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

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

***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.**

I. 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 uncrewed aerial vehicles (UAVs) will navigate 3D aerial highways—be it for public safety or to deliver groceries to our doorstep—and flying taxis will reshape 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: (i) re-engineered and optimized to support aerial end-devices [5], [6], or (ii) 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: (i) deploying dedicated uptilted cells—or partnering with a specialized aerial operator doing so—reusing the same spectrum; (ii) 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.

II. 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.

A. 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- or 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

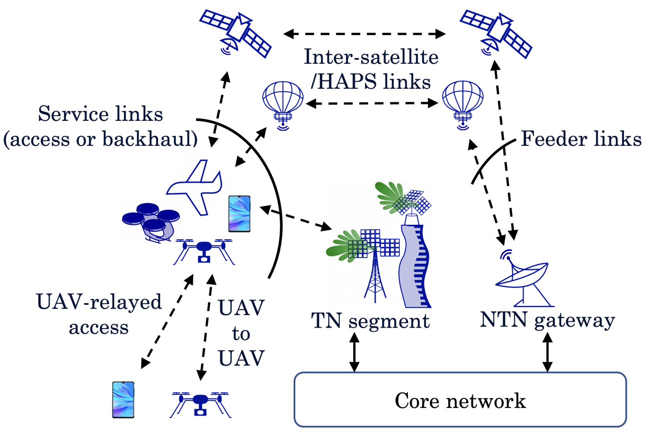

Fig. 1: Exemplified integrated TN-NTN. NTN BS functionalities can be placed onboard satellites or at the NTN gateway, respectively entailing a regenerative or transparent satellite payload [7].

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 in Section III will deliberately focus on this all-important use case.

B. 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 (HAPS) 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.

C. Standardization

Standardization work on non-terrestrial communications in 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 work carried out from Rel-15 up to Rel-17, along with the topics currently under study for Rel-18 are outlined as follows and summarized in Table I.

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 Rel-17, a set of basic features were introduced to enable 5G New Radio (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

TABLE I: Overview of the 3GPP standardization work on NTN and UAV communications [1], [11], [12].

Release	Non-terrestrial Networks (NTN) Enhancements	Support for Uncrewed Aerial Vehicles (UAVs)
Rel-15	**Study on NR to support NTNs [TR 38.811]** 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.	**Enhanced LTE support for aerial vehicles [TR 36.777]** Solutions for interference mitigation, mobility, and UAV identification. Air-to-ground channel models based on TR 38.901. **Enhancements to measurement report triggering [TS 36.331]** Enhancements included the addition of two reporting events to help the network identify a UAV and deal with any potential interference.
Rel-16	**Solutions for NR to support NTNs [TR 38.821]** Below-8 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. **Using satellite access in 5G [TR 22.822]** Use cases considering the integration of 5G satellite-based access components, new services and the corresponding requirements.	**Remote identification of UAVs [TS 22.825]** 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. **UAV connectivity, identification, and tracking [TR 23.754]** 3GPP-supported connectivity between UAVs and the UAV traffic management, detection and reporting of unauthorized UAVs.
Rel-17	**Narrowband IoT (NB-IoT) and enhanced machine-type communication (eMTC) support for NTN [TR 36.763]** Focused on IoT applications by addressing issues related to LTE timing relationships, uplink synchronization, and retransmissions. **Architecture aspects for using satellite access in 5G [TR 23.737]** 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.	**5G enhancements for UAVs [TS 22.125, TS 22.829]** New UAV communication needs related to: payload, command and control link, on-board radio access node, and service restrictions. **Application layer support for UAVs [TR 23.755]** 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 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.	**NR support for UAVs** Enhancements on measurement reports, subscription-based UAV identification and its multicast, conditional handover, and beam management below-8 GHz, including BS uptilt beamforming.

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: 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, 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 uptilting, and signaling to indicate UAV beamforming capabilities, among other enhancements [12].

III. Opportunities for Aerial Services

In this section, we consider two multi-operator case studies to illustrate how terrestrial networks could be (i) efficiently re-engineered to support non-terrestrial end-devices such as UAVs, or (ii) opportunistically complemented by non-terrestrial infrastructure to augment their current capabilities. The main system-level assumptions for these two setups are summarized in Table II.

A. Example I: 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, $\mathsf{MNO_T}$, running a standard network comprised of downtilted cells to serve legacy GUEs.
- An aerial operator, $\mathsf{MNO_A}$, running a dedicated network of uptilted 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 $\mathsf{ISD_T}$ and $\mathsf{ISD_A}$ denote the respective inter-site distances, whereby we fix the former to 500 m, and vary the latter to study its effect. We assume 15 GUEs for each $\mathsf{MNO_T}$ cell, and for all values of $\mathsf{ISD_A}$, we keep the UAV density constant and according to 3GPP Case 3 in TR 36.777, yielding $\{1,\ 4,\ 9\}$ UAVs/cell under $\mathsf{ISD_A} = \{500,\ 1000,\ 1500\}$ 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 omnidirectional 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 $\mathsf{MNO_T}$ and $\mathsf{MNO_A}$ to be respectively downtilted by $-12°$ and uptilted by $45°$, the former being commonplace for $\mathsf{ISD_T} = 500$ m, and the latter yielding the best UAV performance in most cases. Each cell is equipped with an 8×8 massive multiple-input multiple-output (MIMO)

TABLE II: System-level parameters for the operators and end-devices considered [3GPP TR 38.901, 36.777, 38.811, and 38.821].

MNO_T & MNO_A	
Cell layout	Hexagonal, 3 sectors/site, 1 BS/sector at 25 m
Intersite distance	$ISD_T = 500$ m, $ISD_A = \{1500, 1000, 500\}$ m
Frequency band	100 MHz TDD at 3.5 GHz
Spectrum	MNO_T and MNO_A in the same band
Scheduler (round robin)	DL: 50 MHz per GUE, 50 MHz per UAV
	UL: 10 MHz per GUE, 50 MHz per UAV
Precoding	DL: ZF (8 users) or EDA (8 users + 16 nulls)
	UL: ZF (4 users) or EDA (4 users + 8 nulls)
Downlink power	MNO_T: 46 dBm, MNO_A: 46 dBm or less
Uplink power	Fractional power control with $\alpha = 0.80$, $P_0 = -100$ dBm, and $P_{max} = 23$ dBm
Antenna elements	Horiz./vert. HPBW: 65°, max gain: 8 dBi
Antenna array	8×8 X-POL, fully digital
Antenna tilt	MNO_T: 12° (down), MNO_A: $-45°$ (up)
Noise figure	7 dB
MNO_S	
Cell layout	Orbit: 600 km, 7 beams centered on a hexagonal grid, elevation angle: variable
Frequency band	FRF=1: 30+30 MHz (DL+UL) FDD at 2 GHz
	FRF=3: 10+10 MHz (DL+UL) FDD at 2 GHz
Spectrum	MNO_S and MNO_T in orthogonal bands
Scheduler	DL: single-user round robin, whole band
	UL: multi-user round robin, 360 kHz each
Downlink power	34 dBW/MHz per beam
Uplink power	Always max power $P_{max} = 23$ dBm
Beam antenna	Circular aperture, HPBW: 4.41°, max 30 dBi
G/T	1.1 dB/K
Users	
GUE distribution	15 GUEs per MNO_T cell: 80% in buildings of 4–8 floors, 20% outdoor at 1.5 m
UAV distribution	1 UAV per MNO_T cell, at 150 m
eVTOL distribution	0.1–1 eVTOLs per MNO_T cell, at 1500 m
Traffic and load	Full buffer, fully loaded network
User association	Based on RSRP (large-scale fading)
User antenna	Omnidirectional, gain: 0 dBi
Noise figure	9 dB

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 MNO_T and MNO_A for channel state information acquisition, possibly entailing them to belong to the same network provider.

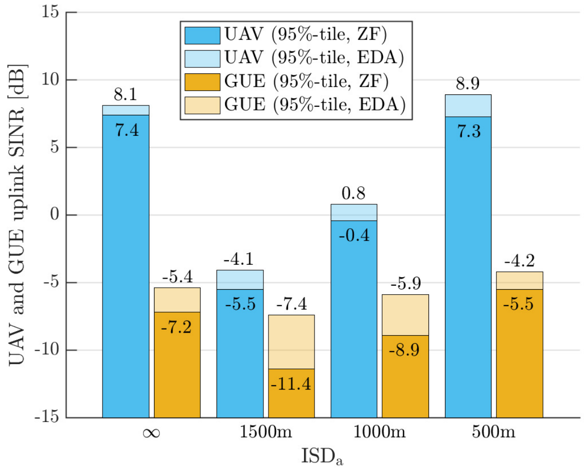

Fig. 2: 95%-tile of the uplink SINR for UAVs (blue) and GUEs (orange), for $ISD_T = 500$ m and a variable ISD_A, and employing ZF (solid) or EDA (transparent) precoding. $ISD_A = \infty$ denotes all GUEs and UAVs served by standalone MNO_T.

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]. Fig. 2 shows the 95%-tile signal-to-interference-plus-noise ratio (SINR) attained by UAVs and GUEs for various values of ISD_A and the two precoding schemes. As a baseline, $ISD_A = \infty$ represents the case without MNO_A, where MNO_T serves all GUEs and UAVs. These results show the following:

- Offloading UAVs from MNO_T sees their SINR reduced, unless the deployment of MNO_A is sufficiently dense. Importantly, $ISD_A \leq 1000$ m is sufficient to keep at least 95% of the UAV in coverage, i.e., with an SINR above -5 dB. Offloading in such MNO_A dense deployments also provides UAVs with higher data rates, as shown later.
- As ISD_A 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 MNO_T, 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 MNO_T. However, the spatial and spectrum reuse gains provided by MNO_A reflect in the UAV data rates, reported in Fig. 3 for the uplink. These largely benefit from increasing the deployment density of MNO_A and employing EDA precoding. Focusing on the 95%-tile, standalone MNO_T with ZF provides 36 Mbps as opposed to the 134 Mbps achievable with MNO_T-plus-MNO_A and $ISD_A = 500$ m. The former may be sufficient for remote UAV controlling through high-definition video,

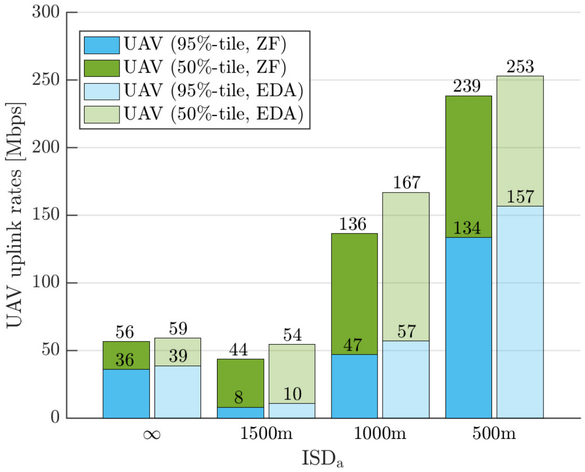

Fig. 3: Uplink UAV rates for $\mathsf{ISD}_\mathsf{T} = 500$ m and a variable ISD_A, and employing ZF (solid) or EDA (transparent) precoding. $\mathsf{ISD}_\mathsf{A} = \infty$ denotes all GUEs and UAVs served by standalone MNO_T. Blue and green bars denote 95%-tile and 50%-tile, respectively corresponding to the 5%-worst and the median user rate performance.

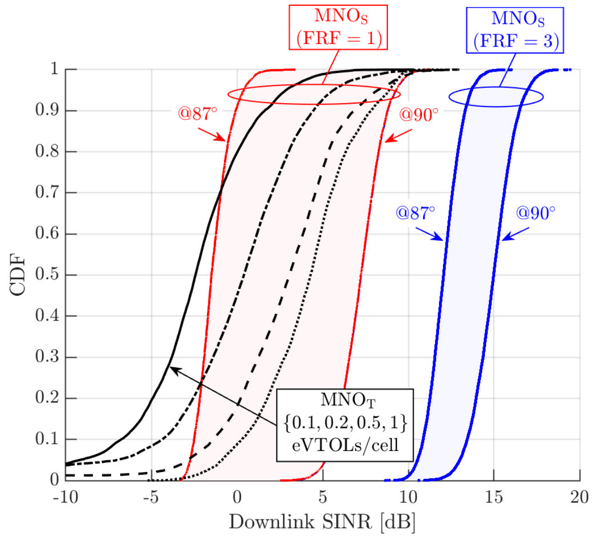

Fig. 4: Downlink SINR for eVTOL passengers when connected to MNO_T and when offloaded to MNO_S. For the latter, various LEO satellite elevation angles and beam FRFs are considered.

whereas the latter may also empower 8K real-time video live broadcast (for future extended reality applications) and 4×4K artificial intelligence surveillance (for control and anti-collision in building-intensive areas, lacking positioning accuracy) [1].

B. Example II: Complementing TNs with NTN Infrastructure

While primarily targeting underserved areas, NTNs 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_T as in *Example I*.
- A satellite operator MNO_S, availing of a LEO constellation and operating in an orthogonal S-band (sub-6 GHz).

Our focus on LEO satellites is motivated by their better capacity and latency with respect to their GSO counterpart. These advantages arise from the LEO higher proximity to the Earth, entailing a stronger link budget, a higher beam reuse, and a shorter propagation delay [3], [4]. Each LEO BS of MNO_S generates multiple Earth-moving beams pointing to the ground in a hexagonal fashion, each creating one corresponding NTN cell [14]. Due to its orbital movement, the LEO satellite may be seen by the users under a variable elevation angle, defined as the angle between the line pointing towards the satellite and the local horizontal plane, whereby angles closer to 90° yield shorter LEO-to-user distances, and are more likely to be in LoS. Besides the elevation angle, the NTN performance is affected by the beam frequency reuse factor (FRF). With $\mathsf{FRF} = 1$, all frequency resources are fully reused across all beams, whereas with $\mathsf{FRF} = 3$, they are partitioned into three sets, each reused every three beams. The assumptions reported in 3GPP TR 38.811 and 38.821 are used to characterize the main NTN propagation features.

This time we focus on the downlink, likely the predominant direction for eVTOL occupants. For the latter, Fig. 4 shows the cumulative distribution function (CDF) of the SINR experienced when all are served by MNO_T and when their traffic is offloaded to MNO_S. For MNO_S, 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., $\mathsf{SINR} < -5$ dB, reaching up to 18% 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 nullsteering (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.
- Moving from $\mathsf{FRF} = 3$ to $\mathsf{FRF} = 1$ 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 $\mathsf{FRF} = 1$. Nonetheless, all offloaded users still remain in coverage, even in the presence of inter-beam interference ($\mathsf{FRF} = 1$).

As for the achievable rates, assuming one eVTOL passenger per cell over an area of $10.8\,\text{km}^2$—the size of Sant Martí, Barcelona's business district—yields a total of 150 users, out of which those in outage (18%, i.e., 27 users) could be offloaded to $\mathsf{MNO_S}$. Under an ideal elevation angle of 90° and $\mathsf{FRF} = 3$, they would experience median rates of 3 Mbps. Reducing the density of eVTOLs rapidly increases their experienced rates as both their absolute number shrinks and so does the outage percentage from $\mathsf{MNO_T}$. Specifically, 0.5 and 0.2 eVTOLs per cell yield 75 and 30 eVTOLs in total, respectively. Out of these, 8.8% and 2.6% experience SINRs below -5 dB, for a total of 7 and 1 eVTOLs incurring outage, respectively. When offloaded to $\mathsf{MNO_S}$, their median rates would be of around 11 Mbps and 80 Mbps, respectively.

While our findings are encouraging, they also suggests that in a future with hordes of high-altitude 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.

IV. 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.

A. 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.

B. 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 uptilted 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.

V. 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 uptilted 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 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 underlaying 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.

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BIOGRAPHIES

Giovanni Geraci is an Assistant 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 ultra-dense networks.

Mohamed Benzaghta is a Ph.D. candidate at Univ. Pompeu Fabra in Barcelona. He received B.Sc. and M.Sc. degrees from Atilim Univ. in Ankara and his research interests include the integration of terrestrial and non-terrestrial wireless communications.

Symeon Chatzinotas is Full Professor and Head of the SIGCOM 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.