy-r18.
eventAxHy-r18	Indicates whether the UE supports events A3H1, A3H2, A4H1, A4H2, A5H1, and A5H2. If the UE indicates support of eventAxHy-r18, then the UE additionally supports multipleCellsMeasExtension-r18 for eventA3H1, eventA3H2, eventA4H1, eventA4H2, eventA5H1, and eventA5H2.
flightPathReporting-r18	Indicates whether the UE supports reporting of the flight path plan through the procedure.
flightPathAvailabilityIndicationUAI-r18	Indicates whether the UE supports indication of the flight path availability through the UAI message. If a UE supports this capability, the UE shall also support flightPathReporting-r18.
multipleCellsMeasExtension-r18	Indicates whether the UE supports measurement reporting triggered based on a number of cells for eventA3, eventA4, and eventA5. It is mandatory if the UE supports aerialUE-Capability-r18.
nr-NS-PmaxListAerial-r18	Indicates whether the UE supports the mechanisms defined for cells broadcasting nr-NS-PmaxListAerial and frequencyBandListAerial. It is mandatory if the UE supports aerialUE-Capability-r18.

Parameters	Definitions for parameters
simulMultiTriggerSingleMeasReport-r18	Indicates whether the UE supports, for all the events of the same type for which the measurement reporting was triggered, measurement reporting considering only the configuration of the event with the smallest value between the altitude of the UE and the corresponding altitude threshold.

2. Altitude-based beam configuration and measurement reporting enable precise matching between low-altitude beams and UAV flight airspace, improving mobility.

- **Event AxHy (R18)**

3GPP R18 defines independent measurement events triggered by altitude (event H1, event H2) and combined events triggered jointly by altitude and signal quality (RSRP, SINR) (event AxHy). The specific meanings are as shown in Table 5-2. The terminal performs measurement reporting according to the measurement events configured by the base station, thereby improving mobility performance.

Table5-2 Aerial UE Parameters

Parameters	Definitions for parameters
event H1	The Aerial UE altitude becomes higher than a threshold
event H2	The Aerial UE altitude becomes lower than a threshold
event A3H1	Neighbour becomes offset better than SpCell and the Aerial UE altitude becomes higher than a threshold
event A3H2	Neighbour becomes offset better than SpCell and the Aerial UE altitude becomes lower than a threshold
event A4H1	Neighbour becomes better than threshold1 and the Aerial UE altitude becomes higher than a threshold2
event A4H2	Neighbour becomes better than threshold1 and the Aerial UE altitude becomes lower than a threshold2
event A5H1	SpCell becomes worse than threshold1 and neighbour becomes better than threshold2 and the Aerial UE altitude becomes higher than a threshold3
event A5H2	SpCell becomes worse than threshold1 and neighbour becomes better than threshold2 and the Aerial UE altitude becomes lower than a threshold3

- **Altitude-based beam measurement(R18)**

To meet the differentiated service requirements of aerial UEs, the base station can pre-configure a set of low-altitude SSB beam groups bound to different altitude ranges for the UAV UE as shown in Figure 5-1. The terminal selects the corresponding low-altitude SSB beam to measure according to its current flight altitude. This effectively improves the accuracy and validity of signal measurements, reduces the UE's measurement complexity and power consumption, and thereby ensures service continuity for UAVs in three-dimensional space.

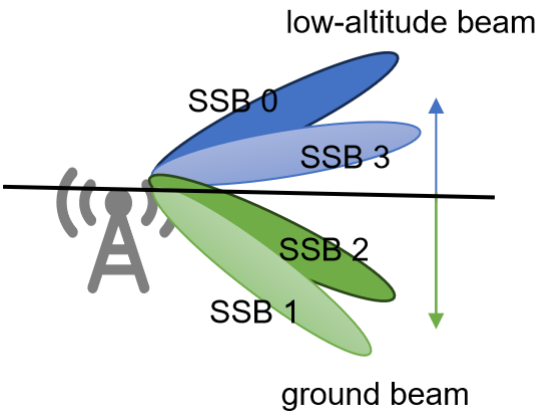

Figure 5-1 altitudeBasedSSB-ToMeasure configuration

- **condEventAxHy(R19)**

For scenarios where channels change rapidly due to high-speed UAV flight, 3GPP R19 introduces a combined conditional event (condEventAxHy) triggered jointly by altitude and signal quality (RSRP, SINR). The terminal performs measurements and reporting according to the conditional measurement events configured by the base station, which enables altitude-based conditional handover (CHO) to improve mobility performance.

- **Altitude based measurement in IDLE/INACTIVE（R19）**

To satisfy differentiated service requirements of low-altitude UAV UEs, the base station configures a set of SSB beam sets associated with grouped by altitude ranges for UAV UEs, via SIB2 and SIB4. The UE measures the corresponding SSB beams based on its current flight altitude, thereby achieving altitude-based cell reselection and enabling better selection of suitable neighboring cells.

3. Minimization of Drive Tests (MDT) reporting based on terminal 3D position coordinates helps facilitate low-altitude network optimization.

- **MDT&CommonLocationInfo (R16)**

To optimize low-altitude networks effectively, the terminal includes its location information (including latitude, longitude, and altitude) and velocity information in MDT reports, as configured by the base station. This allows the network to accurately obtain real-time motion status and network quality of UAVs, supporting low-altitude network optimization.

4. Precise time-based trajectory information reporting enable efficient service assurance for UAVs.

- **Flight Path Information Reporting (R18)**

To address service assurance challenges for UAVs during inter-cell movement, the UE reports timestamp-based trajectory information. After obtaining the UAV flight path plan, the base station can reserve resources for the UAV through inter-base station coordination, thereby providing efficient service assurance.

5. Configuring low-altitude frequency priorities to guide UAVs toward high-quality bands, thereby improving communication service quality during flights.

- **UAV prioritized frequency for cell reselection(R19)**

The base station broadcasts frequency priority and UAV terminals will preferentially camp on high-quality low-altitude frequency bands during cell reselection. This enables differentiated configuration from terrestrial frequency bands and improves communication service quality.

6. Configuring MBS broadcast for remoteID Reception to enhance UAV's obstacle avoidance capability during flights.

- **MBS broadcast Configuration for RemoteID Messages (R18)**

The mobile communication system broadcasts RemoteID messages reported by all UAVs within the coverage area in real time via MBS. UAV users can thereby acquire second-level location and velocity data of surrounding UAVs, significantly boosting obstacle avoidance performance during UAV flights.

7. Secondary authentication with UAV ID to support UAV identity-based authentication and management.

- **UUAA-MM&UUAA-SM（R17）**

By supporting UUAA (USS UAV Authorization/Authentication) during the 5G registration procedure (UUAA-MM) and during PDU session establishment (UUAA-SM), the network can perform secondary authentication of the terminal based on its UAV identity, providing an end-to-end secure and trusted anchor for UAV management.

5.2 Hardware Requirements

5.2.1 Hardware Interface Requirements for Modules

For pre-installed cellular-connected UAV applications, unified interface requirements for low-altitude cellular-connected modules, covering form factor and electrical interface requirements, are needed to ensure efficient and reliable compatibility between UAVs and modules from different vendors. This will reduce integration complexity, enhance the compatibility and reliability of low-altitude cellular-connected UAV systems, and help accelerate the scaled development of the pre-installed cellular-connected UAV industry.

5.2.1.1 Form Factor Requirements

The form factors of low-altitude cellular-connected modules mainly include LCC+LGA/LGA, M.2, Mini PCIe, and BTB. Details of each are specified as follows.

- LCC+LGA/LGA

For LCC form factor, pads are only arranged on the four side edges and bottom periphery of the module, forming a stamp-hole package. The central area of the bottom surface has no pads, nor are there any exposed pins.

For LGA form factor, the entire bottom surface is populated with matrix-arranged planar metal pads, with no edge terminals, pins, or solder balls, as shown in Figure 5-2.

For LCC+LGA form factor, it is a hybrid surface-mount form factor that combines the stamp-hole package of LCC with the matrix pads on the bottom surface of LGA, as shown in Figure 5-3.

LCC+LGA/LGA form factors offer high soldering reliability, making them well suited for the high-reliability requirements of low-altitude cellular-connected UAV applications. For eMBB modules, the recommended module dimension shall not exceed 52 mm × 52 mm; for RedCap modules, the recommended module dimension shall not exceed 29 mm × 32 mm.

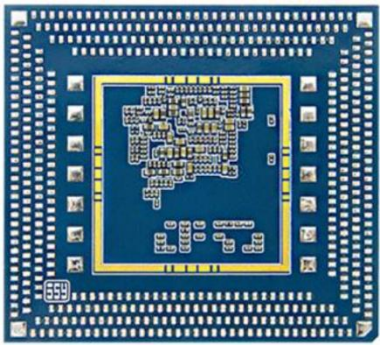

Figure 5-2 Example of LGA form factor

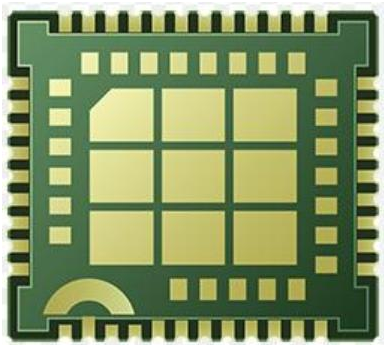

Figure 5-3 Example of LGA+LCC form factor

- M.2

M.2 (formerly known as NGFF, Next Generation Form Factor) is a compact, high-speed interface standard, as shown in Figure 5-4. With its small size, high throughpu and protocol flexibility, it has become a mainstream interface standard. Its advantages include standardized hardware interfaces and dimensions, as well as convenient plug-and-play operation. On the downside, M.2 modules are installed as plug-in cards, which means reinforcement measures are required in UAV flight scenarios to ensure operational reliability.

Figure 5-4 Example of M.2 form factor

- Mini PCIe

Mini PCIe features a plug-in card design with a standard width of 30 mm, dual-screw fixation, and support for both PCIe and USB protocols, as shown in Figure 5-5. Its vibration resistance is

significantly better than that of M.2, making it suitable for high-vibration environments. However, its larger size makes it less competitive than M.2 in the consumer sector.

Figure 5-5 Example of Mini PCIe form factor

For RedCap modules, the dimensions are recommended not to exceed 30 mm × 51 mm, with a single-sided thickness of no more than 3.6 mm and a double-sided thickness of no more than 4.9 mm.

- BTB

BTB (Board-to-Board) is a connector solution that directly connects two printed circuit boards (PCBs). Its advantages include modularity, ease of production, good vibration resistance, and compact size, making it well suited for space-constrained electronic products such as smartphones, wearable devices and consumer drones. Its disadvantages are that it is not intended for frequent plugging and unplugging and has a relatively high cost.

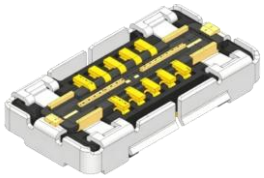

Figure 5-6 Example of BTB interface form factor

For RedCap modules, the recommended BTB package dimensions are 28 mm × 24 mm maximum, with a maximum double-sided thickness of 4 mm. The corresponding BTB connector interface should be no larger than 6.6 mm × 2 mm.

5.2.1.2 Electrical Interface Requirements

- Power Supply Interface

To ensure unified power supply requirements to cellular-connected UAV module, the power interface shall be standardized and support a DC power interface. The data I/O voltage levels shall support Class A voltage (2.8 V to 3.0 V) and Class B voltage (1.8 V).

- Control and Status Interface

To enable control and management requirements of the modules by cellular-connected UAVs, the module shall support a power switch and status indication interface and a module reset interface, and may optionally provide a control interface.

- SIM Card Interface

To ensure service continuity for cellular-connected UAVs during flight, support for a dual SIM card interface (i.e., providing DSDS or DSDA capability) is recommended.

- Data I/O Interface

To support service requirements such as high-speed video transmission for cellular-connected UAVs, high-speed data interfaces shall be supported. A USB interface is recommended, and shall be no lower than USB 2.0 (with a data transfer rate of 480 Mbps).

- WLAN Interface

To meet the reliability requirements of communication links for cellular-connected UAVs, and in line with the multi-link convergence approach (which enables the integration of multiple technologies such as cellular and Wi-Fi to safeguard services), WLAN capability can be extended through an external interface (e.g., SDIO).

- Positioning Interface

To better support the altitude-based R18 UAV features and improve the communication performance of cellular-connected UAV terminals, an interface with a positioning module may be optionally supported.

5.2.2 Hardware Interface Requirements for Terminals

As an airborne communication device integrated into the UAV platform, the hardware interface design of the low-altitude cellular-connected terminals must account for multiple factors, including power supply adaptation, flight control data exchange, payload data transmission and environmental reliability. The hardware interface requirements are as follows:

- Power Interface

The cellular-connected terminal draws power from the UAV platform. The power interface shall support a wide voltage input range to accommodate the power supply specifications of different UAVs. A DC input range of 9 V to 36 V is recommended, and the interface shall feature reverse polarity protection, overvoltage protection, and surge suppression. The power interface shall use anti-loosening and vibration-resistant connectors; connectors such as XT30 or Type-C are recommended. The overall power consumption of the terminal shall not exceed the rated power supply capacity of the UAV platform.

- Human-Machine Interface

The human-machine interface includes indicators for cellular network status, power status, and terminal operating status, as well as a Subscriber Identity Module (SIM) card interface. The use of nano-SIM or eSIM is recommended.

- Antenna Interface

The antenna interfaces of the terminal include those for cellular communication and wireless short-range communication. Connector types may include SMA (SubMiniature version A), MMCX (Micro-Miniature Coaxial), IPEX, etc. Built-in antennas are recommended.

- Flight Control Data Interface

The cellular-connected terminal shall support one or more of the following: a TTL serial port (with a configurable baud rate from 9600 to 921600 bps, for open-source and commercial flight controllers) and an RS232 serial port (for industrial-grade flight controllers), and shall support multi-vendor flight control protocol adaptation and conversion. The flight control data interface shall use anti-loosening and vibration-resistant connectors.

- Payload Data Interface

The cellular-connected terminal shall support an Ethernet interface (e.g., RJ45, for high-bandwidth video payloads) as well as USB 2.0 or higher. The payload data interface shall use anti-loosening and vibration-resistant connectors.

- Device Management and Debugging Interface

The terminal shall support local configuration management (e.g., via Wi-Fi/Ethernet) and remote upgrade capability. If Wi-Fi is used as the configuration interface, the Wi-Fi hotspot shall automatically enter sleep mode when there is no connection or when the UAVs takes off to reduce power consumption and interference.

- Physical and Mounting Interface

The terminal shall be equipped with standardized mounting hardware and interfaces to secure it onto the UAV platform. It is recommended that the antenna be mounted externally on the airframe in an unobstructed location.

6 Standardization

6.1 3GPP

3GPP has developed a clear evolution path for cellular-connected UAVs from LTE to 5G-Advanced. Release 15 was the first to introduce aerial UAV enhancements on the LTE side, covering aerial UE identification and authorization, altitude reporting, interference detection triggered by multi-cell measurements, PUSCH power control enhancement and flight path information reporting. Release 16 further defined the UAS service requirements framework, addressing service requirements for remote identification, tracking, security, public safety and C2 communication. Release 17 refined the system architecture for UAS connection, identification and tracking. Release 18 extended 5G-A support for UAVs, with emphasis on altitude-based measurement reporting, multi-cell measurement reporting, altitude-based beam configuration and flight path information reporting. Release 19 further enhances UAV mobility and service assurance capabilities, including altitude-based SSB measurement configuration in RRC_IDLE/RRC_INACTIVE states, altitude-assisted conditional handover, and UAV-prioritized frequency cell reselection.

6.2 ITU

The International Telecommunication Union(ITU) provides international standards for low-altitude UAV communication services, spectrum usage and UAV applications. Currently, low-altitude standardization efforts are distributed across several ITU Study Groups(SG) as follows:

- SG 21 focuses on multimedia, content delivery and cable television technologies,covering reference frameworks, requirements and service use cases for scenarios such as UAV-based emergency communications and logistics, as well as UAV flights enhanced by edge computing, machine vision, virtual reality and artificial intelligence.
- SG20 focuses on the Internet of Things, digital twins and smart city applications, addressing IoT-based UAV systems, low-altitude sensing systems, functional frameworks for UAV systems over IMT-2020 networks, along with reference frameworks, requirements and service use cases for applications including low-altitude UAV Management, firefighting, agriculture, medical delivery and shared services.
- SG17 focuses on security capabilities, covering UAV identification, security aspects of integrated sensing and communication(ISAC), and telecom security reference architectures and requirements for urban air mobility(UAM) environments.
- SG13 focuses on future network capabilities, addressing reference frameworks and requirements for ISAC over IMT-2020 networks.
- In addition, SG2, SG5 and SG11 are also conducting related work in telecommunication infrastructure operation and maintenance, electromagnetic compatibility, and signaling protocols, respectively.

6.3 GSMA

GSMA (Global System for Mobile Communications Association) published the LTE Aerial Profile (NG.128) in November 2021, defining a minimum mandatory set of 3GPP features required for interoperable LTE aerial services. The GSMA TSG (Terminal Steering Group) is now developing communication requirements for 5G-connected UAV terminals based on diverse application scenarios, aiming to ensure communication performance and service experience for UAVs in complex low-altitude environments and accelerate the ecosystem maturity and scaled development of cellular-connected UAVs.

7 Conclusions

At a time of rapid growth in the low-altitude economy, this white paper surveys global trends and market demand in cellular-connected UAVs, examining ecosystem development, key technologies and standardization progress, while offering a holistic view of the strategic direction of the low-altitude industry. On the technology side, stakeholders across the value chain, ranging from chipsets and modules to terminals, networks, platforms, and applications, are pushing

innovation and collaboration to advance the cellular-connected UAV technology ecosystem. Meanwhile, work on standardization is gathering pace, with industry players actively shaping technical standards, capability frameworks and industry guidelines that enhance coordination and cross-domain interoperability. And at the ecosystem level, steady progress in technical validation, pilot projects, and industry practice has boosted both the technical maturity and commercial viability of cellular-connected UAVs, establishing a robust base for the scaled development of the low-altitude industry.

Looking ahead, as 5G-Advanced, 6G and ISAC technologies continue to evolve, cellular networks will further enhance their capabilities to support low-altitude scenarios in terms of connectivity, service assurance and intelligent coordination, providing more solid support for the large-scale development of UAVs. Industry stakeholders should deepen innovation, collaborate on standardization, and foster ecosystem partnerships to build an open, interoperable and globally coordinated low-altitude industry ecosystem, ushering in a new stage of digital and intelligent development for the low-altitude economy.

8 References

[1] 3GPP TS 22.125, Unmanned Aerial System (UAS) Support in 3GPP (Release 16).

[2] 3GPP TS 23.256, Support of Uncrewed Aerial Systems (UAS) connectivity, identification and tracking; Stage 2 (Release 17).

[3] 3GPP TS 29.256, Uncrewed Aerial Systems Network Function (UAS-NF); Aerial Management Services; Stage 3 (Release 17).

[4] 3GPP TS 36.331, Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Resource Control (RRC); Protocol specification (Release 15).

[5] 3GPP TS 38.300, NR and NG-RAN Overall description; Stage-2 (Release 18).

[6] 3GPP TS 38.331, Radio Resource Control (RRC); Protocol specification (Release 18).