MOBILE COMMUNICATIONS AND NETWORKS

Integrating Terrestrial and Non-Terrestrial Networks: 3D Opportunities and Challenges

Giovanni Geraci, David López-Pérez, Mohamed Benzaghta, and Symeon Chatzinotas

The authors present the key opportunities and challenges arising from this revolution by presenting some of its disruptive use cases and key building blocks, reviewing the relevant standardization activities, and pointing to open research problems.

ABSTRACT

Integrating terrestrial and non-terrestrial networks has the potential of connecting the unconnected and enhancing the user experience for the already-connected, with technological and societal implications of the greatest long-term significance. A convergence of ground, air, and space wireless communications also represents a formidable endeavor for the mobile and satellite communications industries alike, as it entails defining and intelligently orchestrating a new 3D wireless network architecture. In this article, we present the key opportunities and challenges arising from this revolution by presenting some of its disruptive use cases and key building blocks, reviewing the relevant standardization activities, and pointing to open research problems. By considering two multi-operator paradigms, we also showcase how terrestrial networks could be efficiently re-engineered to cater for aerial services, or opportunistically complemented by non-terrestrial infrastructure to augment their current capabilities.

INTRODUCTION

A mobile connection is our window to the world. The current social, economic, and political drive to reach global wireless coverage and digital inclusion acknowledges connectivity as vital for accessing fair education, medical care, and business opportunities in a post-pandemic society. Sadly, nearly half of the population on Earth remains unconnected. Indeed, rolling out optical fibers and radio transmitters to every location on the planet is not economically viable, and reaching the billions who live in rural or less privileged areas has remained a chimera for decades. The long-overdue democratization of wireless communications requires a wholly new design paradigm to realize ubiquitous and sustained connectivity in an affordable manner.

Meanwhile, in more urbanized and populated areas, even 5G may eventually fall short of satiating our appetite for mobile internet and new user experiences. Life in the 2030s and beyond will look quite different from today’s: hordes of network-connected uncrowed aerial vehicles (UAVs) will navigate 3D aerial highways — be it for public safety or to deliver groceries to our doorstep — and flying taxis will re-shape how we commute and, in turn, where we live and work. The bold ambition of reaching for the sky will take the data transfer capacity, latency, and reliability needs for the underpinning network to an extreme, requiring dedicated radio resources and infrastructure for aerial services [1, 2].

In a quest for anything, anytime, anywhere connectivity — even up in the air — next-generation mobile networks may need to break the boundary of the current ground-focused paradigm and fully embrace aerial and spaceborne communications [3, 4]. To this end, the wireless community has already rolled up its sleeves in search for technology enhancements towards a fully integrated terrestrial plus non-terrestrial network (NTN) able to satisfy both ground and aerial requirements. At first glance, terrestrial networks (TNs) could be:

- Re-engineered and optimized to support aerial end-devices [5, 6],
- Complemented by NTN infrastructure such as low Earth orbit (LEO) satellite constellations or aerial base stations (BSs) to further enhance performance [7, 8].

Cost-related factors may advocate for a progressive roadmap. In the present paper, we discuss the great opportunities and challenges lying behind a 3D integrated TN-NTN from a new standpoint. We begin by providing examples of disruptive use cases, an overview of the building blocks of an integrated TN-NTN architecture, and an up-to-date summary of the relevant 3rd Generation Partnership Project (3GPP) standardization activities. We then place the spotlight on aerial services, and introduce novel case studies for a conventional terrestrial operator pursuing aerial connectivity through two plausible choices:

- Deploying dedicated uplinked cells — or partnering with a specialized aerial operator doing so — reusing the same spectrum;
- Leasing infrastructure or solutions from a LEO satellite operator.

We conclude by reviewing the main hurdles that still stand in the way to an integrated TN-NTN and pointing out key open problems worthy of further research.

USE CASES, ARCHITECTURE, AND STANDARDIZATION

In this section, we describe the main use cases and components of a plausible integrated TN-NTN, and we summarize the major NTN and UAV standardization advancements.

Digital Object Identifier

10.1109/MCOM.002.2200366

0163-6804/23/$25.00 © 2023 IEEE

IEEE Communications Magazine • April 2023

Authorized licensed use limited to the terms of the applicable license agreement with IEEE. Restrictions apply.
USE CASES

The opportunities unlocked by integrating TN and NTN capabilities could lead to a vast number of new applications and services. In what follows, we provide a representative down-selection of the key use cases.

Critical Communications: Connectivity from space or air can empower ultra-reliable critical communications in the absence of cellular coverage or during an emergency or natural disaster. When the ground network becomes dysfunctional and the importance of providing rapid and resilient connectivity cannot be overstated, integrated NTNs can ensure replacement coverage through direct access from space/air or even via satellite-to-cellular backhauled UAV radio access nodes.

Massive Internet of Things (IoT) and Immersive Communications: NTNs can complement TNs to cover large areas of land or sea populated with both static and nomadic sensory nodes, all collecting real-time data. Aggregating and displaying the latter through extended reality applications will provide users with spatial and contextual awareness, enabling immersive human-machine interaction, likely one of the 6G killer apps. Depending on the latency requirements and sensory node capabilities, data aggregation could be handled by UAVs, HAPS, or a LEO constellation in the field of view of a ground gateway [8]. NTN broadcast/multicast could then pursue content scalability and uninterrupted delivery to users in cars, trains, and vessels.

Aerial Communications: Beyond standalone TNs, primarily designed for 2D usage, an integrated TN-NTN could support reliable data and control links to multiple UAVs, electrical vertical take-off and landing vehicles (eVTOLs), and aircrafts. These services would be guaranteed in specific 3D areas — aerial corridors or waypoint trajectories — where end-devices will be allowed to fly at different heights. The potential of UAVs may only truly be unleashed once the network capabilities and regulations allow for autonomous operation beyond visual line-of-sight (LoS) [9, 10]. Our studies later will deliberately focus on this all-important use case.

ARCHITECTURE

A simplified integrated TN-NTN architecture is illustrated in Fig. 1, with service links connecting a user terminal — either handheld/IoT or very-small-aperture terminal (VSAT) — to TN/NTN BSs, feeder links connecting the NTN segment to the ground core network, and (optionally) inter-satellite and/or inter-high-altitude platform stations (HAPSs) links. While in the remainder of the article we focus on radio frequency (RF) systems, some of the aforementioned links could also be established via free-space optical communications, potentially offering higher data rates and more immunity to interference.

Network Platforms: The 3D TN-NTN will avail of a multi-layered multi-band infrastructure, arranged hierarchically, with the following nodes operating at different altitudes and offering user-centric service:

- TN BSs of various size, power, height, and orientation, operating in sub-6 GHz, mmWave, and eventually THz bands, and deployed with different densities. Along with conventional downtilted BSs, mobile operators may choose to deploy dedicated infrastructure, e.g., uptilted cells, to serve aerial end-devices.
- Geostationary orbit (GSO) satellites, orbiting the equatorial plane at an altitude of about 35786 km, and creating fixed beams with a footprint radius of up to 3000 km.
- Non-GSO satellites, such as LEO, deployed at altitudes between 300–1500 km, creating footprints of up to 1000 km radius per beam. Unlike their GSO counterpart, LEO satellites move fast with respect to a given point on the Earth, with an orbital period of just a few hours, and thus require large constellations for coverage continuity.
- Aerial BSs such as HAPSs, placed in the stratosphere at around 20 km, and creating multiple cells sized about 10 km each, or UAV radio access nodes, flying at heights somewhere between 0-1 km.
- Ground gateways connecting aerial and spaceborne platforms to the core network through so-called feeder links.

Terminals: The end-devices of a 3D TN-NTN can be classified as follows:

- Stationary and vehicular ground users (GUEs), in areas ranging from dense urban to suburban, rural, and remote.
- UAVs, eVTOLs, and aircrafts, demanding in-flight connectivity at altitudes of few hundred meters, 1–3 km, and 10–12 km, respectively [5].

Satellite-connected devices can either be handheld/IoT or equipped with a VSAT. The more benign link budget in the S-band (sub-6 GHz) enables direct access to omni- or semi-directional terminals. The Ka-band (mmWave spectrum) incurs a higher attenuation, which must be compensated with a larger antenna gain by employing a VSAT. The latter can be either fixed or mounted on a moving platform, thus giving options for either mobile or fixed broadband access.

STANDARDIZATION

Standardization work on non-terrestrial communications in the 3GPP dates back to 2017 [11]. This effort can be classified nowadays into two separate areas, namely NTN enhancements and TN support for UAVs. The objectives and outputs of the 3GPP
TABLE 1. Overview of the 3GPP standardization work on NTN and UAV communications [1, 13].

| Release | Non-terrestrial Networks (NTN) Enhancements | Support for Uncrewed Aerial Vehicles (UAVs) |
|---------|---------------------------------------------|-------------------------------------------|
| Rel-15  | Study on NR to support NTNs [TR 38.811]     | Enhanced LTE support for aerial vehicles [TR 36.777] |
|         | Relevant scenarios for NTN deployment studies and integration in terms of: frequency bands, typical footprint sizes and minimum elevation angles, antenna models and beam configurations (Earth-fixed vs. moving beams), and NTN terminals (handheld vs. VSAT). NTN-specific channel models based on TR 38.901. | Solutions for interference mitigation, mobility, and UAV identification. Air-to-ground channel models based on TR 38.901. |
| Rel-16  | Solutions for NR to support NTNs [TR 38.821]| Remote identification of UAVs [TS 22.825] |
|         | Below-6-GHz handheld and IoT satellite access. System-level simulation assumptions. Impact of delay on random access, scheduling, and hybrid automatic repeat request, and LEO mobility management. | Requirements and use cases for remote UAV identification, allowing air traffic control and public safety agencies to query the identity and metadata of a UAV and its controller to regulate UAV operations. |
|         | Use cases considering the integration of 5G satellite-based access components, new services and the corresponding requirements. | UAV connectivity, identification, and tracking [TR 23.754] |
| Rel-17  | Narrowband IoT (NB-IoT) and enhanced machine-type communication (eMTC) support for NTN [TR 36.763] | 5G enhancements for UAVs [TS 22.125, TS 22.829] |
|         | Focused on IoT applications by addressing issues related to LTE timing relationships, uplink synchronization, and retransmissions. | New UAV communication needs related to: payload, command and control link, on-board radio access node, and service restrictions. |
|         | Architecture aspects for using satellite access in 5G [TR 23.737] | Application layer support for UAVs [TR 23.755] |
|         | Enhancements for RF and physical layer, protocols, and radio resource management. Identified a suitable architecture, addressed TN-NTN roaming and timing issues, enhanced conditional handover. | Studied use cases for UAV identification and tracking, their impact on the application layer, and protocols for route authorization, location management, and group communication support. |
| Rel-18  | NR NTN enhancements | NR support for UAVs |
|         | NR NTN coverage for realistic handheld terminals and access above 10 GHz to fixed and moving platforms. Network-verified user location, mobility and TN-NTN service continuity. | Enhancements on measurement reports, subscription-based UAV identification and its multicast, conditional handover, and beam management below-8 GHz, including BS upilt beamforming. |

work carried out from Rel-15 up to Rel-17, along with the topics currently under study for Rel-18 are outlined follows and summarized in Table 1.  

**NTN Enhancements:** In 3GPP parlance, the term NTN refers to utilizing satellites or HAPS to offer connectivity services and complement terrestrial networks, especially in remote areas devoid of cellular coverage. The 3GPP work in Rel-15 and Rel-16 identified the main scenarios of interest and technical challenges, also specifying channel modeling and system-level simulation assumptions for the research community, with a focus on satellites. In 3GPP Rel-17, a set of basic features were introduced to enable 5G New Radio (NR) operation (NR) operation over NTNs up to 7.125 GHz. 3GPP Rel-18 will enhance 5G NR NTN operation by improving coverage for handheld terminals, studying deployments above 10 GHz, addressing mobility and service continuity between TNs and NTNs as well as across different NTNs, and investigating regulatory requirements for network-verified user location [12].  

**Support for UAVs:** The 3GPP introduced 4G Long-term Evolution (LTE) support for UAVs back in Rel-15, including signaling for subscription-based UAV identification, reporting of height, location, speed, and flight path, and new measurement reports to address aerial interference up to a certain density of low-altitude UAVs. An aerial channel model was also defined, subsequently leveraged in many research works. In subsequent releases, the 3GPP addressed application layer support and security for connected UAVs, also defining the service interactions between UAVs and the traffic management system. As 5G use cases evolve, Rel-18 will introduce 5G NR support for devices onboard aerial vehicles, studying additional triggers for conditional handover, BS upllating, and signaling to indicate UAV beamforming capabilities, among other enhancements [12].

**Opportunities for Aerial Services**

In this section, we consider two multi-operator case studies to illustrate how terrestrial networks could be:

- Efficiently re-engineered to support non-terrestrial end-devices such as UAVs,
- Opportunity complemented by non-terrestrial infrastructure to augment their current capabilities.

The main system-level assumptions for these two setups are summarized in Table 2.

**Example 1: Re-Designing TNs for NTN Terminals**

As the penetration of UAVs increases, a terrestrial mobile network operator (MNO) may choose to cater for aerial connectivity or partner with another MNO intending to do so [5]. The latter gives rise to the following hypothetical setup with two operators sharing the same spectrum, namely:

- A terrestrial operator, MNO\_1, running a standard network comprised of downtilted cells to serve legacy GUEs.
- An aerial operator, MNO\_2, running a dedicated network of upilted BSs reserved exclusively for connected UAVs.

These two arrangements are exemplified in the center of Fig. 1. The deployment sites of both operators are on a hexagonal layout and comprised of three co-located BSs, each covering one sector (i.e., a cell) spanning an angular interval of 120°. Let ISD\_1 and ISD\_2 denote the respective intersite distances, whereby we fix the former to 500 m, and vary the latter to study its effect. We assume 15 GUEs for each MNO\_1 cell, and for all values of ISD\_2, we keep the UAV density constant according to 3GPP Case 3 in TR 36.777, yielding 1, 4, 9 UAVs/cell under ISD\_2 = 500, 1000, 1500 m, respectively. GUEs are located both outdoor at 1.5 m and indoor in buildings consisting of several floors. UAVs fly outdoor at a height of 150 m. We
assume all GUEs and UAVs to have a single omni-directional antenna, and to connect to the strongest available cell. Both UAVs and GUEs employ the open-loop power control policy specified in 3GPP TR 36.213. The models reported in 3GPP TR 38.901 and TR 36.777 are invoked to characterize the propagation features of all links.

We assume the BSs of MNOT and MNOA to be respectively downtilted by −12° and up tilted by 45°, the former being commonplace for ISDT, and respectively downtilted by –12° and uptilted by 45°, the latter yielding the best UAV performance in most cases. Each cell is equipped with an 8 × 8 massive multiple-input multiple-output (MIMO) array of cross-polarized semi-directive elements, each connected to a separate RF chain, resulting in a total of 128 RF chains. For both operators, we assume perfect channel state information, and consider two different multi-user paradigms:

- **Zero-forcing (ZF) precoding**, where each BS spatially multiplexes a subset of its users. On one hand, this paradigm requires low-to-no coordination for radio resource allocation since all scheduling, beamforming, and networking decisions are performed individually by each BS. On the other hand, such a simplification comes at the cost of inter-MNO co-channel interference.
- **Eigendirection-aware (EDA) precoding**, where BSs dedicate a certain number of spatial degrees of freedom to place radiation nulls, thereby canceling interference on the dominant eigendirections of the inter-cell channel subspace [13]. This approach requires coordination between MNOT and MNOA for channel state information acquisition, possibly entailing them to belong to the same network provider.

We focus our analysis on the uplink, the more data-hungry direction for UAVs, whose generated transmissions may pose a threat to legacy GUES [1]. Figure 2 shows the 95 percent-tile signal-to-interference-plus-noise ratio (SINR) attained by UAVs and GUES for various values of ISDA and the two precoding schemes. As a baseline, ISDA = ∞ represents the case without MNOA, where MNOT serves all GUES and UAVs. These results show the following:

- **Offloading UAVs from MNOA** sees their SINR reduced, unless the deployment of MNOA is sufficiently dense. Importantly, ISDA ≤ 1000 m is sufficient to keep at least 95 percent of the UAV in coverage, i.e., with an SINR above −5 dB. Offloading in such MNOA dense deployments also provides UAVs with higher data rates, as shown later.
- **As ISDA is reduced**, UAVs are no longer forced to connect to far-off dedicated BSs, and can afford reducing their transmission power and interference generated. This results in an increasing SINR for UAVs and GUES alike.
- **Upgrading from ZF to EDA precoding** allows both operators to neutralize the increased intercell interference arising from spectrum sharing. For MNOT, this countermeasure is key to preserve the legacy GUEs performance. Under the right deployment and interference mitigation choices, the dual-MNO paradigm can offer comparable SINRs to a setup where GUES and UAVs are all served by MNOT. However, the spatial and spectrum reuse gains provided by UAVs and GUES.

### TABLE 2. System-level parameters for the operators and end devices considered [3GPP TR 38.901, 36.777, 36.81, and 38.21].

| MNOT & MNOA | Cell layout | Inter-site distance | Frequency band | Spectrum | Scheduler (round robin) | Precoding | Downlink power | Uplink power | Antenna elements | Antenna array | Antenna tilt | Noise figure |
|-------------|-------------|---------------------|----------------|----------|------------------------|-----------|----------------|--------------|----------------|--------------|-------------|--------------|
| Hexagonal, 3 sectors/site, 1 BS/sector at 25 m | ISDT = 500 m, ISDA = {1500, 1000, 500} m | 100 MHz TDD at 3.5 GHz | MNOA and MNOA in the same band | DL: 50 MHz per GUE, 50 MHz per UAV | UL: 10 MHz per GUE, 50 MHz per UAV | DL: ZF (8 users) or EDA (8 users + 16 nulls) | MNOA: 46 dBm, MNOA: 46 dBm or less | Fractional power control with a = 0.80, P0 = −100 dBm, and Pmax = 23 dBm | Horiz./vert. HPBW: 65°, max gain: 8 dBi | 8 × 8 X-POL, fully digital | MNOA: 12° (down), MNOA: −45° (up) | 7 dB |
Our focus on LEO satellites is motivated by their better capacity and latency with respect to their GSO counterpart.

Example II: Complementing TNs with NTN Infrastructure

While primarily targeting underserved areas, TNs may also be leveraged to augment urban connectivity, e.g., with MNO T opportunistically leasing spectrum and infrastructure from a satellite service provider. In this example, we study the benefits of such an arrangement when offering service to passengers onboard eVTOLs, flying at 1500 m over an urban area [5]. Although we will show that TN-to-NTN offloading is particularly effective for UAVs, we remark that it could be applied to terrestrial users too. Let us define:

- The same operator MNO S as in Example I
- A satellite operator MNO T employing ZF and EDA (transparent) precoding. ISDA = \( \infty \) denotes all GUEs and UAVs served by standalone MNO T.

For MNO T, various LEO elevation angles are considered. The following remarks can be made:

- A standalone MNO T employing ZF struggles to guarantee coverage to eVTOLs as they proliferate. Indeed, increasing their number from 0.1 to 1 per cell incurs a progressively larger outage, i.e., SINR < –5 dB, reaching up to 18 percent of the cases (solid black).

This is due to the insufficient angular separation between users, caused by their density and sheer height, which also renders null-steering (not shown) unhelpful.

- Offloading traffic from MNO T to MNO S yields universal coverage with SINRs ranging between –3 dB and 17 dB for the elevation angles and beam FRFs considered.

- The SINR experiences a prominent degradation when the LEO satellite moves from 90° to 87°, owing to a larger propagation distance and a lower antenna gain, with the median loss in excess of 8 dB for FRF = 1.

- Nonetheless, all offloaded users still remain in coverage, even in the presence of inter-beam interference (FRF = 1).

As for the achievable rates, assuming one eVTOL passenger per cell over an area of 10.8 m² — the size of Sant Martí, Barcelona’s business district — yields a total of 150 users, out of which those in outage (18 percent, i.e., 27 users) could be offloaded to MNO S. For MNO S, various LEO elevation angles are considered. The following remarks can be made:

- Moving from FRF = 3 to FRF = 1 entails full reuse and thus inter-beam interference, degrading the median downlink SINR by approximately 8 dB and 14 dB for elevation angles of 90° and 87°, respectively.

- The SINR experiences a prominent degradation when the LEO satellite moves from 90° to 87°, owing to a larger propagation distance and a lower antenna gain, with the median loss in excess of 8 dB for FRF = 1.

While our findings are encouraging, they also suggest that in a future with hordes of high-alti-

![Figure 2](image-url)

**FIGURE 2.** 95%-tile of the uplink SINR for UAVs (blue) and GUEs (orange), for ISDA = 500 m and a variable ISD, and employing ZF (solid) or EDA (transparent) precoding. ISD = \( \infty \) denotes all GUEs and UAVs served by standalone MNO T.

![Figure 3](image-url)

**FIGURE 3.** Uplink UAV rates for ISD = 500 m and a variable ISD, and employing ZF (solid) or EDA (transparent) precoding. ISD = \( \infty \) denotes all GUEs and UAVs served by standalone MNO T. Blue and green bars denote 95%-tile and 50%-tile, respectively corresponding to the 5%-worst and the median user rate performance.
trade vehicles, broadband aerial communications may require higher NTN spatial reuse through narrow beams and possibly operating in the Ka-band [4, 14]. This option may be viable for relayed access through a more directive receiver mounted onboard the eVTOL.

**CHALLENGES AND RESEARCH DIRECTIONS**

The availability of TN plus NTN segments is a prerequisite for realizing a 3D wireless network. Jointly and optimally designing and operating all platforms and nodes require further disruptive and interdisciplinary research. In this section, we identify the key obstacles that stand in the way along with the most needed technological enablers.

**The Challenge of Extreme Heterogeneity**

One chief challenge in realizing an integrated TN-NTN arises from its extreme heterogeneity, reflected at different levels as outlined below.

**Radio Propagation Features:** NTNs comprise systems and end-devices at different altitude layers, each with own service features. For instance, GSO satellites provide stable and continuous links to ground devices with a considerable propagation delay, whereas LEO satellites are characterized by lower-delay interfaces, but may suffer from service discontinuity depending on the constellation density. Combining the use of RF with free-space optical links further compounds this heterogeneity. The type of service provided by each layer must be mapped to the user demand, factoring in the interplay of different layers, through dynamic TN-NTN quality of experience management and scheduling.

**Node and Device Capabilities:** By design, GSO differ from LEO satellites in terms of redundancy mechanisms, antenna designs, transceivers, operational frequency, and/or internal resources (e.g., storage, processing, and power availability). The variance in capabilities is yet more apparent with aerial vehicles, conceived for largely different purposes and environments, and terminals, whose antennas range from small and isotropic to active ones capable of tracking.

**Ownership and Operations:** Mega-constellations are emerging to expand Internet coverage through thousands of satellites, bringing about frequency coordination and collision avoidance issues, among others. While current systems lack interoperability, with each operator featuring a vertically integrated stack, 3GPP standardization will be crucial for interconnection, giving way to more heterogeneous scenarios. With multiple systems designed and operated in an ad-hoc fashion, their decentralized management and optimization may be a cornerstone to realizing a practical integrated TN-NTN.

**Research Directions**

Its extreme heterogeneity makes realizing a 3D network a remarkable endeavor. In the sequel, we propose much-needed research towards an integrated TN-NTN [1, 7].

**3D Radio Access:** Next-generation networks will have to connect flying end-devices at all heights. Our preliminary results vouch for exploiting dedicated upilted cells and NTN platforms to support aerial services. Nonetheless, operators will have to seek optimal performance-cost tradeoffs, ensuring coexistence between aerial and legacy ground users, and between different co-channel technologies. This goal calls for sophisticated interference management schemes leveraging time, frequency, power, and spatial degrees of freedom, and designed atop realistic air-to-ground channel models [15].

**3D Mobility Management and Multi-Connectivity:** While our case studies have dealt with improving coverage and capacity for aerial services, integrated TN-NTN will face the unprecedented mobility challenges brought about by flying end-devices and a mobile infrastructure, dynamically dealing with user cell selection, re-selection, and configuration. Beyond current power-triggered procedures, novel case-specific and asymmetric approaches will be required, also accounting for the handover direction, e.g., within a LEO constellation or across technologies. Optimal mobility management policies will need to trade off reliability, spectral- and energy-efficient load balancing, and signaling overhead caused by handover preparations and radio link failures.

**3D Network Management and Orchestration:** Meeting the heterogeneous and ever more stringent traffic needs across a 3D wireless network will require optimal load distribution, defining the slices of radio resources to be assigned to each service class, accounting for the features of the available TN/NTN radio links, and following their rapidly varying topology. Besides communications, computation and caching resources scattered across TN and NTN nodes will also need to be optimally allocated and leveraged.

**Conclusion**

In this paper, we connected the dots between ground, aerial, and spaceborne communications, and reviewed the key opportunities and challenges brought about by integrating terrestrial and non-terrestrial networks. We studied augmenting a ground deployment with upilted cells, and also complementing it with a LEO constellation. We found both to be promising avenues for supporting aerial communications, under the right design choices: the former entails advanced interference mitigation capabilities, the latter hinges on a sufficiently dense constellation — to guarantee

![FIGURE 4. Downlink SINR for eVTOL passengers when connected to MNO, and when offloaded to MNOS. For the latter, various LED satellite elevation angles and beam FRFs are considered.](image)
near-zenith coverage — and a carefully designed beam reuse.

Research progress in terms of 3D radio access, mobility management, and network orchestration will help addressing the challenge of extreme heterogeneity arising within an integrated TN-NTN. The sheer dimension, complexity, and dynamicity of the network, paired with its numerous underlying performance tradeoffs, calls for efficient data-driven developments ranging from learning-based spatially consistent channel modeling to a large-scale, distributed, stochastic, multi-objective optimization of the integrated TN-NTN.

REFERENCES

[1] G. Geraci et al., “What Will the Future of UAV Cellular Communications Be? A Flight from 5G to 6G,” IEEE Commun. Surveys and Tuts., vol. 24, no. 3, 2022, pp. 1304–135.

[2] Q. Wu et al., “A Comprehensive Overview on 5G-and-beyond Networks with UAVs: From Communications to Sensing and Intelligence,” IEEE JSAC, vol. 39, no. 10, 2021, pp. 2912–2945.

[3] F. Rinaldi et al., “Non-Terrestrial Networks in 5G & Beyond: A Survey,” IEEE Access, vol. 8, 2020, pp. 165,178–200.

[4] M. Giordani and M. Zorzi, “Non-Terrestrial Networks in the 6G Era: Challenges and Opportunities,” IEEE Network, vol. 35, no. 2, 2021, pp. 244–251.

[5] M. Mozaffari et al., “Toward 6G with Connected Sky: UAVs and Beyond,” IEEE Commun. Mag., vol. 59, no. 12, 2021, pp. 74–80.

[6] M. U. Chowdhury et al., “Ensuring Reliable Connectivity to Cellular-Connected UAVs with Uptilted Antennas and Interference Coordination,” ITU J. Future and Evolving Technol., 2021.

[7] O. Kodheli et al., “Satellite Communications in the New Space Era: A Survey and Future Challenges,” IEEE Commun. Surveys Tuts., vol. 23, no. 1, pp. 70–109, 2021.

[8] G. Karabulut Kurt et al., “A Vision and Framework for the High Altitude Platform Station (HAPS) Networks of the Future,” IEEE Commun. Surveys Tuts., vol. 23, no. 2, 2021, pp. 729–759.

[9] Y. Zeng et al., UAV Communications for 5G and Beyond, Wiley — IEEE Press, 2020.

[10] W. Saad et al., Wireless Communications and Networking for Unmanned Aerial Vehicles, Cambridge University Press, 2020.

[11] X. Lin et al., “5G From Space: An Overview of 3GPP Non-Terrestrial Networks,” IEEE Commun. Standards Mag., vol. 5, no. 4, 2021, pp. 147–153.

[12] X. Lin, “An Overview of 5G Advanced Evolution in 3GPP Release 18,” IEEE Commun. Standards Mag., vol. 6, no. 3, 2022, pp. 77–83.

[13] A. Garcia-Rodriguez et al., “The Essential Guide to Realizing 5G Connected UAVs with Massive MIMO,” IEEE Commun. Mag., vol. 57, no. 12, 2019, pp. 84–90.

[14] J. Sedin et al., “Throughput and Capacity Evaluation of 5G New Radio Non-Terrestrial Networks with LEO Satellites,” Proc. IEEE Globecom, 2020.

[15] W. Xia et al., “Generative Neural Network Channel Modeling for Millimeter-Wave UAV Communication,” IEEE Trans. Wireless Commun., 2022, pp. 1–1.

BIOGRAPHIES

GIOVANNI GERACI (giovanni.geraci@upf.edu) is an Associate Professor at Univ. Pompeu Fabra in Barcelona. He is an IEEE ComSoc Distinguished Lecturer, co-edited the book “UAV Communications for 5G and Beyond,” and received the IEEE ComSoc EMEA Outstanding Young Researcher Award.

DAVID LÓPEZ-PÉREZ is an Expert and Technical Leader at Huawei Research in Paris. He was a Bell Labs Distinguished Member of Technical Staff and has co-authored 150+ research articles, 50+ filed patents, and two books on small cells and ultradense networks.

MOHAMED BENZAGTA is a Ph.D. candidate at Univ. Pompeu Fabra in Barcelona. He received B.Sc. and M.Sc. degrees from Atılım Univ. in Ankara and the IEEE Globecom 2022 Best Paper Award.

SYMEON CHATZINOTAS is Full Professor and Head of the SIG-COM Research Group at SnT, Univ. of Luxembourg. He was co-recipient of the 2014 IEEE Distinguished Contributions to Satellite Communications Award and has co-authored more than 450 technical papers.