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6G in the sky: On-demand intelligence at the edge of 3D networks (Invited paper)

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Abstract

Sixth generation will exploit satellite, aerial, and terrestrial platforms jointly to improve radio access capability and unlock the support of on-demand edge cloud services in three-dimensional (3D) space, by incorporating mobile edge computing (MEC) functionalities on aerial platforms and low-orbit satellites. This will extend the MEC support to devices and network elements in the sky and forge a space-borne MEC, enabling intelligent, personalized, and distributed on-demand services. End users will experience the impression of being surrounded by a distributed computer, fulfilling their requests with apparently zero latency. In this paper, we consider an architecture that provides communication, computation, and caching (C3) services on demand, anytime, and everywhere in 3D space, integrating conventional ground (terrestrial) base stations and flying (non-terrestrial) nodes. Given the complexity of the overall network, the C3 resources and management of aerial devices need to be jointly orchestrated via artificial intelligence-based algorithms, exploiting virtualized network functions dynamically deployed in a distributed manner across terrestrial and non-terrestrial nodes.

KEYWORDS

3D connectivity, 3D services, 5G, 6G, B5G, high-altitude platform stations, mobile edge computing, non-terrestrial communications, satellite, unmanned aerial vehicle

1 | INTRODUCTION

Coverage is a critical key performance indicator (KPI) when deploying wireless networks. Up to 4G networks, most efforts have been focused on increasing link capacity while ensuring sufficient coverage in the two-dimensional (2D) plane. Fifth generation (5G), with its multi-dimensional requirements, adds more stringent constraints, for example, for mission-critical services that require low latency and high reliability (URLLC), massive amounts of devices (eMMB), range extensions, and operational costs (OPEX) of the communication infrastructure. Further, 5G allows the exploitation of new opportunities by sharing the underlying infrastructure among isolated and self-contained networks through the concept of network slicing. Moreover, starting from the 4G-LTE all-IP architecture, such networks offer communication coverage and the integration of cloud support. Nevertheless, these services are offered on a 2D plane, and cloud services were conceived for data fetching/storage (over significant distances between data centers and connected users) and to provide services (for example, social media or instant messaging) to mobile Internet users. Newly emerging 5G services ask for solutions going beyond this framework, including ubiquitous coverage/capacity availability and service scalability adapted to new use cases, application scenarios, and traffic conditions, which would be a tough challenge for the one-network-fits-all 4G-LTE architecture.

While the availability of good terrestrial coverage has become common in densely populated areas and regions, the underlying business model based on a flat fee per user does not scale well in sparsely populated regions or areas with difficult orography (eg, islands, rugged mountainous terrain, or offshore). Worldwide mobile network operators usually provide no, poor, or at best low-quality connectivity in those cases, while the potentials of these regions can only be fully exploited when providing connectivity for the digitization of their economic activities, for example, smart agriculture or mining. The relevant KPIs in this context are ubiquitous connectivity, scalability, and affordability. Moving from 2D to 3D coverage is an enabling solution, the third dimension results from placing network elements up in the sky and space.

1.1 | Cooperation among terrestrial and aerial/spatial networks

Many recent research projects have investigated the cooperation between terrestrial and low earth orbit (LEO) satellite networks for 5G new radio (NR). Within the 3GPP framework, use cases and associated system requirements for satellite integration in the 5G ecosystem are specified and continuously updated by the working group SA1 in [1]. The impact of standardization on the NR specification was studied in [2,3], considering non-terrestrial networks (NTNs) as an integral part of NR. The successful outcome from these studies led to normative work in Release 16, which specifies extensions to NR for unmanned aerial vehicles (UAVs) [4], high-altitude platform stations (HAPSs), and satellites based on well-defined channel models, deployment scenarios, and system parameters. Likewise, future 3GPP releases will focus on solutions for radio access network (RAN) protocols and architecture.

The 5G AgiLe and flexible integration of SaTellite and cellulaR (5G-ALLSTAR) H2020 project [5] investigates multi-connectivity technologies that integrate cellular and satellite networks to provide reliable, ubiquitous, and broadband services for 5G NR. This is the first investigation regarding terrestrial and non-terrestrial communication integration in the 5G CHAMPION project [6]. Multi-connectivity requires significant innovations in the integration of millimeter-wave (mmWave) 5G-NR-based cellular system with an NR-based satellite system as well as adoption of spectrum sharing and interference management techniques. The H2020 project VITAL addresses terrestrial and satellite networks by enabling software-defined networking (SDN)-based, federated resource management in hybrid satellite-terrestrial networks. The H2020 project SANSA aims to enhance the capacity and resilience of wireless backhauling through the cooperation of terrestrial-satellite networks. In these projects, load balancing, efficient spectrum usage, improved coverage, and link performance are sought.

High-altitude platform stations [7] are unmanned aircraft positioned at an altitude of over 20 km in the stratosphere for very long-duration flights counted in years. Since the 1990s, a number of initiatives have been launched worldwide to explore potential applications, including telecommunications services. HAPSs offer a wide area coverage with advantages compared to satellites in terms of cost, ease of deployment/reuse, large payloads, lower delays, and signal attenuation. Recently, Google's Loon project has deployed a network of high-altitude solar-powered balloons that move using wind jets. They carry regenerative payloads and inter-balloon communication links, and their networks coexist with terrestrial LTE networks, providing services to rural mobile broadband users in areas where terrestrial coverage does not exist. Some other operational HAPS with higher payload capacity (such as Thales-Alenia's Stratobus dirigible) are expected by 2021–2023.

At a lower altitude, drones are UAVs that have the capacity to dynamically provide radio on-demand coverage exploiting embarked light base stations (BSs) [8,9]. UAVs and HAPSs have received considerable attention [10] in terms of data traffic management [11], network coverage enhancement [12,13], improving the quality of service [14,15], propulsion and transmission powers [16], latency minimization [17], and exploitation of network access [18].

1.2 | Hierarchical BS fleets for providing computing and intelligence functionalities

Several studies in the literature such as [16,17,19] and [13] proposed different architectures and mathematical models for 3D networks comprising multiple UAVs, focusing in particular on the communication aspects such as data backhauling and reduced latency, whereas the architecture that will be presented in this paper focuses on joint communication, computation, and caching (C3) capabilities, which are considered to be the components of a single 3D system. Extending the use of UAVs to provide not only radio access but also mobile computing functionalities is actually considered a promising paradigm for satisfying *on-demand* communication and computation requests as well as delivering *context-aware* cloud services to mobile users. The first attempt to host cloudlet processors on a UAV was addressed in [20]. The target is to minimize the energy at the user equipment (UE) while optimizing transmission data rates jointly with the UAV's trajectory under latency constraints. In [21], the authors include an edge computing scenario with aerial platforms and heterogeneous Internet-of-Things (IoT) devices. A dynamic formulation appears in [22], where computation offloading is handled with stochastic optimization tools that have energy consumption as a goal while optimizing the trajectory of UAVs. In [23], a dynamic online strategy jointly allocates communication and computation resources while selecting the vehicle's altitude with the aim of minimizing the system energy and satisfying latency constraints. The work in [24] introduces fog computing into drones, with the aim of handling computation-intensive offloading of tasks. In [25], the sum power consumption was minimized for a multi-UAV-enabled mobile edge computing (MEC) network.

In our vision, research is needed to investigate solutions in realistic scenarios in which 3D services are supported by a hierarchical fleet BS carried on UAVs, HAPSs, and LEO satellites, each having its own specific features in terms of payload, flight autonomy, mobility, service coverage time, altitude, revisit time, computation, storage, coverage area, link power budget, and other factors. In such a challenging context, ensuring end-to-end service continuity for ground users or to users moving in 3D space entails rethinking the mobility management mechanisms incorporating proactive allocation of the content, smart proactive caching of recurrent computational results [26], instantiation of virtual machines, interference management, and joint handover between radio access points (APs) and MEC hosts. This will require the development of a fast live migration of light virtual machines, for example, dockers, and an extension of NFV/SDN orchestration schemes to make them more inclusive with respect to the types of network nodes as well as faster to support the mobility of both user terminals and network elements.

Artificial intelligence (AI) can help solve these issues. The last decade has witnessed rapid progress in the field, driven by the increased computational capacity of computers and the wide availability of data sets. In end-to-end communications, the ETSI Experiential Network Intelligence group investigates how 5G networks can leverage AI to achieve autonomy and thus cost-effectiveness, slice management, and orchestration. Inspired by the success of AI in solving complicated control and decision-making problems, distributed AI approaches are enablers that allow the network functionalities learn about the network and make the best decisions accordingly.

Looking into the predictions of new technologies and services for the next decade, there is a clear need to move beyond 2D service coverage to truly 3D native services. In future, 6G networks will enable end users to move in the 3D space to perceive a surrounding "huge artificial brain" offering virtually zero latency services, unlimited storage, and immense cognition capabilities [27]. To match this vision, future 6G networks will seamlessly incorporate terrestrial, aerial, and satellite radio APs to teleport *on-demand* cloud functionalities *where* and *when* intelligence support is needed in 3D space.

1.3 | Purpose and structure of the paper

The purpose of this article is to identify a set of technological advances in order to highlight the main research challenges and open issues for the next decade of research to move beyond pure 2D service coverage to truly 3D native service. In this direction, Section 2 details the foreseen 3D hierarchical system architecture for future 6G networks. Section 4 presents the enhancement of 2D terrestrial connectivity and services for 3D support of joint C3. Section 3 details the current status of standardization bodies, future trends in the integration of NTN for 5G NR, and opportunities for innovation for 6G networks. Section 5 evaluates the solutions for interference management in 3D hybrid intelligent networks. Section 6 describes possible solutions for the effective management of multiple radio access technology (RAT) resources in 3D space through dynamic admission control mechanisms and load balancing. Key observations and concluding remarks are presented in Section 7.

2 | SYSTEM ARCHITECTURE

Hierarchical 3D networks with multiple and heterogeneous types of flying layers are key to providing enhanced 2D services [28] and 3D native services, including connectivity and intelligence support. Figure 1 illustrates the high-level architecture of the hierarchical 3D networks unifying diverse 3D network nodes distributed over ground and flying layers. Different types of aerial nodes, such as UAVs, and more generally low altitude platforms (LAPs), HAPSs, and LEO/GEO satellites are located on different flying layers. Because aerial nodes can be equipped with on-board computation/storage capabilities, they can serve as 3D base stations alone, in swarm formation, or as 3D relay, which comprises integrated access and backhaul (IAB)-based hierarchical 3D networks.

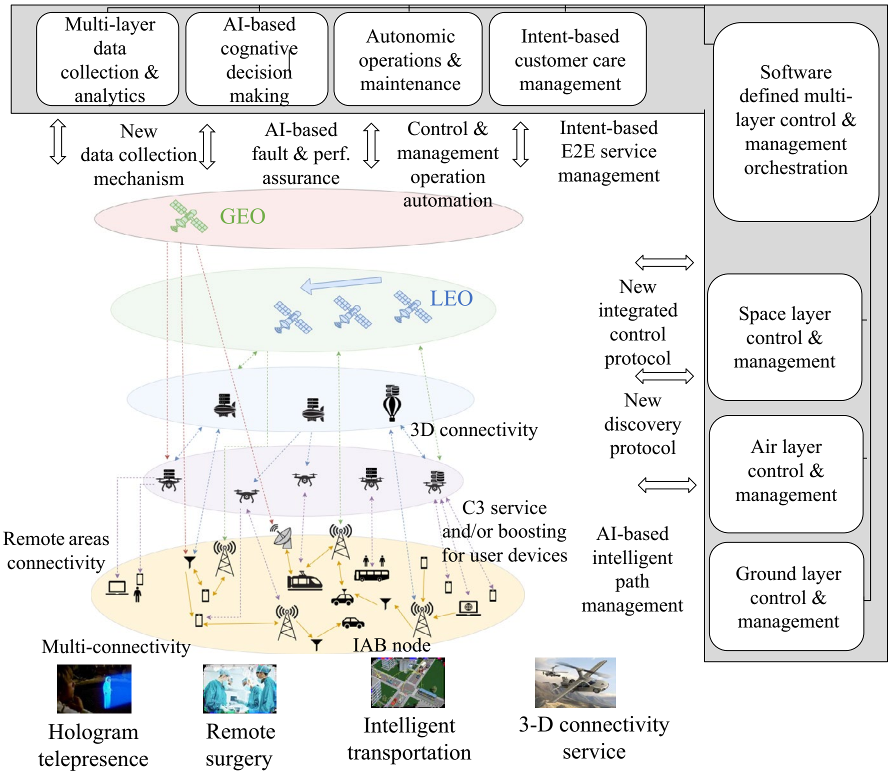

FIGURE 1 Hierarchical 3D network system architecture

Although the current IAB standardization in 3GPP focuses on the ground network, in 6G, it will be extended to air and space networks as well as their integrated networks.

Low- and high-altitude platforms have several key potential applications in wireless communication systems owing to their high mobility, flexibility, adaptive coverage capacity, and low cost. Equipped with MEC servers, these aerial vehicles can provide opportunities for ground mobile users to offload heavy computation tasks. Then, after computation, the mobile users can download the computation results via reliable, cost-effective wireless communication links, and download each kind of required content. The proposed integrated 3D architecture enables the boosting of C3 performance in areas with existing infrastructure and provides a network infrastructure for C3 services in areas without coverage. These 3D connectivity services exploit the flexibility to accommodate a wide spectrum of applications ranging from two-way telecommunications (eg, interactive 3D video or 3D intelligent services), remote sensing, pollution monitoring, meteorological measurements, real-time earth monitoring, traffic monitoring and control, land management, and agriculture.

The connectivity of UEs, BSs, and relays placed on different flying layers can lead to much larger connectivity handover instances, mainly because of the difference in the heights and speeds of nodes belonging to different flying layers. Today, open research problems for offering 3D service continuity and handover instance minimization include the cross-layer harmonization of selected UAV, HAPS, and satellite placement as well as the optimization of flying trajectories. In addition, in 2005, NASA proposed the vision of a *Space-Wide Web network*, where messages can hop between intermediate nodes to reach close planets that have every orbiter, rover, space-borne telescope, or any other skyward-launched device working as a node of the 3D network [29]. At the horizon of 2030, with 6G, 3GPP standards will not go so far. Nevertheless, a *Sky-Wide Web or Internet of the Sky* might already be interconnected with 6G non-terrestrial 3D networks. In this hierarchical 3D network, 3D multi-connectivity allows UEs to establish multiple different traffic links with 3D network nodes, thereby significantly improving the service performance of the UE with a dynamic load balancing scheme over the established links. However, this requires specifically designed, highly efficient, and intelligent control and management of 3D layers.

In our view, future 3D system architectures will apply network slicing not only across terrestrial nodes as designed for 5G networks, but also across non-terrestrial nodes to facilitate different use cases and services provisioned in 3D space. The proposed architecture shall then be able to offer services that go beyond pure connectivity and at the same time offer deep customization of connectivity and intelligent mobile network services at different granularity levels, with spacing from dedicated slices per data of users to slices per individual and groups of users and to slices dedicated to 3D applications and 3D subnetworks. This will require a new adaptable *midhaul* for an era of services that goes well beyond the services of today's 5G networks and those envisaged in most studies that focus on integrating UAVs into 5G networks.

AI-based approaches for network control also play a pivotal role in intelligent routing selection across 3D network layers and load balancing. For this reason, the proposed architecture should be able to provide network intelligence capabilities at various levels and include device-to-device (D2D) communication, which may be enhanced by the addition of a new dimension and moving network equipment such as UAVs. In 3GPP, the first version of an NR sidelink for the support of advanced V2X applications was developed in Release 16, and in 3GPP Release 17, sidelink-based relaying functionality will be studied on top of the Release 16 sidelink specification for the purpose of sidelink/network coverage extension and power efficiency improvement. In 6G, D2D communications will be further extended to 3D layers, which could have great potential in facilitating a wider range of applications and services, such as next-generation intelligent transportation services.

3 | STANDARDIZATION PERSPECTIVE

Terrestrial mobile telecommunication standards are grouped into generations (1G, 2G, 3G, 4G, and 5G), and the related 3GPP technical specification documents with particular feature sets have evolved with associated release numbering, for example, Release 8 is the first release of 4G-LTE and Release 15 is the first of 5G-NR. Typically, a new generation arises at the confluence of significant maturity of new groundbreaking technologies and the societal need for the introduction of new services that cannot be efficiently offered by current technologies. Standards define the set of new technologies to be included in the new generation. To this end, in order to have particular features become a part of a standard release and/or specific technologies supported by the standard, many aspects must be considered. Beyond economic potential and technological maturity, it is very important to evaluate the standardization impact with respect to the required changes to existing specifications and features, which might already be rolled out in the market for billions of devices and BSs. The smaller the impact with respect to the technical specification and the bigger the expected commercial benefit in the ecosystem, the higher the chances a feature will be adopted into a standard.

3.1 | Terrestrial networks and NTNs

For many years, researchers have been advocating solutions for a converged integration of terrestrial and satellite communication into handheld devices and mission control centers [8], which range from over-the-top multi-RAT approaches [30] to fully unified air interfaces [31]. Conducted field trials with adapted 4G-LTE system parameters [32] proved feasibility, but only recent advances in 5G-NR standardization [8] have finally brought commercial impact into graspable reach.

Continuous efforts were made by the satellite community to engage in and contribute to the 3GPP process, which has focused on land mobile networks for decades. The inclusion of NTN use cases and deployment options into the 3GPP technology feature roadmap is a best-practice example of how vertical industries can actively push boundaries and obtain vital technologies included in an evolving standard. Initial skepticism by many critics was overcome by a gradual approach, first to study the impact of NTN use cases on 5G-NR and to provide suitable channel models [3] and simulation assumptions [33] matched well with the well-established 3GPP evaluation procedures and, after successful completion, continuing with nominal work in Releases 16 and 17.

The 3D component is a new territory for network design, particularly when aspects and KPIs such as coverage, capacity, reliability, interference, and mobility must be extended and evaluated in 3D. It is expected that providing ubiquitous connectivity in 3D will require significant changes in architecture, function placement, and network node design beyond the current approaches for terrestrial 5G BSs and satellites deployed in recent times. One example is MEC placement in an LEO satellite network to provide, for example, a virtual private network slice for maritime or air fleet applications with low latency service requirements. MEC placement may require fundamentally new approaches for dynamic allocation of C3 resources on LEO nodes, including inter-node connections in space and between space and the ground. Thus, the standardization impact goes beyond 3GPP and will touch standardization groups in charge of MEC, SDN, fronthaul, and other interfaces involved in building a fully functional communication network.

The latest satellite network deployments will increasingly populate LEO at 500 km–1000 km in altitude. Various corporations and consortia, for example, Amazon's Project Kuiper, OneWeb, Telesat, or Elon Musk's Starlink, plan to provide Internet services from 2021, with current deployments ranging from a few dozens to hundreds of satellites, some targeting more than 10 000 in the future. Bend-pipe satellites retain flexibility for air-interface selection, for example, DVB, S2X, or LEO adapted variants of LTE, NB-IoT, or 5G-NR. On the other hand, on-board signal processing helps to reduce e2e latency in space packet routing and MEC. This will further open the existing satellite ecosystem for interoperability and scalability in market size at chip, module, device, and signal processing platform manufacturer, system, and service provider levels. Because satellite networks provide coverage footprints beyond the boundaries of countries or continents, infrastructure and spectrum sharing will become increasingly important for cost and spectrum efficient deployment as well as the operation of terrestrial networks and NTNs including very LEO, cube sats, and HAPSs.

3.2 | UAVs as machine type devices

For many years, UAVs have been used for research and tactical applications, and remote-controlled mini drones had to follow line of sight (LOS) constraints within a few hundred meters. With a sufficient coverage footprint, mobile networks can enable new UAV use cases treating drones as UEs. As a consequence, the coverage footprint has to be extended reliably into 3D, where cross-link interference becomes an issue because LOS links between a UAV, and many BSs have not been considered in cellular network design so far. Similar considerations apply for connecting airplanes from the ground using 4G or 5G BSs [8], where the flight corridors for civil aviation are sufficiently well separated from the close-to-ground drone traffic. Release 15 3GPP has studied [34] the ability for UAVs to be served by LTE and NR networks, identifying further performance enhancements for UE- and network-based solutions, DL and UL interference mitigation, mobility performance, and aerial UE identification. Further enhancements [35] addressed the issue of aerial UE interference, helping the eNodeB to see the UAV and to deal with any potential interference. Release 16 specified mechanisms for the remote identification of UAVs [4], and 3GPP SA1 completed a study into requirements and use cases for the services to be offered, based on remote UAS identification, which are to be continued in Release 17 [36]. With the given maturity of UAV support in the 3GPP standard, UAV operation and/or assistance over cellular networks is becoming close to commercial deployments aside from regulatory constraints, which seem to be undergoing changes in many regions in exploratory steps. Full-scale deployments of UAVs for use cases such as parcel delivery are years ahead, providing sufficient time from early field trials and commercial roll-outs to feed back into the standardization process for 5G+ and 6G.

3.3 | UAVs as a RAN

Instead of connecting UAVs with an existing RAN for control and communication from on-board equipment and/or sensors, UAVs may serve as deployed BSs or provide relaying functionality between devices and BSs of the RAN. Prominent examples of flying BSs for emergency networks or networks in remote areas are Google's Loon project [37] or unmanned airplanes supporting a larger coverage area while moving above the targeted coverage area at an altitude of 10 km–20 km. Alternative approaches consider drones at very low altitudes of 10 m–50 m to provide extra capacity at hotspots [38], for example, during large public gatherings. Considering non-stationary positions and a varying number of infrastructure components, for example, UAV mounted BSs to provide an extended cellular coverage, such dynamic topology with all its flexibility comes at the cost of additional features at the RAN side to be standardized. So far, moving BSs and/or networks have been tested and deployed in relative isolation, using proprietary interfaces, particularly for backhaul and interlinking between several BSs using LOS links over potentially hundreds of kilometers with mmWave or laser technology. For a wider acceptance in co-existence with terrestrial RAN deployments, further studies must be conducted beyond the ongoing discussions for 5G-NR.

3.4 | MEC mobility: ETSI

The framework and reference architecture for multi-access edge computing was specified in ETSI [39] and provides interfaces and messaging for integration and orchestration within a RAN specified by 3GPP for 5G-NR and IEEE for 802.11ac/ay and used for feasibility studies [40]. The dynamics of NTN topologies and the fact that we have a network of moving nodes impact on the existing standard with respect to predictive multi-access edge computing handover, user group handover, and session migration as well as meshed backhaul and multi-connectivity for mobile access.

4 | FROM 5G NR 2D ENHANCED SERVICES TO 6G 3D SERVICES

In this section, we focus on the coverage extension from 2D to 3D. First, we analyze the benefits of the inclusion of aerial devices in terms of connectivity. We then move to the service level, highlighting the need to move to a holistic approach that looks at C3 as components of a single system. We distinguish between 2D services involving devices on the ground potentially benefiting from 3D connectivity and 3D services involving devices on the ground and in the air. We discuss these aspects from the perspective of mobility management, handover, and live migration of virtual machines, and control of C3 services. Finally, we focus on the importance of including AI mechanisms in designing a cost-effective system, incorporating proactive mechanisms, and learning from online observations.

4.1 | 3D connectivity

Including UAV-based devices in wireless communication networks provides a cost-effective solution to improve connectivity, especially if the data traffic is non-homogeneous and non-stationary, that is, it is expected to be highly varying across space and/or time. In such a case, a fixed infrastructure is highly ineffective for both CAPEX and OPEX expenditures. As in many real-world situations, the opportunities offered by UAV-based devices face several challenges. To highlight these challenges, it is first necessary to classify the role that UAV-based devices can play in the network. The UAV devices may act as flying base stations (UAV-BSs), flying UEs (UAV-UEs), or flying relays (UAV-Rs).

A UAV-BS brings connectivity to the mobile devices on demand. The challenges arise from the nature of the UAVs. HAPSs have sufficient energy availability and are typically supported by solar-powered batteries; thus, they are able to support continuous coverage for a long time. They can typically be used to support long-term coverage purposes. On the contrary, the support of coverage in highly time-varying situations is better handled by LAPSs, which can be flown at the location of interest on demand. However, LAPSs have very limited energy availability and can hover over a given area only for a relatively short period of time. This means that flight and energy constraints should be taken into account when allocating the resources of the network. The limited weight payload that can be placed on a LAP suggests the use of higher frequency bands, for example, mmWave bands, to use smaller size antennas, and to achieve better spectral efficiency. However, the use of mmWave links faces the problems of link attenuation in the case of rain and blocking effects. To reduce link attenuation, it is necessary to limit the coverage area, possibly flying at the lowest permitted altitude. However, flying at low altitudes increases the probability of blocking. Momentary blocking also severely impacts the reliability of high-capacity radio links and MEC-assisted service continuity [41]. In 2D networks, the detrimental effects of blocking are reduced using multiple RATs or multiple interfaces of the same RAT. The adoption of 3D connectivity to enhance the performance of 2D networks brings interesting new opportunities and challenges to be solved [10] for the next decade in 5G and beyond-5G networks. The selection of the altitude plays a key role. Intuitively, the higher the altitude, the larger the coverage offered by the platform and the lower the chance of shadowing effects because of favorable LOS propagation conditions. However, high altitudes also imply larger distances and higher attenuation. The altitude has then to be carefully selected depending on the distribution of the UEs [23].

To enable several applications of UAV-assisted services, the UAVs need to communicate with the existing wireless network, either cellular or Wi-Fi. In such a scenario, the UAV acts as the UE of the wireless network. UAVs can also act as UE in applications such as delivery drones, real-time surveillance, and UAV-assisted transportation networks. In this case, we have a true *3D service exploiting a 3D network architecture*. An interesting example of a 3D service is a virtual reality scenario in which the UAV flies over a location of interest carrying a 360° camera, which is controlled from the end user UE to select the view angle specifying which part of the video needs to be transmitted with sufficient quality. To handle these 3D services properly, it is necessary to handle the interference that UAV-UEs can bring to terrestrial UEs. Typically, the antennas of current terrestrial BSs are designed to handle an essentially 2D coverage problem, so that the radiation patterns are usually attenuated at high elevation angles. As a consequence, the communication between UAV-UEs and conventional BSs typically relies on sidelobes or back lobes of the BS antenna. Clearly, a better design involves a proper redesign of the 3D beamforming at the BS, which is able to track the UAV-UEs. In [34], 3GPP specifies new BS antenna design and cellular communication techniques for UAV coverage up to the maximum altitude of 300 m. Most likely, it will be necessary for the BS to distinguish between the aerial and terrestrial UEs to handle them separately.

Finally, UAV devices can act as relays (UAV-R) to provide backhaul the connectivity between the terrestrial/aerial UEs and the terrestrial/aerial BSs. In such a case, the key challenge is to devise effective cooperative communication strategies that consider the mobility of the aerial devices. In principle, one could make near-distance UAV devices operate as a huge virtual antenna, with the possibility of adapting the shape of the constellation by making the UAVs move as needed, provided that the resulting synchronization problems are properly handled. In general, using UAVs as wireless relays can boost (on demand) the link quality between the ground BSs and the terrestrial UEs, but it also raises an interference issue toward the neighboring BSs that should be handled consequently.

4.2 | C3 support extension

UAVs can be used not only to improve connectivity, but also to bring (cloud) services closer to the end user on demand, thus extending the concept of edge computing, or fog computing, to incorporate the aerial devices as the edge of the network. In this way, delay-sensitive services can be delivered where and when needed [27]. Of course, the flight and energy constraints of some aerial devices, such as LAPSs, need to be incorporated in the system design. As an example of an application, in the IoT scenario, multiple sensors send their data for processing and the detection of possibly anomalous situations. Flying a UAV-BS with sufficient computational capability close to these sensors can be very effective in implementing a computation offloading strategy able to extract relevant information from the data near the location where the data are collected, thus accommodating strict delay constraints. In this way, the UAV-BS can help sensors run (remote) sophisticated algorithms or prevent excessive energy consumption. In other applications, such as disaster recovery, it is useful to bring content on demand to areas where context-aware information is needed. In this case, flying a UAV-BS with caching resources around the disaster area may be beneficial. We also note that 3D networks enhance the capabilities of D2D communications, a technology in which UEs communicate with one another to exploit and share their resources, which is studied in both emergency scenarios [42] and normal operations, such as decentralized and distributed computing [43,44]. In fact, a moving fleet of UAVs may also be used to coordinate such D2D connections and enhance their coverage.

In other scenarios, when the computation requests cannot be handled even by the UAV, it can still be useful to fly the UAV close to the end user and let it act as a relay to enable computation offloading to terrestrial devices that could otherwise be more difficult to reach within the required delay constraints. In all these cases, because the overall delay incorporates the delay of (round-trip) data transmission from the UE to the UAV, the delay associated with computation, and possibly the (round-trip) communication delay between the UAV and the terrestrial edge cloud, it becomes clear that C3 resources should be handled *jointly*. Indeed, in a 3D network scenario, the C3 resources should also be managed together with the control of the UAV position, taking into account the battery level on the UAV and the period of time in which the UAV can hover over the location of interest. This vision calls for a joint optimization of resources for control and C3 services.

This vision calls for a very flexible orchestration of control and C3 resources, building on the virtualization of many functionalities. In this way, virtual machines serving different purposes can be moved around to minimize the service delay, use resources only when needed, and then release them when not. This requires the design of the fast live migration of "light" virtual machines across moving nodes of the same network tier or cross-network tiers.

4.3 | Intelligent handovers for the handover of intelligence at the mobile edge of 3D networks

The handover of the UAV-BSs to the ground BSs becomes a part of the ground UE handover management problem. In such a case, both the ground UEs and the UAV-BSs compete for the same radio resources available at the ground BSs and, at the same time, the UEs can be also associated with the UAV-BSs.

The mobility of all types of UE is typically managed by individual BSs, and the serving BS is responsible for monitoring and controlling the UE's handover. Nevertheless, with the introduction of computing capabilities (eg, edge computing) in the network, the handover control functionalities can be deployed at any node having computation capabilities or even distributed across multiple nodes including UAVs in 3D space. However, UAVs nodes are often limited in terms of available energy. Thus, the control functionalities and the computation handled by these nodes in 3D can be handed over (or migrated) to another node over time to jointly optimize the deployment of communication, computation, and control functionalities with respect to the energy currently available at these nodes. Thus, handover of communication and/or computation might also lead to handover of the control functionalities among the network nodes and vice versa. This calls for a completely redesigned handover management incorporating not only communication, but also real-time control and computation aspects managed jointly with the possibility of associating users with UAV-BSs in order to jointly manage seamless handover of communication, control, and computation in 3D.

4.4 | Pervasive and on demand distributed AI at the 3D edge

The joint management of C4 resources (ie, C3 with the addition of control) requires prior knowledge of many parameters of interest, such as channel state, interference level, computation, content requests, and UAV navigation data, to be able to run the dynamic optimization algorithms necessary to allocate resources for satisfying end user requests, especially in delay-constrained services. However, most of these parameters are not known or are only known in imperfect or outdated forms. In this scenario, it is of paramount importance to resort to AI mechanisms to learn the unknown parameters from past observations and to predict the behavior of parameters of interest to enable proactive resource allocation strategies, which are especially useful when dealing with delay-constrained services. A recent survey on the application of machine learning tools in a 3D scenario involving UAV-based networks is [45]. Machine learning algorithms, including supervised, unsupervised, and reinforcement learning mechanisms, have been developed to learn physical layer parameters, such as channel states and interference levels, as well as to predict the received signal strength at the UAV's side. The user association problem, from multiple UEs to multiple UAV-BSs, is formulated as a clustering problem, solved using simple k-nearest neighbor algorithms. Several studies also address the challenges associated with the extension of the edge cloud to UAV-assisted devices. In [46], a new method for UAV clustering was proposed to enable efficient multi-modal multi-task offloading. Content caching on the UAVs was also proposed in [47], where the authors exploit user-centric information related to content request distribution and mobility patterns for deploying UAVs and for determining content caching on their buffers. Reinforcement learning mechanisms are well suited to the dynamic scenario modeling 3D communications. However, they may suffer from slow convergence because they typically start with no prior assumptions. To speed up online learning, it may be beneficial to resort to stochastic optimization or online convex optimization mechanisms, extending the approach of [48] to the 3D communication scenario.

5 | INTERFERENCE MANAGEMENT FOR 3D HYBRID INTELLIGENT NETWORKS

Hybrid 3D networks present a strong potential for enhancing service performance and reliability in the 2D plane as well as for enabling innovative services in 3D space. Nevertheless, this is just a prospective gain. Interference can strongly limit such benefits, and effective solutions for managing them have to be designed, implemented, and validated. The common understanding is that interference, classically processed as additive noise, compromises the transmission and therefore must be ideally avoided or at least strongly limited. Recent work models the impact of UAV and satellite generated interference on 2D communications. In [49], it was shown how interference will be a major limiting factor when terrestrial networks benefit from UAV support and how the density of UAVs may generate rude inter-cell interference, causing catastrophic performance degradation.

The 5G-ALLSTAR project investigates refined channel models and interference mitigation solutions for terrestrial communication enhanced by satellite links [5]. It will be crucial for 3D multi-RAT systems to transmit with high out-of-band rejection to dynamically take advantage of any available spectral resource, with limited guard bands. Figure 2 shows an evaluation of the performance degradation on a satellite link due to interference caused by a terrestrial BS transmitting on adjacent channels. We evaluate the impact of the guard band and relative interferer power on the packet error rate for the K-band. We compared the performance of three waveforms that can be demodulated with a 5G compliant receiver: cyclic prefix (CP)-OFDM and two filtered waveforms: filtered (F)-OFDM and block filtered (BF)-OFDM [50]. It can be noted that the use of BF-OFDM makes it possible to avoid the insertion of large guard bands, even when the interference is *strong*. In the case simulated here, the band gain is larger than 5%.

The results in [5] also show that non-terrestrial generated interference is either *strong* compared to the intended signal or *weak*. This result is also valid for 3D hybrid networks in which interference depends on many factors such as UAV elevation and the azimuth between receivers and interfering transmitters, side lobe gain, beam width, distance of transmitter and receiver pairs, and UAV volumetric density. This opens novel opportunities for the design of innovative interference management techniques in which interference is not considered as an opponent but as a potential ally [51].

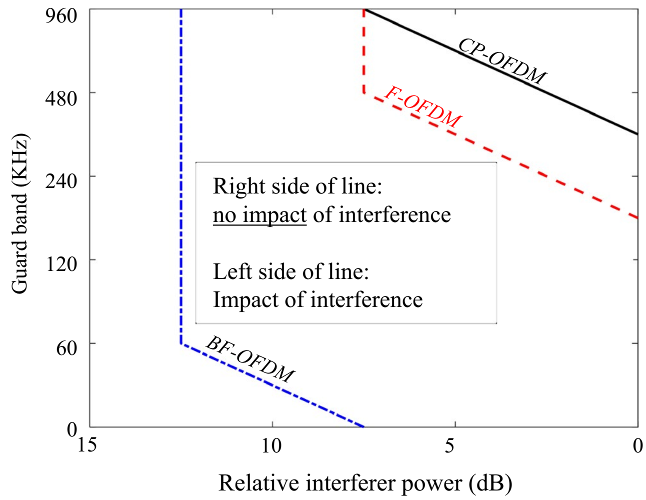

FIGURE 2 Impact of terrestrial interference on satellite link (based on satellite packet error rate). Satellite bandwidth: 15.36 MHz

Recent studies have investigated how coordinated multipoint (CoMP) transmission and reception techniques applied to terrestrial communications can be optimized to limit their complexity. In [52], it was shown how a two-layer interference cancelation strategy assisted by MEC can notably limit useless CoMP-associated processing for users that are in the *weak* interference regime. Looking at the future, applying such concepts to clusters of non-terrestrial BS might require intense exchange of information to cancel the intra-cluster interference. Nevertheless, because inter-cluster interference is not addressed by CoMP techniques and the 3D backhauling link might be unreliable, in the case of dense clusters, the system capacity improvement can be negligible. Moreover, CoMP requires a large exchange of information and computationally intense support for MEC. This might limit the NTN cluster size and indeed its potential support for 2D networks and pure 3D services.

From our perspective, there is a strong potential for mitigating the performance degradation caused by interference in and to NTN. In this context, we advocate that ignoring or allocating resources for interference avoidance is not always the best option. In our view, in future 3D hybrid 6G networks, interference management techniques should exploit *interference classification* techniques, following the concepts introduced in [53] and then further evolved in [51] by introducing the *interference perception* concept and the simplification to a low-complexity *two regime interference classifier*, which has only two admissible interference regimes for each user, the *weak* and *strong* regimes, for which close to optimal solutions can be designed. While the benefits of IC techniques can notably improve performance, owing to the associated complexity and many parameters to estimate, effective IC hardware implementations are still an open issue. We strongly believe, for future 6G 3D networks, in the potential of interference detection (possibly using machine learning techniques), combined with multi-layered CoMP [52] with a *two regime interference classifier* [51], and to consider tradeoffs caused by practical implementation limitations of IC techniques, coordination signaling, and 3D MEC processing associated energy and latency costs.

6 | DYNAMIC RESOURCE MANAGEMENT FOR 3D CONNECTIVITY

6.1 | Multi-RAT connection admission control

Mobile nodes acting as relays or BSs in UAVs can handle sporadic congestion events occurring in specific areas in a radio access network by offloading communication and MEC traffic from the fixed terrestrial links (from the protocol stack viewpoint).

This scenario impacts the connection admission control algorithms, which now have to consider not only UE mobility, but also the mobility of the AP. To demonstrate the capacities of this new scenario, a simulation study made through an ad hoc open-source 5G network simulator [54] is presented, in which the multi-RAT simulation environment is composed of one type of fixed RAT, provided by a satellite cell, and two types of mobile RATs: a 5G NR mobile relay node and a 5G NR mobile BS.

Besides the fact that admission control must be capable of handling mobile APs in a 3D environment, the key to success is the readiness of the intervention. Using traffic and mobility data, AI algorithms are needed to foresee when and where traffic peaks will occur to enable the UAV to reach the identified area in a timely manner.

6.2 | Resource allocation

The resource allocation process differs depending on the RAT. For 5G NR RATs, we consider the type 1 frame structure defined by 5G NR standards, which uses frequency division duplex for both downlink and uplink, with a minimum allocation unit defined as a resource block (RB). An RB is composed of 12 frequency subcarriers, whose bandwidths depend on the numerology μ [55]. The NR frame structure is composed of 10 ms frames, in turn, composed of a number of time slots, depending again on the numerology μ. Each RB is made up of 12 or 14 OFDM symbols (with extended and normal cyclic prefix).

A different number of RBs are defined for each channel bandwidth, depending on the frequency band used (either FR1 [56] or FR2 [57]) and on the subcarrier bandwidth.

Once the UE requests a bitrate from an NR RAT, the AP computes the required number of RBs. First, the AP computes the signal-to-interference-plus-noise ratio (SINR) for the UE. The inter-AP interference is estimated as

$$I_{ij} = kj \neq \sum P_{i,k} \cdot \mathrm{RBUR}_k, \quad \text{where} \quad \mathrm{RBUR}_k = \frac{\sum_{\tau \in (t-T,t)} \sum_i I_{ij} N_{i,k}(\tau)}{T \cdot \#\mathrm{RB}} \tag{1}$$

is the RB utilization ratio, $I_{ij} = 1$ if UE i is connected to AP j and $I_{ij} = 0$ otherwise, $N_{ij}(t)$ is the number of RBs allocated to user i by AP j, and T is the time window for the computation of the average RBUR. The data rate that can be transmitted by a single RB is computed using the best modulation coding scheme [58] with the Shannon formula $r_{ij} = B_{\mathrm{RB}} \log_2\left(1 + \mathrm{SINR}_{ij}\right)$, where B_{RB} is the bandwidth of a single RB (that is, $12 \cdot 15 \cdot 2^{\mu}$ KHz). Finally, the number of RBs needed to satisfy UE requirements is

$$n_{ij} = \frac{R_i}{r_{ij}}. \tag{2}$$

If the relative position between the UE and the AP changes, the SINR changes and the number of RBs allocated to the UE must be updated.

The simulated satellite RAT uses time division multiple access for concurrent UE access. Given a time frame, a certain number n_{tot} of symbols are available for the UE transmissions. Moreover, for each time frame, some of the symbols are used for synchronization purposes (n_{sync}), each communication contains a header (of length n_{head}), and there is a guard space of n_{space} symbols between each communication to avoid intra-RAT interference. The simulated satellite is an Inmarsat implementation, with $n_{\mathrm{tot}} = 120\,832$ symbols (which is equivalent to a time frame of 2 ms), $n_{\mathrm{sync}} = 288$ symbols (with two synchronization messages inside the time frame), $n_{\mathrm{head}} = 280$ symbols for each UE communication, $n_{\mathrm{space}} = 64$ symbols, $n_{\mathrm{slice}} = 39\,104$ symbols (which comprise about a third of the total symbols), and $n_{\mathrm{block}} = 64$ symbols [59]. The data rate that can be obtained by a single block is obtained from the Shannon formula, and the number of blocks that must be allocated to satisfy the UE request R_i is computed using (2). The actual integer number of symbols occupied by a UE is equal to $\overline{n}_{ij} = n_{\mathrm{head}} + n_{ij} + n_{\mathrm{space}}$.

6.3 | Simulation setup

The environment is represented by a 4 km × 4 km grid containing 50 UEs, a single satellite AP, and two mobile 5G NR APs. Each UE requires a bit rate of 10 Mbps, its starting position is randomly computed, and it moves on a straight line in a random direction at a speed of 10 m/s. We also consider that the service is interrupted if the bitrate falls below 5 Mbps. The satellite AP is geostationary and uses a carrier frequency of 28.4 GHz with a bandwidth of 220 MHz [60]. Its antenna equivalent isotropic radiated power is 62 dBW [61]. The path loss considers both the FSPL and atmospheric loss (0.1 dB) and the user terminal G/T (−9.7 dB/K). The mobile 5G NR APs transmit with a power of 15 W has an antenna gain of 15 dB, a feeder loss of 1 dB, and a 800 MHz carrier frequency with a bandwidth of 100 MHz and $\mu = 2$ numerology.

The connection procedure consists of the following steps: (a) The UE measures the receiving power of the APs within its range; (b) the UE chooses the AP with which to connect according to the received power with a user-centric, RAN-controlled, or RAN-assisted approach; and (c) upon communications with the UE, the AP allocates the resources based on the SINR on a best-effort basis. Owing to the dynamicity of traffic and network elements, connection updates are required following each procedure. The measured received power depends on the characteristics of the antenna of generic AP j and on the path loss from the antenna to UE i, that is, $P_{ij} = P_j G_j L_j L_{ij}$, where P_j and G_j are the antenna power and gain, respectively, and L_j and L_{ij} represent the losses at the antenna side and the path loss between UE i and AP j, respectively. The received power depends, via the path loss L_{ij}, on the relative positions of UE i and AP j. The simulated path loss model of the satellite RAT is the free space path loss, whereas for terrestrial RATs (5G NR), we chose the COST-HATA path loss model [62]. If a UE measures a receiving power lower than the threshold $P_{\min}$ for a certain AP, then the AP is considered not visible to the UE (Figure 3).

6.4 | Simulation results

The simulation scenario shows how the use of mobile nodes can solve the congestion of fixed APs and assure *service continuity*. The initial height of the two mobile 5G NR APs is 200 m, and they are far from the UE positions, which in turn can only be connected to the satellite.

The UEs start communicating at random times, causing the satellite AP load to increase with time. With no mobile nodes available, the satellite AP eventually becomes congested, and new UE service requests are rejected, as shown in Figure 4A. Moreover, some of the UE bitrates fall below 5 Mbps, causing connection drops and service interruption, as shown in Figure 4B. On the contrary, if UAV APs are available, as shown in Figure 5, the UEs start connecting to the mobile APs. In this case, no UE has to interrupt the service and service continuity is granted, maintaining the connections at 10 Mbps for the entire simulation time and maintaining all the UEs connected to some AP.

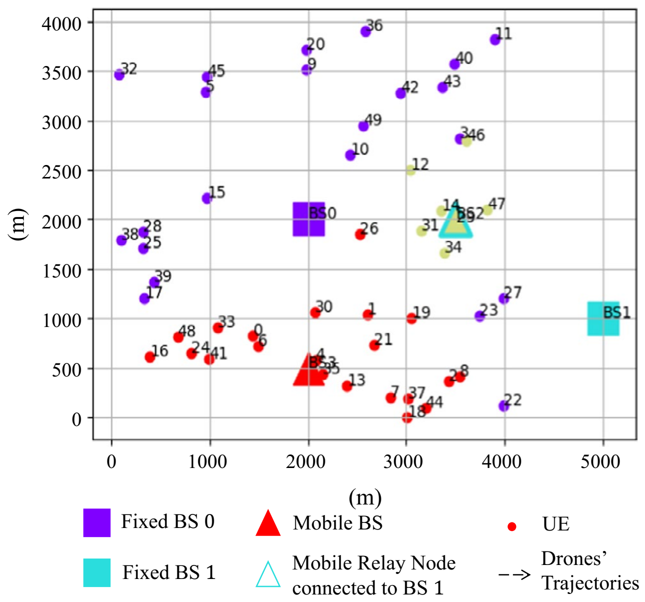

FIGURE 3 Intervention of mobile BSs in the area covered by a BS and a satellite spot. The final positions of the APs and UEs are shown [Colour figure can be viewed at wileyonlinelibrary.com]

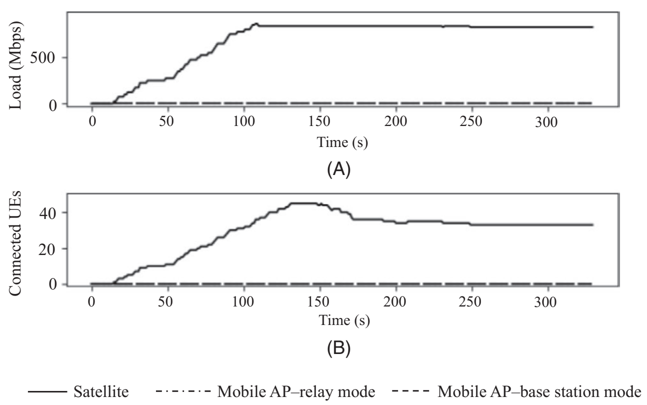

FIGURE 4 (A) Load of the satellite without the mobile APs. (B) Number of UEs connected to the satellite

6.5 | Future research directions for dynamic resource management

We mention that this section reports only a preliminary simulation result, aimed at demonstrating the potentiality of a dynamic resource management algorithm for 3D connectivity. At the moment, there are some limitations related to the 5G channel emulation that focus mostly on the estimation of the bitrate that could be sent over the radio link.

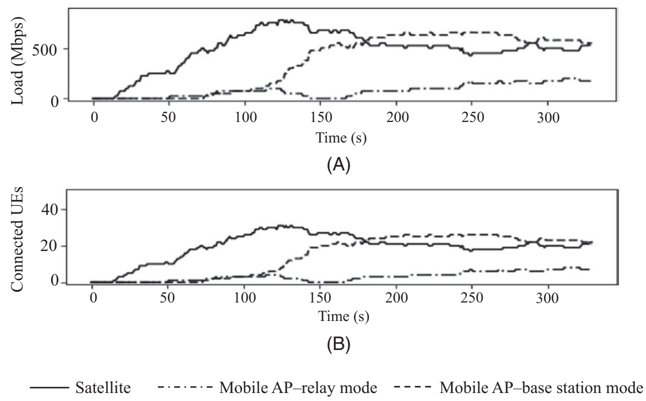

FIGURE 5 (A) Load of the satellite and of the mobile APs. (B) Number of UEs connected to the satellite and mobile APs

Moreover, there are limitations in the planning of mobile BSs trajectories in the 3D space to minimize UE connection interruptions. Various research activities are being carried out regarding dynamic network resource management, proposing more advanced network controllers, such as [63]. We also note that the inclusion of non-terrestrial BSs brings new challenges in the network controller design because in fact, both the serving and interfering BSs can move at the same time in the 3D plane. Another challenge is the prediction of user movements, which may avoid excessive handovers.

In parallel to the provisioning of connectivity to the ground users, the connectivity of the non-terrestrial BSs to the core network should be guaranteed. This connection can be provided by dedicated resources (different from user-to-ground BSs) or shared resources (the same as those used for common users). The management of connectivity and handover of the non-terrestrial BSs among the ground BSs at the dedicated resources is, in its nature, the same as the conventional handover management of ground users in terrestrial-only mobile networks (such as 4G/5G). In such a case, the non-terrestrial BSs compete for a connection to nearby terrestrial BSs only with other non-terrestrial ones. However, an allocation of the dedicated band for communication between the ground and non-terrestrial BSs is inefficient in terms of spectrum use. In contrast, the second approach with radio resources shared by all links from any BS to any user as well as to any non-terrestrial BS increases the spectrum reuse and enables more efficient exploitation of radio resources.

7 | CONCLUSIONS

The nature of new applications in the next decade and the desire for ubiquitous availability will most likely require technologies supporting truly 3D on-demand services, rather than today's 2D service coverage. In our view, while the integration of terrestrial networks with NTN for 2D service enhancement will come as a natural evolution of 5G, providing demand connectivity and edge intelligence to support truly 3D services will not come before 6G. In this article, we provided an in-depth overview of a future hierarchical 3D network architecture in which heterogeneous flying devices, providing different levels of mobility, coverage, and service level, enable revolutionary new on-demand connectivity and intelligent support.

NTN use cases are already being considered for new features and technology extensions in the 3GPP standard Releases 16 and 17. On the roadmap for 5G-NR, the integration of terrestrial networks and NTNs will enable global 5G service enhancements and new functionalities. Beyond Release 18 up to 6G, further extensions of 3GPP and other standardization bodies will enable advanced dynamic and meshed interconnection and relaying between NTN nodes and MEC placement in 3D space.

Some fundamental challenges remain open for future research. We highlighted promising innovation directions, such as on-demand distributed C3 support, 3D interference management, 3D multi-link load balancing and admission control, live intelligence handover and migration mechanisms, and AI-based joint orchestration of C4 distributed resources in 3D space. Preliminary results, currently under investigation in the H2020 5G-ALLSTAR project on interference management and 3D multi-RAT admission control, show that it is crucial for a 3D multi-RAT system to transmit with high out-of-band rejection to dynamically take advantage of any available spectral resources. Recent results show that interference by NTNs at the receiver is either perceived as *strong* or *weak* compared to the intended signal. We suggest that this opens opportunities for the design of innovative interference management techniques in which interference is not considered as an opponent but as a potential ally. Moreover, we showed how additional 3D nodes can effectively be exploited to dynamically handle network congestion, for example, by using drones as on-demand mobile relay nodes or mobile BSs, to offload traffic from fixed terrestrial links and/or to provide an extended opportunistic cellular coverage. In our opinion, new admission control procedures are needed to cope with the extended 3D network topology and, specifically, with the increased network handover occurrences implied by the dynamic 3D network.

CONFLICTS OF INTEREST

The authors declare no potential conflicts of interest.

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