Robust and Resilient Terrestrial–Non-Terrestrial Connectivity for In-Flight Connectivity in the Beyond-5G/6G Era

Christoffer Hjalmarsson, Tasos Dagiuklas,
Brahim El Boudani and Jonathan Rodriuguez

Department of Computer Science and Digital Technologies
London South Bank University, UK

***Abstract*—The integration of terrestrial networks (TN) and non-terrestrial networks (NTN) is a key step towards providing reliable, secure, and ubiquitous connectivity with clear quality of service (QoS) guarantees. Native TN/NTN integration will enable use cases such as in-flight broadband connectivity (IFBC) and mission-critical operations. Although 3GPP has begun publishing normative requirements for TN/NTN integration, a few technical challenges remain. Aircraft antenna design must improve to reduce drag while ensuring robust connectivity across satellites in different orbits (LEO, MEO, GEO) as well as TN. Equally, handover procedures in multi-radio access (multi-RAT) environments require proactive and optimised solutions to minimise control overhead, reduce interference, and maintain end-user QoS. To address these challenges, an architecture has been proposed where aircraft and satellites act as mobile wireless access and backhaul (WAB) nodes, while also hosting multi-access edge computing (MEC) for latency-sensitive services. This architecture enables flexible deployment scenarios, but necessitates advanced self-organising networks (SON) and network optimisation technologies.**

***Index Terms*—In-flight broadband connectivity, SATCOM, TN/NTN integration**

I. Introduction

The 5G mobile business case extends towards the air, where in-flight broadband connectivity (IFBC) is an emerging reality. In fact, a new study by the London School of Economics and Political Science in association with Inmarsat shows that in-flight broadband has the potential to create a $130 billion global market within the next 20 years, resulting in $30 billion of additional revenue for airlines by 2035 [1]. There has already been some market penetration in this area, with legacy on-board systems served by satellite communications and complemented by on-board Wi-Fi access. Furthermore, the market has introduced direct air-to-ground (DA2G) mobile services that are able to guarantee quality of service (QoS) such as the European Aviation Network (EAN) which is providing lower grade 4G-LTE [2].

In response to aviation stakeholders requirements towards IFBC services, the Next Generation Mobile Network Alliance (NGMN) has proposed key performance indicators (KPIs) for beyond 5G use-cases targeting mobile backhauling for aircraft [3]. Given their estimations, each user will have 15/(7.5) Mb/s download/(upload), so that 1.2/(0.6) Gb/s download/(upload) speed is required per aircraft, assuming 20% active users per aircraft and 400 passengers in each aircraft. To achieve these anticipated data rates, quite clearly there is a need for further satellite integration within the current 5G standard.

In fact, 5G-satellite integration has already been playing a pivotal role in 5G standardization. The service requirements were captured in 3GPP (3rd Generation Partnership Project) Release 14 (R14), highlighting the added value that satellite coverage brings, as a complementary network forming part of the 5G paradigm, especially for mission-critical and industrial applications. 3GPP R15 introduced a study on New Radio (NR) support for non-terrestrial networks (NTN), examining potential architecture options and deployment scenarios. These included, for example, providing NTN-based broadband connectivity between the core network and cells located on board moving platforms such as aircraft or trains. R17, in contrast, was the first release to include normative requirements for NTN. It provided specifications for interoperability in both air-to-ground (A2G) handover scenarios and across different radio access technologies and satellite orbits, such as geosynchronous (GSO) and non-geosynchronous (NGSO) systems at various altitudes. R18 addressed further satellite integration under the new 5G advanced marker, including multi-RAT (Radio Access Technologies) resource control at the 5G core (5GC) to manage multiple radios and enabling effective load balancing. R18 also included steps towards empowering unmanned aerial systems (UAS) and supporting their diverse applications, among others. R19 still has satellite architecture evolution as a priority topic, and whilst previous releases focused on transparent payloads, R19 focuses on regenerative payloads where the NTN vehicle hosts 5G system functions. R19 also considers NR-NTN coexistence and functionalities such as mobility management and dual connectivity for user equipment (UE). Handover between TN and NTN is still under discussion, but will build on the 5G integrated access backhaul (IAB) technology towards wireless access backhaul (WAB) nodes, where gNB nodes assume wireless data forwarding roles to provide low-cost coverage and flexibility overcoming the constraints associated with ground-based rigid optical deployments. The aim of this paper is to provide an integrated TN/NTN supporting IFBC services.

The structure of the paper is the following; section II presents the state-of-the-art in TN/NTN integration, Section III presents the proposed TN/NTN architecture, and research challenges to support in-flight connectivity in B5G/6G are outlined in Section IV.

II. State-of-the-Art in TN/NTN Integration

Satellite technology can be seen as a pivotal element of non-terrestrial networks (NTNs), which aim to extend the coverage of terrestrial networks (TNs) to provide seamless, ubiquitous connectivity. These networks also support the ambitious data rate, reliability, and latency targets outlined in ITU-R's IMT-2030 vision for 6G systems [4]. Achieving this requires a complex, multi-layered architecture where terrestrial and non-terrestrial components operate cohesively as a single unified network. Traditional single-orbit SATCOM (satellite communication) systems such as low earth orbit (LEO), medium earth orbit (MEO), and geostationary orbit (GEO), offer distinct performance trade-offs: GEO provides high throughput and wide coverage but suffers from latency; LEO delivers low latency but requires frequent handovers and dense ground segment infrastructure; MEO provides intermediate performance but with limited flexibility. These constraints are well documented in ITU-R S.1716 and 3GPP R17 NTN specifications, which highlight the performance and interoperability challenges across orbital regimes.

3GPP Releases 18–20, enable seamless handover, carrier aggregation, and dual connectivity across LEO, MEO, and GEO assets. This ensures global coverage, spectral efficiency, enhanced resilience against denial-of-service or jamming, and mission continuity under contested or degraded environments. Multi-orbit SATCOM represents not only a technical evolution but also a strategic necessity to safeguard decision advantage in multi-domain operations.

Multi-orbit satellite communications systems rely on highly agile and adaptive hardware architectures capable of interfacing across GEO, MEO, and LEO satellites. One key enabler is the multi-layered satellite system (MLSS) approach, where different orbital layers are tightly integrated to exploit their complementary strengths; GEO for wide coverage and stability; LEO/MEO for lower latency and higher link margins. These MLSS architectures have been demonstrated in systems that blend GEO and LEO capabilities to boost service resilience, latency performance, and coverage continuity [5].

Modern multi-orbit hardware incorporates techniques such as beam-sharing and hybrid beamforming, especially in multi-satellite and multi-user contexts. Recent research works introduce novel physical beam-sharing schemes enabling a single satellite or terminal to serve multiple users concurrently with enhanced spectral efficiency [6].

Multi-connectivity (MC) enables concurrent connections across multiple carriers and presents an effective solution. Building on its success in terrestrial networks, the 3GPP introduced MC support for satellite and integrated TN/NTN in standards TR 38.821 and TR 23.737. MC can be implemented at different layers of the protocol stack; carrier aggregation (CA) at the medium access control (MAC) layer and dual connectivity (DC) at the packet data convergence protocol (PDCP) layer, facilitating dynamic splitting and duplication of user traffic. This approach provides rapid adaptation to changing link quality in real time, making CA and DC well-suited to address the challenges of multi-band multi-orbit (MBMO) satellite architecture. Theoretical analyses and experimental trials have demonstrated that MC significantly enhances data throughput, spectral efficiency, coverage, and reliability while lowering latency in NTNs. This foundation has been primarily applied to networks limited to a single orbit or band.

Inter-satellite links (ISLs) and emerging inter-orbit links (IOLs) play pivotal roles in connecting satellites across orbits, thereby forming space information networks (SINs) [7]. SIN architectures incorporate ISLs and IOLs for in-space backhauling and enable real-time, high-throughput relay among satellites, reducing reliance on ground stations.

Multi-orbit SATCOM hardware must integrate advanced antenna and RF front-end technologies to support seamless communication across LEO, MEO, and GEO. Electronically steerable phased-array antennas and flat-panel designs (e.g., Kymeta u8, Intellian v240MT) replace bulky parabolic dishes, enabling agile beam steering, multi-band support (Ku/Ka/Ka-Q/V), and orbit diversity. Hardware integration also extends to RF front-end modules, which must accommodate multi-chain processing for concurrent links, and baseband chipsets that handle dual or multiple protocol stacks. Antenna miniaturization, low-power amplifiers, and ruggedized designs are critical for defense and mobility scenarios. These architectures are evolving in line with 3GPP NTN standards (TR 38.811, TR 38.821), which define RF requirements and mobility support for NGSO systems.

Multi-orbit SATCOM can offer a resilient, flexible, and globally available connectivity layer that can be seamlessly integrated into NATO's Federated Mission Networking (FMN) to enhance mission effectiveness and interoperability. By leveraging LEO, MEO, and GEO systems in combination, FMN participants can benefit from assured communications that adapt to operational requirements, whether low-latency links for tactical edge operations or high-capacity GEO/MEO backhaul for strategic command. The integration of multi-orbit with FMN can be mapped to specific spiral specifications as follows:

- Core Mission Services & Interoperability: Multi-orbit SATCOM can support standards-based interfaces for mission-essential services (voice, data, video) across heterogeneous national contributions. Standardized SATCOM gateways and cross-domain solutions allow seamless participation of coalition partners, even in bandwidthconstrained or denied areas.

- Cloud-Enabled C2 & Federated Services: By integrating software-defined networking (SDN) and network function virtualization (NFV), multi-orbit SATCOM provides adaptive routing and bandwidth-on-demand to support federated cloud-based mission services. This ensures reliable access to C2 applications, ISR data, and coalition services hosted in FMN mission clouds.
- Mobility, Agility, and Mission Resilience: Multi-orbit SATCOM enhances secure mobile networking by enabling low-latency LEO links for tactical edge users, complemented by MEO/GEO for strategic backhaul. Seamless handovers and orbit diversity improve continuity of operations in highly mobile scenarios (e.g., maritime task groups, air operations, rapid deployment). Its inherent redundancy across orbits and bands also supports mission assurance in contested or denied environments.

III. Proposed IFBC Architecture in Resilient TN/Multi-Orbit Network Architecture

This paper proposes an architecture that capitalises on ongoing 5G standardization trends to envisage an integrated virtualised 5G-based architecture, as shown by Fig. 1, with multi-access edge computing (MEC). The 5G services can be delivered either through the 5G direct air-to-ground (DA2G) service, or through the satellite air-to-ground (SA2G) service when there is no option to connect to a ground station, for instance when flying over sea. Moreover, the proposed architecture provides the enabler for aeroplane-to-aeroplane (A2A) connectivity which can be used when the aircraft is flying in airspace above land borders where terrestrial coverage starts to diminish and can benefit from backhauling through other aircraft.

The architecture defines scenarios, requirements, and performance metrics (including throughput, fairness, latency, and availability) providing the foundation for subsequent innovations. In particular, the IFBC architecture needs to enable reliable communication for diverse use cases such as between pilot and air traffic control (ATC), collection of real-time data from aircraft sensors for centralised analysis, and in-flight entertainment systems such as video streaming.

IV. Research Challenges

In-flight 5G services will require antenna designs that operate at 5G NR-NTN frequencies used by both 5G NR A2G and NTN satellite bands (FR1, FR2), and adopt a proactive stance to maintaining beam-locking and synchronization given the challenging atmospheric environment and the changing position of the aircraft. Smart localisation based on angle of arrival (AoA), is a proven technique. Moreover, contemporary aircraft can include up to 25 protruding antennas, that not only disrupt the aircraft aesthetics, but also results in significant aerodynamic drag and heightened fuel consumption providing a need for antennas to be conformal in nature to the body of the aircraft [8]. How to provide conformal designs for aircraft

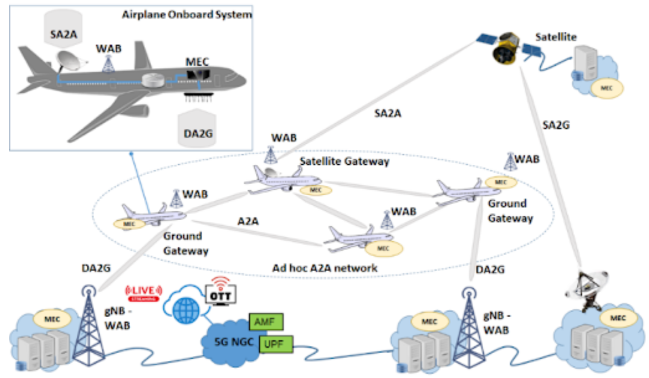

Figure 1. In-flight connectivity.

applications that operate at mmWave frequencies with adaptive multi-beam formation based on intelligent localization to achieve high-throughput transmission while maintaining beam-locking and synchronization is an open issue.

Advanced antenna arrays, scalable to millimetre-wave frequencies, leverage conformal geometries based on planar leaky-wave and surface-wave technologies to integrate seamlessly with aircraft surfaces. Their compact, conformal design offers low dielectric losses and moisture resistance, ensuring reliable performance in harsh environments. Full spatial beam scanning for DA2G (Direct Air-to-Ground) and inter-aircraft links will exceed current multi-beam capabilities, supporting both static and dynamic beam formation. Seamless gate-to-gate IFBC concept has been proposed in [9] considering a high speed communication backhaul based on LTE (DA2G) complemented by onboard Licensed LTE, LTE licensed assisted access (LTE-LAA) and Wi-Fi. In [10], the capacity limitations of 4G radio technologies for DA2G connectivity was shown and compared with benefits of using 5G technology to boost link capacity. In [11], the interplay between the number of antenna array elements, number of ground BSs and spectrum resources to provide high performance DA2G connectivity capacity without taking into account mobility was investigated. Whilst [12] provided new insights on radio link capacities based on flight tests for urban areas and airports, and how they can be scaled up for higher altitudes. Furthermore, the challenges for utilizing aircraft within an integrated space-terrestrial network are outlined in [13]. However, these works still highlight gaps in knowledge for integrated systems, where challenges still exist in terms of interference and mobility management.

Mobility management and dual connectivity for UE handover is still under discussion in 3GPP, but the technology drive aims to build on 5G IAB terminology and associated mobility procedures (Xn/N2 interfaces) towards an WAB architecture and protocol. However, there are still many radio challenges to solve regarding flying vehicles to achieve efficient mobility handover, particularly when considering mobility between WAB (WAB-gNB) nodes and the serving 5GC. Previous works addressed aircraft connectivity and handover decision for aerospace applications, but do not consider optimum solutions to predict handovers. A key research challenge emerges targeting intelligent (proactive) handover solutions to address efficient handover connectivity, that includes ground-aerial-satellite use-cases (mobility between WAB nodes, and operators).

Network slicing, is an important technology developed under 5G ecosystems where logically isolated networks can be deployed over multi-domain, multi-technology physical networks that provide different resource guarantees. Each SDO (e.g. IETF, ETSI, 3GPP etc) develops its own standards with respect to specific part of the network architecture; RAN, Core Network and Transport Network. Evolution in network slicing towards multi-domain, TN/NTN integration has been considered in 3GPP R19. Self-Organized Network (SON) functionalities are being standardized in order to ensure automatic management procedures in 5G systems, and several studies are being pursued in order to have an autonomous managed network. ML technology is having widespread adoption for intelligent decision-making solutions such as automatic systems. Going a step further, there are limited studies that demonstrate how intelligence and SON can be applied to network slicing to ensure effective and autonomous resource reservation in integrated TN-NTNs.

There is a challenge to develop an autonomous self-configuration, optimizing and healing self-organizing network (SON) for a unified TN-NTN to meet the demands for network-sliced SFs, where ground-air networks are considered. This necessitates smart traffic routing by considering real-time fluctuation and dynamics, taking into account the aerial networks are highly dynamic and may not have a permanent feeder link connectivity to the ground based network.

V. Conclusion

The telecommunication industry is clearly moving towards native integration between TN and NTN to meet the demand for reliable, secure, and ubiquitous coverage with guaranteed QoS. Native integration will enable applications such as IFBC and mission-critical services, yet several barriers remain before large-scale deployment can be deployed. In particular, aircraft antenna design must advance to reduce drag and enable robust connectivity across LEO, MEO, and GEO systems, and intelligent handover mechanisms are needed to manage mobility across diverse RAT environments with minimal overhead and interference.

The proposed architecture introduces aircraft and satellites as mobile WAB nodes capable of acting as both access and backhaul, and hosting MEC for latency-sensitive services. Whereas this architecture offers high flexibility and the potential to support a broad range of applications, its success will depend on the development of advanced SON functionalities, AI-driven network optimization, and proactive handover solutions. Future research should therefore focus on predictive mobility management, cross-layer optimization, and adaptive resource allocation to fully realize the vision of seamless TN/NTN integration.

References

[1] LSE Consulting. *Sky High Economics: Chapter One*. Research Report. Accessed: 24 September 2025. London School of Economics and Political Science (LSE), n.d. URL: https://www.lse.ac.uk/business/consulting/assets/documents/sky-high-economics-chapter-one.pdf.

[2] Deutsche Telekom AG. URL: https://inflight.telekom.net/ean/.

[3] NGMN Alliance. *5G White Paper*. Accessed: 2025-09-25. 2015. URL: https://www.ngmn.org/wp-content/uploads/NGMN_5G_White_Paper_V1_0.pdf.

[4] ITU 2025. *IMT towards 2030 and beyond (IMT-2030)*. Accessed: 2025-09-25. URL: https://www.itu.int/en/ITU-R/study-groups/rsg5/rwp5d/imt-2030/pages/default.aspx.

[5] Marko Höyhtyä et al. "Multi-Layered Satellite Communications Systems for Ultra-High Availability and Resilience". In: *Electronics* 13.7 (2024). ISSN: 2079-9292. DOI: 10.3390/electronics13071269. URL: https://www.mdpi.com/2079-9292/13/7/1269.

[6] Yan-Yin He, Shang-Ho Tsai, and H. Vincent Poor. "Physical Beam Sharing for Communications With Multiple Low Earth Orbit Satellites". In: *IEEE Transactions on Signal Processing* 72 (2024), pp. 2783–2798. DOI: 10.1109/TSP.2024.3408061.

[7] Hayder Al-Hraishawi et al. "Multi-layer Space Information Networks: Access Design and Softwarization". In: (Oct. 2021). DOI: 10.48550/arXiv.2110.08031.

[8] Arjuna Veera SE, Suganthi J, and T. Kavitha. "Conformal Antenna for Aircraft Applications". In: *2023 7th International Conference on Computation System and Information Technology for Sustainable Solutions (CSITSS)*. 2023, pp. 1–7. DOI: 10.1109/CSITSS60515.2023.10334078.

[9] E. Dinc, M. Vondra, and C. Cavdar. "Seamless Gate-to-Gate Connectivity Concept: Onboard LTE, Wi-Fi and LAA". In: *IEEEE VTC-Fall* (2017).

[10] Vondra, Michal and Dinc, Ergin and Prytz, Mikael and Frodigh, Magnus and Schupke, Dominic and Hofmann, Sandra and Cavdar, Cicek. "Performance Study on Seamless DA2GC for Aircraft Passengers toward 5G". In: *IEEE Communications Magazine* PP (July 2017). DOI: 10.1109/MCOM.2017.1700188.

[11] E. Dinc et al. "Multi-user Beamforming and Ground Station Deployment for 5G Direct Air-to- Ground Communication". In: *IEEE Globecom* (2017).

[12] A. Garcia et al. "Direct Air to Ground Communications for Flying Vehicles: Measurement and Scaling Study for 5G". In: *IEEE 5G World Forum* (2019).

[13] X. Huang et al. "Airplane-Aided Integrated Networking for 6G Wireless: Will It Work?" In: *IEEE Vehicular Technology Magazine* (2019).

WIRELESS WORLD RESEARCH FORUM

WWRF Copyright License

To ensure uniformity of treatment among all contributors, other Forms may not be substituted for this Form, nor may any wording of the Form be changed. This Form is intended for original material submitted to the Wireless World Research Forum (the "WWRF") and must accompany any such material in order to be published by the WWRF. Please read the Form carefully and keep a copy for your files.

TITLE OF PAPER/ARTICLE/REPORT/PRESENTATION/SPEECH (hereinafter, "the Work"):
Robust and Resilient Terrestrial–Non-Terrestrial Connectivity for In-Flight Connectivity in the beyond-5G/6G Era

COMPLETE LIST OF AUTHORS: Christoffer Hjalmarsson, Tasos Dagiuklas, Brahim El Boudani and Jonathan Rodriuguez

WWRF Event: Kingston University

Author Responsibilities

- Authors must ensure that their Work meets the requirements including provisions covering originality, authorship, author responsibilities and author misconduct. It is the responsibility of the authors, not the WWRF, to determine whether disclosure of their material requires the prior consent of other parties and, if so, to obtain it. It shall be acknowledged that statements and opinions given in work published by the WWRF are the expression of the authors. Responsibility for the content of published papers rests upon the authors, not WWRF.
- The Author confirms that, to the extent the Work incorporates text passages, figures, data or other material from the work of others ("Third Party Material"), such Third-Party Material is identified and the Author has obtained any necessary permission.
- The Author believes that to the best of the Author's knowledge and belief, the information contained in the Work is accurate complete and correct at the time of grant of this license.

Copyright Assignment

- The undersigned represents that he/she has the power and authority to make and execute this assignment.
- If you are employed and prepared the Work on a subject within the scope of your employment, the copyright in the Work belongs to your employer as a work-for-hire. In that case, the WWRF assumes that when you sign this Form, you are authorized to do so by your employer and that your employer has consented to the copyright license to all terms and conditions of this Form. If such authorization and consent has not been given to you, an authorized representative of your employer should sign this Form as the Author.
- For jointly authored Works, all joint authors should sign a separate Form, or one of the authors should sign as authorized agent for the others taking into account the terms and conditions of this Form.
- In the event the above work is not accepted and published by the WWRF or is withdrawn by the author(s) before acceptance by the WWRF, the foregoing copyright license shall become null and void and all materials embodying the Work submitted to the WWRF will be destroyed.
- The undersigned of the work hereby grants to the WWRF the right to consider the submission for the "Best Paper Award" as per the rules mentioned in **WWRF Best Paper Award**, and also, under Author's copyright in the Work, a non-exclusive, perpetual, irrevocable, royalty-free, fully paid-up and world-wide copyright license, including the right to sublicense, to:
  a) incorporate the Work in part or as a whole in any material prepared by the WWRF;
  b) reproduction and distribution of the Work in part or as a whole and alone or in connection with other material, including reprints, translations, photographic reproductions, microform, electronic form (offline, online), or any other reproductions of similar nature.

Christoffer Hjalmarsson

Signed: <the Author>/<Authorized Agent for Joint Authors>

London 28/9 - 2025

Date and place

This copyright license should be submitted together with the contribution! A copy of this Form should be sent to the WWRF Secretary ramukdoniv@outlook.com. *The signed version of this Form should be sent by postal mail to, Dr Nigel Jefferies Montreal Cottage, Deacons Lane, Hermitage, Berks RG18 9RH, UK*