engineering proceedings

MDPI

Proceeding Paper

Integrated UAS–Satellite Communications in 6G: An Overview †

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† Presented at the 15th EASN International Conference, Madrid, Spain, 14–17 October 2025.

Abstract

Efficient communication infrastructure is essential for Unmanned Aircraft Systems (UASs) operating beyond visual line of sight (BVLOS). Both terrestrial and non-terrestrial networks struggle with coverage gaps and are susceptible to disruptions. This paper analyzes integrated terrestrial–non-terrestrial network (TN-NTN) architectures for UAS communications in 6G, focusing on three connectivity methods: terrestrial connectivity, indirect satellite connectivity, and direct UAS–satellite links. We provide the assessment of different connectivity options. Major challenges are discussed, including antenna limitations, reliability, channel modeling, and regulatory alignment.

Keywords: UAS; UAV; NTN; 6G; satellite communications

1. Introduction

The rapid expansion of UAS operations across commercial and civilian sectors demands robust communication infrastructure capable of supporting diverse mission requirements. Economic projections indicate substantial growth potential, anticipating nearly 1.5 million UAS operations in Europe by 2029 [1]. Diverse UAS applications range from healthcare delivery (achieving a 11.31% maternal mortality reduction from 2018 to 2020 in Latin American regions [2]) to environmental monitoring. UASs also have the potential to improve air quality: as an example, a Lithuanian startup Thrust and the national technology company Agmis, together with AB Kelių priežiai (Kaunas, Lithuania), are developing an ambitious and innovative project GreenBee. The project seeks a 90% CO_2 emissions cut by using UASs for road inspections over 21,000 km long road [3].

Current terrestrial networks (TNs) are not designed for UASs. In many cases, TNs are optimized for ground users, with antennas tilted downward. This configuration often results in poor to no radio coverage in the airspace, where UASs operate. Alternatively, UASs might detect signals from numerous terrestrial base stations (BSs), which can cause excessive signal interference. TNs also face challenges supporting UASs in rural areas and are prone to large-scale outages (such as the 2025 Iberian Peninsula blackout). Satellite networks can also face disruptions; for instance, Starlink had a two-hour outage on 24 July 2025.

This paper makes several key contributions: (1) based on the state-of-the-art (SOTA) analysis, we provide a systematic comparison of three primary UAS connectivity approaches in an integrated TN-NTN; (2) we discuss trade-offs of these approaches; (3) we identify and categorize key technical challenges in UAS–satellite integration; and (4) we

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Academic Editors: Spiros Pantelakis, Andreas Strohmayer and Gustavo Alonso

Published: 19 May 2026

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examine current regulatory frameworks and their implications for deployment. The remainder of this paper is organized as follows: Section 2 describes the review strategy, Section 3 provides the SOTA in UAS-TN-NTN communications, Section 4 presents the system architecture analysis, Section 5 examines communication requirements, Section 6 discusses challenges and solutions, and Section 7 concludes this paper and presents future directions.

2. Materials and Methods

This work presents current advancements in integrated UAS–satellite communications within the 6G framework through a systematic literature review and industry assessment. A literature review was conducted across multiple databases including IEEE Xplore, Scopus and Google Scholar, covering in total 35 relevant scientific publications. The search strategy employed keyword combinations including: "UAS satellite communications", "UAV NTN", "6G non-terrestrial networks", "UAV BVLOS communications", "integrated TN-NTN". Further, publication selection was refined according to the following criteria: relevance to the intersection of UAS and satellite communications within the context of 6G or NTNs; publication date between 2020 and 2025 to ensure time relevancy; mandatory inclusion of both UAS including unmanned aerial vehicle (UAV) and satellite/NTN elements; and a focus on 6G or advanced 5G-NTN technologies. Eligible publications were required to provide technical content, including architectural design, protocol development, or performance evaluation. Ultimately, 17 publications [4–20] were included in this study. Beyond a scientific literature overview we incorporated information from technical reports from 3GPP, regulatory documents on spectrum framework evolvement [21–23], and white papers from the European Space Agency [24–27], UAS industries [28–31] and European Union Aviation Safety Agency (EASA) [32,33]. Industry case studies were included [1–3], closing the gap between the theoretical research and practical capability. From the selected sources we extracted information related to connectivity architectures, technical specifications (i.e., frequency bands, data rates, etc.), and regulatory and implementation challenges, addressed in the following sections.

3. Technical Background and Recent Developments

3.1. Technical Research in UAS-TN-NTN Integration

Recent research investigates integrated NTN architectures for UASs, focusing on 5G New Radio (NR) technology and its implications for 6G services [4]. In [5], analysis of 6G-enabled UAS traffic management emphasizes the roles of NTN links. UAS–satellite connectivity, especially via low Earth orbit (LEO) satellites, greatly improves coverage in areas without ground networks. The work [6] highlights that intelligent handover optimization further enhances service continuity. Furthermore, UAS–satellite collaboration can be effectively used for Integrated Sensing and Communication (ISAC) applications as presented in [7], where cooperative LEO-UAS imaging systems achieved a 54% improvement in resolution. The paper [8] describes a UAS–satellite architecture designed to integrate localization and communication for continuous positioning and connectivity. The work [9] presents performance analysis across LEO, medium Earth orbit (MEO), and geostationary Earth orbit (GEO) constellations and discusses varying connectivity capabilities for rotary-wing aircraft depending on orbit types and frequency bands. Findings from [10] demonstrate that shifting UAS traffic to NTNs helps reduce both outage rates and uplink interference. Many studies have also concentrated on utilizing LoRaWAN communications for UAS and NTN links [11]. In [12], the authors present a UAS-based LoRa architecture offering low-power Internet of Things (IoT) connectivity in remote areas.

https://doi.org/10.3390/engproc2026133157

3.2. Industry Implementation Progress

Commercial UAS–satellite integration shows practical feasibility, with capabilities depending on the trade-off between the UAS's payload and communication systems. The UAS X10 model from american Skydio, Inc. company located in California, uses 5G and Starlink for BVLOS operations, supporting Wi-Fi (2.4/5 GHz) and cellular (600–4400 MHz) communications. The X2 Dock system is used together with Starlink for Internet access and remote control via satellite [28].

Another example provided by the american company uAvionix (US, Montana) demonstrated megabit-per-second data rates with latency under 100 milliseconds by mounting a Starlink terminal on a UAS for C2 communications [29]. This shows that a medium-sized satellite terminal can fit on a UAS, although it may leave limited space for other mission-critical payloads.

The Technology Partnership Group (TTP Group plc) located in Melbourn, United Kingdom, has developed a compact multi-link terminal that enables UASs to communicate via satellite L-band and LTE networks globally via Viasat's Velaris system. While optimizing for minimal size, weight, power, and cost (SWaP-C) [30], the terminal supports data rates of up to 200 kbps.

3.3. Standardization Evolution

The European Union Aviation Safety Agency (EASA) sets aviation safety standards in Europe, covering aircraft certification, maintenance, and flight operations. The regulation (EU) 2019/945 [32] sets out the technical requirements for the design and manufacture of UASs. Additionally, EASA sets requirements for common interoperable open communication protocols between authorities, service providers and UAS operators, as well as data quality, latency and protection requirements, specified in Regulation (EU) 2021/664 [33].

The European Space Agency (ESA) supports research on High-Altitude Pseudo-Satellites (HAPSs) and airborne platforms via satellite technology projects [34]. ESA has completed several HAPS–satellite initiatives, including HAPSAt [24] and RPAS-HAPS [25], covering feasibility studies and demonstrations. ESA also launched the NTN 5G/6G forum to advance collaborative and commercially driven NTN solutions [26].

In 3GPP Releases 16 [35] and 17 [36], the focus was on integration of UASs and non-terrestrial networks to provide comprehensive drone communications, enabling real-time data sharing, precise tracking, and global coverage. Key developments include 5G NR for satellite integration, UAS flight mode detection, and Service-Based Architecture (SBA) for dynamic network control. 3GPP Release 17 actively addresses UAS enhancements, particularly focusing on UAS application layer architecture and protocols [13].

Spectrum Allocation Evolution and Spectrum Sharing Frameworks

European UAS communications are regulated by the Electronic Communication Committee (ECC) and national agencies. ECC Decision (22)07 [21] establishes harmonized technical conditions for aerial user equipment (UE) communications using LTE and 5G NR technologies across specified frequency bands. In Finland, Traficom oversees radio frequencies to ensure interference-free communications (Regulation 15) [22].

3GPP Release 18 defines a limited range of 5G NTN satellite frequency bands. For NTN FR1 (410–7125 MHz), the main bands are n255 (1.6 GHz) and n256 (2 GHz), which include the L-band and S-band. In the Ka-band for NTN FR2 (17,300–30,000 MHz), three proposed bands have been identified: n510, n511, and n512. Ongoing discussions about future satellite communication frequencies involve existing Ku- and Ka- bands, with efforts moving toward higher frequencies to enhance capacity and performance. Such frequen-

cies include Q-/V-band (40 GHz), W-band (around 80 GHz), D-band (around 100 GHz), and terahertz bands.

The allocation of new frequency bands in the C-band (4.4–4.8 GHz), X-band (7.125–8.4 GHz), and Ku-band (14.8–15.35 GHz) for International Mobile Telecommunications (IMT) will be addressed at the World Radiocommunication Conference in 2027 (WRC'27, Agenda Item 1.7) [23]. This review will focus on expanding IMT services while ensuring the protection of existing users. Also possible new spectrum allocations for Mobile–Satellite Service (MSS) to enable direct connectivity between satellites and IMT user equipment, supplementing terrestrial networks, will be reviewed at WRC'27 (Agenda Item 1.13) [23]. The analysis will cover frequencies from 694/698 MHz up to 2.7 GHz considering spectrum needs, technical and regulatory factors, and how new users can coexist with existing services without causing interference. Especially the satellite downlink direction and interference to terrestrial networks has to be considered.

4. Communication Architecture Analysis

Based on Sections 3.1 and 3.2, we have identified three primary connectivity approaches for UAS operations in the integrated TN-NTN architecture shown in Figure 1:

1. Terrestrial Cellular Connectivity: . an UAS is equipped with onboard cellular antennas connected directly to terrestrial base stations (such as gNB in 5G). In Figure 1, the gNB is connected to a 5G Core Network (5G CN), where an application server may reside for data processing. This approach provides high data rates and low latency in areas with adequate cellular coverage but suffers from coverage limitations in rural areas. The maximum communication range with sufficient link quality to the gNB will depend on the communication frequency and will be less than 1 km for 5G [14]. The reliability of the communication link may be compromised at higher altitudes due to potential interference or diminished signal strength resulting from base station antenna down-tilt [6,15].
2. Indirect Satellite Access via Satellite-Enabled Ground Stations (GSs): an UAS has a direct connection to a ground dock station equipped with satellite backhaul. The satellite terminal is located at the dock station, enabling efficient UAS-to-dock communication with uplink capability. While this type of connectivity can provide a sufficient data rate, a visual line of sight might be needed between the UAS and the dock station to maintain good link quality. When Wi-Fi technology is used for communications between the UAS and the dock station, the maximum range is restricted to a few kilometers. The application server in this case can be located at the gateway (GW) to minimize the communication delay. The dock station can also be connected directly to the terrestrial network if available.
3. Direct UAS–Satellite Communication: an UAS equipped with satellite communication capabilities connects directly to satellite networks. Implementation options include: (1) SWaP-C-optimized satellite terminals, offering limited throughput; (2) Direct-to-Satellite IoT (DtS IoT) for sensor data applications [16]; (3) Direct-to-Cell (D2C) technology using mounted UE. In the case of the DtS IoT option, the satellite must employ an IoT GW onboard. This type of connectivity may support a limited amount of data, from hundreds of kbps to several Mbps.

Technical differences between communication options are presented in Table 1.

https://doi.org/10.3390/engproc2026133157

Table 1. Comparison of different communication options.

Connectivity Type	Communication Frequency	Communication Range	Max Data Rate UL	Coverage	Redundancy	Ref.
Cellular	700–2600 MHz, 3.4–3.8 GHz, 24–28 GHz	640 m @ 3.5 GHz	50 Mbps–1 Gbps	Urban/near-urban	Only terrestrial	[14]
Satellite-Enabled GS	5 GHz	~4 km @ 5 GHz	5–10 Mbps	Near GS	Terrestrial or NTN	[31]
SWaP-C terminal	L-band, LTE bands	from 3 km (LTE) to several hundred km (L-band)	200 Kbps	Global	Terrestrial + NTN	[30]
DtS IoT	Sub-GHz, L-, S- bands	several hundred km	few hundred Kbps	Depending on the constellation size	NTN	[16]
D2C	L-, S- band	several hundred km	several Mbps	Global	Terrestrial + NTN	[37]

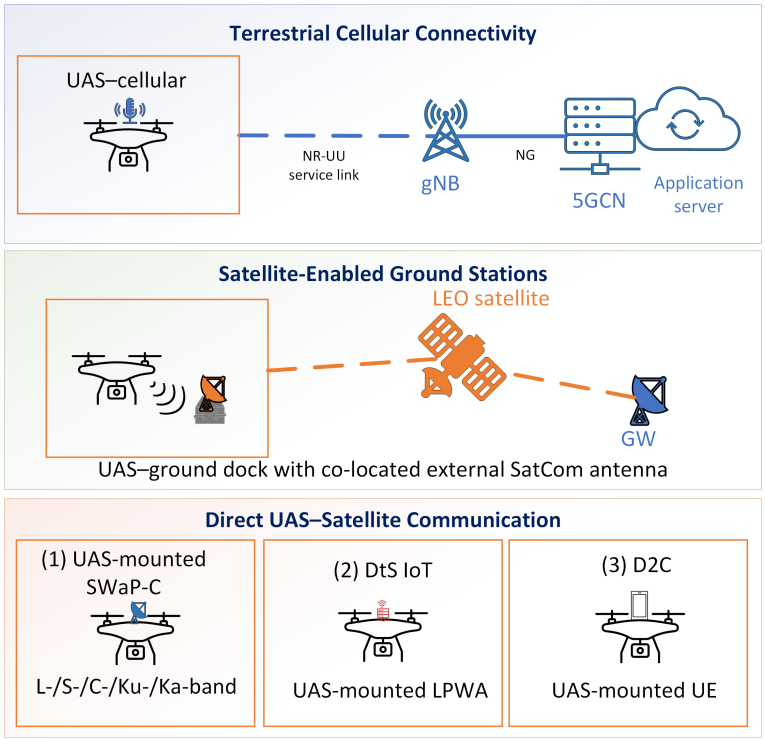


Figure 1. Types of UAS–satellite communication architectures.

5. Communication Requirement Analysis

5.1. Control and Command (C2) Requirements

For airborne devices in unpredictable environments, rapid command transmission is essential. Automated features and collision avoidance depend on timely air traffic updates. Lower latency is achieved in 5G with an improved protocol and the utilization of Edge routing and processing. In 6G it is planned to utilize satellite networks to provide global coverage along with terrestrial networks, which would further improve reliability aspects of a UAS C2 link [27].

The widely adopted MAVLink2 C2 protocol offers a command and telemetry capability that has been thoroughly tested and proven effective. This protocol works seamlessly over standard IP networks, making it suitable for 5G/6G use. Telemetry streams are broadcast to multiple devices without specific recipients. MAVLink2 supports hybrid networking, enabling both broad telemetry distribution and reliable delivery of critical updates, such as

UAS mission parameters from ground stations. Built-in error correction enhances reliability further when combined with 5G/6G error correction. Data rates with this protocol can be adjusted by changing the transmission interval and selecting specific parameters for telemetry exchange between the UAS and the ground station [38]. Usually the data rate is in the range of 57,600 bits/s which makes it possible to also route this traffic through existing GEO satellite constellations, although with higher latency. In a 5G/6G network packets from this protocol could be prioritized in the network using the quality of service (QoS) functionalities resulting in a reliable C2 link regardless of the network load.

5.2. Payload Requirements

Payload communication requirements vary significantly by application [17]. For UAS inspections different payloads are utilized to measure the environment. Camera payloads producing video and pictures are utilized as they give good situational awareness and overall status of the inspected area. For more detailed structure analysis LiDAR and RADAR can be utilized to generate precise measurements of position in the inspection area. Video streaming represents the most demanding real-time requirement, while sensor data (LiDAR and Radar) involves burst transmissions with substantial data volumes but lower frequency requirements. Table 2 summarizes key payload requirements.

Table 2. Examples of UAS payload characteristics.

Payload Function	Description	Encoding	Bandwidth	Reference
Video	1080p24	H.265	3.1 Mbps	[19]
Image	1280 × 1024	12-bit image	984 KB/frame	[39]
LiDAR	2 Mbps, update rate 1 Hz	–	200 MB/picture	[40]
Radar	100 Kbps, update rate 0.4 Hz	–	375 KB/file	[40]

6. Discussion

6.1. Antenna Design Constraints

In UAS applications, antennas are typically designed to direct energy horizontally and downwards for effective ground communication. While traditional dipole antennas are common, microstrip/patch antennas have gained popularity due to their customizable patterns and cost-effectiveness. These antennas offer moderate gain and can be used in satellite communications if sufficient power is supplied [18].

In UAS–satellite communications, high-gain satellite antennas are recommended to mitigate link path loss and atmospheric attenuation. Unlike in the terrestrial links, the antenna must be directed to the sky or track the satellite for optimal performance. While directive microstrip antennas may be sufficient for less demanding links, high-data-rate LEO connections need precise beam tracking, typically achieved with beamforming arrays. Furthermore, UAS movement and tilting caused by navigation and wind require either a wide antenna pattern to tolerate tilting or mechanical/electronic steering towards the satellite. LEO constellations such as Starlink use large phased-array antennas to deliver high data rates which can support applications like video uplink. This dependency on large or complex antennas in high-data-rate links poses challenges for integration with UASs as the antenna's dimensions, mass and placement have restrictions.

6.2. Positioning and Navigation

The Global Navigation Satellite System (GNSS) is a widely used navigation system. It is worth emphasizing that the GNSS signals are vulnerable and provide inaccurate measurement when spoofed or jammed. There is a critical need for a resilient UAS navigation system that not only complements GNSS but can also serve as a backup solution during

GNSS failures, jamming, or spoofing attacks. Post-processed kinematic (PPK) and real-time kinematic (RTK) positioning methods are often used to improve GNSS accuracy, allowing UASs to achieve positioning within a few centimeters. In navigation, another method called geofencing is used to keep UASs out of restricted or no-fly zones. Notably, geofencing heavily relies on GNSS. In cellular networks, UAS navigation could be supported by network positioning to provide resilience against jamming and improve reliability in challenging operating conditions, for example in areas with GNSS jamming.

6.3. Channel Modeling

Most of the existing UAS–satellite studies reported in Section 3.1 are simulation-based with simplified simulation models. UAS mobility leads to rapid channel changes and frequent handovers between ground stations, satellite beams, and satellites. Moreover, UAS design may contribute to additional interference, caused, e.g., by spinning blades in rotary-wing UASs [9]. This must be taken into account when modeling the performance.

6.4. Spectrum Sharing

UAS–satellite systems are moving to higher-frequency bands for increased data rates, but this shift may cause spectrum overlap with terrestrial and other satellite networks. For example, weather satellites use high power and antenna gain for atmospheric monitoring, leading to potential interference with integrated localization and communication. Effective spectrum management, such as non-orthogonal multiple access and cognitive radio, can help address these challenges [8]. Moreover, regulatory measures, such as power thresholds are necessary to prevent interference between operators both domestically and internationally, especially in closely bordered regions like Europe [20].

7. Conclusions and Future Work

This paper reviews recent progress in UAS–satellite communications. While UAS use is increasing, relying only on cellular networks limits operations to urban areas and reduces redundancy during disaster scenarios. Combining satellite and cellular connectivity poses challenges due to limited space for essential equipment at the UAS side. We have identified three main connectivity methods, each differing in communication and operational range. The optimal communication solution depends on mission requirements. From a spectrum allocation standpoint, both industry and standardization groups are actively involved. Numerous studies have examined UAS–satellite integration, often through simulations, although most models are simplified. In the future, we aim to improve simulations by including real channel effects. We also plan to implement a satellite-controlled UAS for practical experiments, starting with Starlink constellation tests and extending it to 3GPP NTN connections.

Author Contributions: Conceptualization, A.Y.-C., H.K., M.M. and M.H.; methodology, A.Y.-C., S.T. and M.A.U.; validation, A.Y.-C., S.T. and M.A.U.; formal analysis, H.K., M.M. and M.H.; investigation, A.Y.-C., S.T. and M.A.U.; resources, H.K.; data curation, A.Y.-C.; writing—original draft preparation, A.Y.-C., S.T., M.A.U. and M.M.; writing—review and editing, A.Y.-C., S.T., M.A.U. and M.M.; visualization, A.Y.-C.; supervision, H.K. and M.H.; project administration, H.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article. The information presented in this study was derived from the following resources available in the public domains, including: IEEE Xplore, Scopus, Google Scholar, 3GPP.

Conflicts of Interest: A.Y.-C., S.T., H.K., M.A.U., M.H. and M.M. were employed by the company VTT Technical Research Centre of Finland Ltd. The remaining author declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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