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Unified 3D Networks: Architecture, Challenges, Recent Results, and Future Opportunities

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ABSTRACT The very new evolution towards 6G networks necessitates a paradigm shift towards unified 3D network architectures, encompassing space, air, and ground segments. This paper outlines the conceptualization, challenges, and prospects of such a transformative architecture. We outline the foundational principles, drawn from standardization endeavors and cutting-edge research initiatives, to articulate the envisioned architecture poised to redefine network capabilities. Driven by the need to enhance capacity, increase data rates, support diverse mobility models, and facilitate heterogeneous connectivity, the conceptual framework of a unified 3D network is presented. The focus is on seamlessly integrating diverse network segments and fostering holistic network orchestration. In examining the technical challenges inherent to the realization of a unified 3D network, we outline our strategies to address mobility management, handover optimization, interference mitigation, and the integration of distributed physical layer concepts. Proposals encompass federated learning mechanisms, advanced beamforming techniques, and energy-efficient computational offloading strategies, aimed at enhancing network performance and resilience. Moreover, we outline compelling utilization scenarios and highlighted promising avenues for future research.

INDEX TERMS 6G, non-terrestrial networks, mobile communications, 3D networks, interference management, handover strategies, distributed PHY techniques.

I. INTRODUCTION

The escalating demand for ubiquitous, high-speed, and reliable connectivity has driven the development of diverse communication networks, including terrestrial, satellite, and aerial networks (encompassing unmanned aerial vehicles (UAVs), high-altitude platforms (HAPs), and flying nodes) [1], [2]. While each network possesses distinct strengths and limitations, the emergence of three-dimensional (3D) unified networks has emerged as a compelling solution to transcend the boundaries of traditional infrastructure and deliver seamless 3D connectivity across all network segments: space, air, and ground [3], [4]. This unified network approach envisions a holistic design, encompassing flying network nodes and terrestrial network components working in tandem to dynamically provide functionalities on demand. This holistic approach has the potential to surpass the limitations of 5G non-terrestrial networks (NTNs) approach standardized by the third-generation partnership project (3GPP), enabling more comprehensive and profound exploitation of flying network components. The network nodes involved comprise

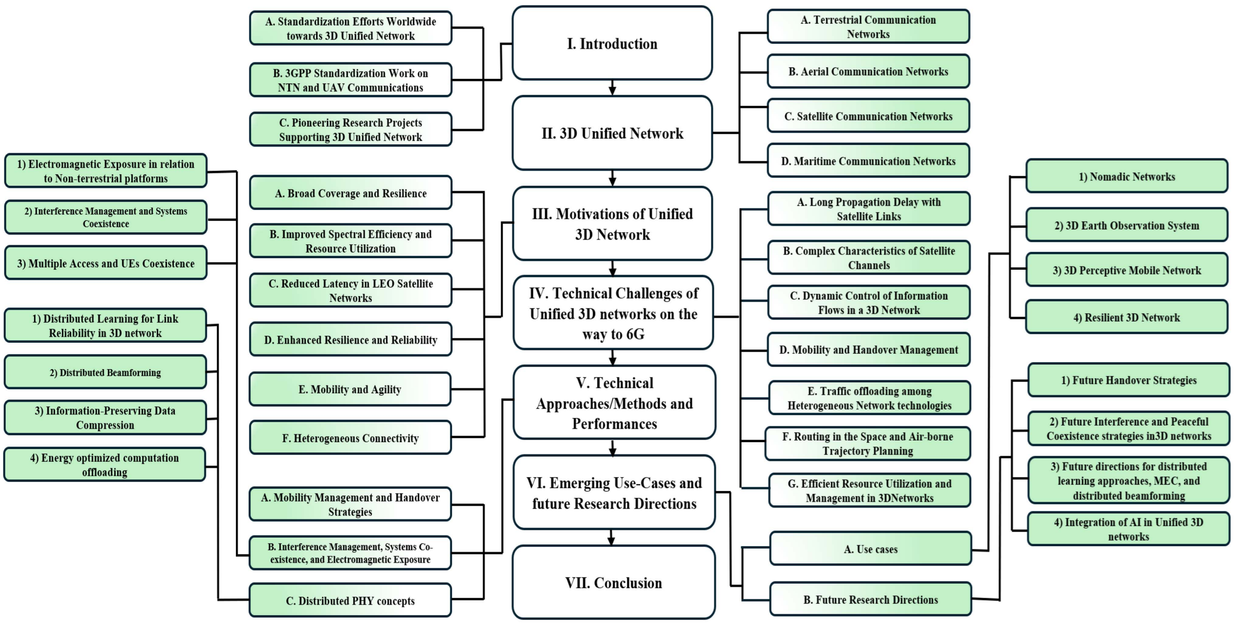


FIGURE 1. Structure of the paper and topic classification.

IoT/end-user devices, terrestrial access nodes, and 3D components, such as Low altitude platforms (LAPs), HAPs, and satellites, either in low Earth orbits (LEOs) or geostationary Earth orbits (GEOs), each with its unique characteristics [5], [6]. A 6G system design aims at seamlessly connecting these network components in a highly flexible, autonomous, and infrastructure-independent manner, adapting to evolving requirements.

Terrestrial networks (TNs), the backbone of modern communication infrastructure, provide extensive coverage and relatively low latency. However, their reach is constrained by geographical limitations and infrastructure availability. In contrast, satellite networks offer global coverage but suffer from high latency and limited bandwidth. Aerial networks, including UAVs, HAPs, and other flying platforms, bridge the gap between terrestrial and satellite networks, offering intermediate coverage and latency characteristics [1], [2]. By integrating these diverse network segments into a unified 3D network, we can revolutionize connectivity, enabling seamless communication across all three dimensions.

The promise of 3D unified networks extends far beyond mere connectivity enhancement. They hold the potential to bridge the connectivity gap in remote and under-served areas, providing essential services, such as education, healthcare, and financial inclusion. In industries like transportation, logistics, and manufacturing, 3D unified networks can enable real-time monitoring, control, and automation, revolutionizing operations. Additionally, they can power immersive and interactive experiences, such as virtual reality and augmented reality, transforming entertainment, education, and training.

In this paper, we embark on an exploration of the opportunities and challenges presented by unified 3D networks encompassing TNs and NTNs. We begin by providing an overview on the architectural building blocks that form this unified network, summarizing standardization activities worldwide, pioneering research projects that underpin the architecture, and highlighting the most pertinent 3GPP standardization efforts. Next, we introduce the concept of 3D unified network architecture as nomadic network, 3D unified Earth observatory system, 3D perceptive mobile network, and resilient 3D network, illustrating its potential to revolutionize data collection and analysis across diverse domains. We then delve into a comprehensive analysis of the technical challenges that must be addressed to realize this vision of a unified 3D network. Subsequently, we'll explore the technical details and accomplishments to date from the **Open6GHub project**,[1] focusing on advancements in resource management, mobility management, and security. Finally, we conclude by summarizing the primary obstacles impeding the advancement of 3D unified networks and identifying key open problems deserving further investigation. To improve the material flow, we provide the structure of the paper in Fig. 1 and the list of acronyms in Table 1. Table 2 presents a summary of survey papers related to 3D networks, emphasizing their primary focus and key contributions.

A. STANDARDIZATION EFFORTS WORLDWIDE TOWARD 3D UNIFIED NETWORK

The development of a 3D unified network concept has stimulated a global effort to establish standardized protocols and architectures. Leading organizations, including the International Telecommunication Union-Radio Communications Sector (ITU-R) [17], [18], the Institute of Electrical and Electronics Engineers (IEEE) [19], and 3GPP [20], [21],

[1] [Online]. Available: https://www.open6ghub.de/en/

TABLE 1. List of Acronyms

Acronym	Definition	Acronym	Definition
3D	Three-Dimensional	IoT	Internet of Things
3GPP-TR	3^{rd} Generation Partnership Project - Technical Report	IEC	International Electrotechnical Commission
5G and 6G	fifth and Sixth Generation (Wireless)	IoE	Radio Link Failure
AAP	Aerial Access Point	IoS	Internet of Ships
AI	Artificial Intelligence	ISAC	Integrated Sensing and Communication
AOCS	Attitude and Orbit Control System	ISD	Inter-Site Distance
ATG	Aerial to Ground	ISL	Intra-Satellite Link
AWGN	Additive White Gaussian Noise	ITU-R	International Telecommunication Union-Radio communications Sector
BS	Base station	IUI	Inter-User Interference
C & S	Communication and Sensing	JSCC	Joint Source-Channel Coding
CA	Carrier Aggregation	KPI	Key Performance Indicator
CapEx, OpEx	Capital Expenses and Operational Expenses	LAN	Local Area Network
CDF	Cumulative Distribution Function	LAP	Low Altitude Platform
CINR	Carrier-to-Interference-plus-Noise Ratio	LTE	Long-Term Evolution
CSI	Channel State Information	LS	Least Square
CPE	Customer Premises Equipment	LSTM	Long Short-Term Memory
DL, ML	Deep Learning and Machine Learning	LVM	Latent Variable Model
DoD	Department of Defense	MD-ML-MB	Multi-Dimensional Multi-Layered Multi-Band
V-DRA	Vertical - Dynamic Resource Allocation	MEC	Mobile Edge Computing
DRL	Deep Reinforcement Learning	mMTC	Massive Machine Type Communication
EIRPD	Effective Isotropic Radiated Power Density	NIST	National Institute of Standards and Technology
EIRP	Deep Reinforcement Learning	NGMN	Next Generation Mobile Networks (Alliance)
ELBO	Evidence Lower-Bound	NGSO	Non-Geostationary Satellite Orbit
eMBB	Enhanced Mobile Broadband (5G)	NLoS	Non-Line of Sight
EMF	Electromagnetic Exposure	NR	New Radio
ESA	European Space Agency	NSF	National Science Foundation
ESIM	Earth Stations in Motion	NTN	Non-Terrestrial Network
EU	European Union	QPSK	Quadrature Phase Shift Keying
FAVIB	Forward-Aware Vector Information Bottleneck	RAN	Radio Access Network
FDD, TDD	Frequency and Time Division Duplexing	RIS	Reconfigurable Intelligent Surface
FR	Frequency Range	RPU	Remote Processing Unit
GEO, MEO, HEO, LEO	Geostationary, Medium, High, and Low Earth Orbit	RRM	Radio Resource Management
gNB-CU-CP	gNodeB-Central Unit-Control Plane	RSMA, SDMA	Rate Splitting and Space Division Multiple Access
GNSS	Global Navigation Satellite Systems	PMN	Perceptive Mobile Network
HAP	High Altitude Platform	UAV, USV	Unmanned Aerial and Surface Vehicles
HARQ	Hybrid Automatic Repeat Request	UEOS	Augmented Reality
HetNets	Heterogeneous Networks	UE, VSAT	Very Small Aperture Terminal
HO	HandOver	SON	Self-Organizing Network
IB	Information Bottleneck	URLLC	Ultra-Reliable Low Latency Communication
ICNIRP	Interna. Commission on Non-Ionizing Radiation Protection	VHF, UHF	Very and Ultra High Frequency

TABLE 2. Recent Works on RIS-Assisted Communication and Radar Systems

Ref.	Network Segments	Key-Words	Contributions	Main Focus	3D ?
[1]	Space Air Ground	SAGIN 6G SatCom	6G-SAGIN optical network architecture, Hash-based chain authentication architecture	Space access network, Laser space com., Deep space optical com., Optical payload, Mobile crowd sensing, Chain authentication	Yes
[2]	Space Air	NTN UAVs SatCom	Channel Modeling, Spectrum Co-Existence PHY Procedures, HARQ, Synchronization Constellation Management.	Architecture, Spectrum, and Antenna Advancements, Higher-Layer techniques individual link budget guarantees.	No
[3]	Space Air Ground	TN-NTN Architecture 6G	Listing use cases, 3D architecture, and 3GPP standardization efforts. Exploring opportunities for aerial services.	Describing 3D Architecture, and PHY characteristics, Complementing TN with NTN Infrastructure.	Yes
[5]	Space	SatCom LEO 5G	Highlighting 5G SatCom system aspects, air interface, medium access techniques, and networking and upper layers.	New constellation types, on-board processing capabilities, NTN and space-based data collection/processing.	No
[7]	Space Ground	5G LEO SatCom	Provide Network architecture for integrated terrestrial and LEO SatCom to offer more reliable and flexible access.	Developing PHY techniques such as effective interference management, diversity techniques, and cognitive radio schemes.	No
[8]	Space	LEO Broadband ISL	Develop the architecture and PHY techniques for broadband satellite network.	LEO constellation design, Coverage schemes, Interference coordination between LEO and GEO systems, RRM in LEO systems.	No
[9]	Space Air Ground	LEO RRM UAVs	Collaborative control and management, cooperative data transmission, inter-connection and inter-communication.	System integration, protocol optimization, resource management, and allocation in SAGIN.	Yes
[10]	Space Ground	SatCom RRM IP Net.	Envision network topology, Resource allocation and management, Satellite and and ISL handover management.	The networking operation between the satellite and terrestrial domains.	No
[11]	Space Ground	6G LEO Broadband	Integrated satellite-terrestrial network architectures for 6G.	Architectures, applications, challenges, and potential techniques to enable seamless global connectivity while ignoring air segment.	No
[12]	Space Air Ground	3D NTN 6G	Integration of NTN with 6G terrestrial networks, highlighting new use cases for UAS, the role of AI/ML in overcoming NTN challenges, and reviewing standardization activities.	Comparing standardization approaches for 3GPP, ITU-R and NGMN toward integration of 6G-NTN to terrestrial networks.	Yes
[13]	Space Air Ground	Slicing AI SAGIN	Proposing a software defined framework for SAGVN to achieve flexible, reliable, and scalable network resource management.	Resource Management in Space-Air-Ground Integrated Vehicular Networks: SDN Control and AI Algorithm Design.	Yes
[14]	Space	NGSO NTN RAN	Analysis for NGSO system development, deployment, and integration challenges, as well as the operational issues.	Present a comprehensive survey on the NGSO communication system aspects starting from the physical layer up to the application layer.	No
[15]	Air	UAVs SON Routing	Survey of Important Issues in UAV Communication Networks.	Multi-UAV Network, Self-Organization in Networks, SDN-Automating UAV Network Control, Routing in UAV communication Networks.	No
[16]	Air	Protocols ATG UTM	Provide a comprehensive review and vision for enabling the connectivity applications of aerial vehicles utilizing current and future communication technologies.	Survey of Wireless Networks for Future Aerial Communications.	No

[22], are actively engaged in standardization initiatives to define the technical specifications and frameworks for this emerging technology. These standardization efforts aim to ensure interoperability and compatibility across diverse network segments, enabling seamless communication across all three dimensions: space, air, and ground.

The ITU-R plays a crucial role in coordinating global radio communication spectrum management and ensuring harmonized regulations for NTNs [18]. The ITU-R is currently developing a series of recommendations for NTNs, leading to 6G NTN systems, to lay the groundwork for future 3D unified network. The IEEE is also actively involved in exploring some concepts related to 3D unified network standardization [19]. The IEEE 802.11 working group, responsible for wireless LAN standards, is investigating the integration of aerial access points (AAPs) into existing Wi-Fi networks. Additionally, the IEEE 802.15 working group, responsible for low-power wireless personal area networks, is exploring the use of UAVs for backhaul and relay applications, which could be of interest to the 3D unified networks community. The 3GPP is spearheading the standardization of cellular technologies for 5G and beyond. Recognizing the potential of 3D unified networks, 3GPP is actively exploring the integration of aerial nodes and satellite systems into 5G NR and 6G NR architectures [20], [21], [22]. This standardization effort aims to enable seamless connectivity between terrestrial, aerial, and satellite networks, paving the way for a truly ubiquitous and seamless 3D unified network.

B. 3GPP STANDARDIZATION WORK ON NTN AND UAV COMMUNICATIONS

The standardization of aerial communications commenced in 2010 with the development of broadband direct Air-to-Ground (ATG) communications, utilizing frequency ranges from 790 MHz to 5,150 MHz [23]. Subsequently, the standardization efforts were extended to encompass other frequency bands [24], [25], [26], culminating in the comprehensive specification of ATG systems. These efforts have been formally documented in 3GPP TR 38.876 [27]. ATG has been defined in 3GPP technical reports as the networks that provide in-flight connectivity by utilizing ground-based cell towers that transmit signals to an aircraft's antenna(s), which are part of the onboard ATG terminal [27]. As the aircraft moves through different airspace regions, the onboard ATG terminal automatically connects to the cell with the strongest received signal, functioning similarly to a mobile phone on the ground. A direct radio link is established between the BS on the ground and the customer premises equipment (CPE)-type UE mounted in the aircraft. From trials and commercial operations of LTE-based ATG solutions, certain characteristics have been identified as critical for ATG network deployment scenarios. First, the ATG network operates with extremely large inter-site distances (ISD) and extensive coverage areas. To control network deployment costs and account for the relatively low number of flights, a large ISD ranging from 100 to 200 kilometers (km) is preferable. When an aircraft is flying over the sea, the distance to the nearest base station (BS) can exceed 200 km, reaching up to 300 km, requiring the ATG network to support such coverage distances. Additionally, ATG and TNs often utilize non-disjoint frequencies, meaning the same frequency band is used with adjacent carriers for both networks. While this approach conserves frequency resources, it introduces the potential for interference between ATG and TNs, which must be carefully managed. Finally, the onboard ATG terminal is considerably more powerful than standard terrestrial user equipment, that is equipped with higher effective isotropic radiated power (EIRP) through increased transmission power and larger onboard antenna gain [27].

The 3GPP has also been actively engaged in standardization efforts for non-terrestrial communications since 2017 [20], [21], [22]. These efforts can be broadly categorized into two main areas: NTN enhancements and TN support for UAVs. The former aims to establish a global standard for future space-borne communications, while the latter focuses on ensuring the compatibility of mobile standards with UAV operations and minimizing the impact of UAVs on other network users. The objectives and outcomes of the 3GPP work conducted from Release 15 to Release 17, along with topics currently under investigation for Release 18 [20], [21], [22], are outlined in Table 3.

C. PIONEERING RESEARCH PROJECTS SUPPORTING 3D UNIFIED NETWORK

The development of 6G, the next generation of wireless technology, is underway with a focus on complementing TNs with NTNs. Several pioneering research projects are underway worldwide, including the 6G Flagship Initiative in Finland, Hexa-X in Europe, and Open 6GHub and 6G Takeoff in Germany [28], [31], [32], [33]. These projects aim to develop new technologies and standards for 6G, such as Terahertz communications, quantum communications, and in-band full-duplex transmission. They also aim to foster collaboration among stakeholders from academia, industry, and government, to accelerate the development and deployment of 6G. Table 4 lists the pioneering 6G projects, programs, and initiatives worldwide.

II. UNIFIED 3D NETWORK

The 6G of cellular networks is expected to introduce a paradigm shift in network architecture, with a focus on hybrid architectures that integrate various network modalities. This visionary 6G network will converge disparate domains, from short-range, ultra-high capacity networks to the farthest reaches via novel spatial network dimensions [2], [3]. Such a transformative direction necessitates the seamless integration and synergistic reinforcement of diverse network typologies, including space networks (satellites), aerial networks (UAVs and HAPs), and TNs (cellular networks) [2], [34]. This convergence is pivotal in addressing the expected requirements of 6G, encompassing ubiquitous connectivity across time, location, and device spectra. It is imperative to note, that influential stakeholders within the 6G landscape, along with

TABLE 3. 3GPP Standardization Progression

3GPP Release	Support for Non-terrestrial Networks (NTN)	Support for Unmanned Aerial Vehicles (UAVs)
Rel-15	**Study on New Radio (NR) that support NTNs [TR 38.811]** Outlined relevant scenarios for NTN deployment and integration, covering various aspects such as frequency bands (S band at 2 GHz versus Ka band at 27–40 GHz), footprint sizes, minimum elevation angles, antenna types, beam configurations (Earth-fixed, directed towards a fixed ground area, or mobile beams), and NTN terminal types (handheld versus VSAT). Additionally, defined are propagation channel models according to TR 38.901, incorporating NTN-specific adjustments.	**Enhanced LTE support for aerial vehicles [TR 36.777]** Outlined are suggested solutions, both user-centric and network-centric, aimed at mitigating interference in downlink and uplink transmissions, managing mobility, and identifying UAVs. These solutions are tailored to address channel models derived from TR 38.901, taking into consideration the altitude of UAVs. **Enhancements to measurement report triggering [TS 36.331]** Improvements encompassed the introduction of two new reporting events, namely H1 (above) and H2 (below) user height thresholds, designed to facilitate UAV identification by the network and manage potential interference effectively.
Rel-16	**Solutions for NR to support NTNs [TR 38.821]** The emphasis was placed on FR1 for handheld and IoT satellite connectivity. Necessary adjustments for both the physical and higher layers, along with modifications to system-level simulation assumptions, were identified. Examination was conducted on the effects of delay on random access, scheduling, and hybrid automatic repeat request (HARQ), alongside the investigation of mobility management for mobile Low Earth Orbit (LEO) platforms. **Using satellite access in 5G [TR 22.822]** Use-cases were identified to outline service provisions in the context of integrating 5G satellite-based access components. Additionally, new services and their corresponding requirements were defined.	**Remote identification of UAVs [TS 22.825]** Research focused on analyzing the prospective demands and applications for remote UAV identification and the subsequent provision of services. The objective was to enable air traffic control and public safety agencies to access UAV identity and metadata through the UTM (Unmanned Traffic Management) system. This facilitates the authorization, enforcement, and regulation of UAV operations. **UAV connectivity, identification, and tracking [TR 23.754]** Examined the connectivity options supported by 3GPP for communication between UAVs and UAV Traffic Management (UTM). The study also addressed the processes involved in detecting and reporting unauthorized UAVs to the UTM.
Rel-17	**NB-IoT and eMTC support for NTN [TR 36.763]** The focus is on IoT applications, aiming to resolve challenges associated with LTE timing relationships, uplink synchronization, and Hybrid Automatic Repeat Request (HARQ) mechanisms. **Architecture aspects for using satellite access in 5G [TR 23.737]** Outlined specified enhancements across RF and physical layer aspects, protocols, radio resource management, and frequency bands. Additionally, a suitable architecture was identified, addressing issues such as TN-NTN roaming and timing concerns, improved conditional handover, and location-based triggering mechanisms.	**5G enhancements for UAVs [TS 22.125, TS 22.829]** Generated new Key Performance Indicators (KPIs) for UAVs and identified communication requirements concerning payload, command and control traffic, on-board radio access node (UxNB), as well as service limitations and network exposure for the UAV. **Application layer support for UAVs [TR 23.755]** Studied various use-cases pertaining to UAV identification and tracking, including their influence on the application layer. Explored UAV-UTM interactions for tasks such as route authorization, location management, and facilitating group communication support.
Rel-18	**NR NTN enhancements [TR 21.918]** The forthcoming study will examine NR NTN coverage to ensure compatibility with practical handheld terminals and access above 10 GHz, catering to both stationary and mobile platforms. It will delve into the prerequisites for network-validated user location and tackle challenges related to mobility and service continuity, both within TN-NTN networks and across various NTNs.	**NR support for UAVs [TR 23.700]** The upcoming research will focus on enhancing measurement reporting mechanisms, refining signaling protocols for subscription-based UAV identification and its multicast, introducing supplementary triggers for conditional handover, and optimizing beam management. This includes investigating UAV directional antennas and base station uptilt beamforming techniques.
Rel-19	**Satellite Use-cases & NR NTN enhancements [TR 22.865]** This study focuses on enhancing 5G for satellite communications (SatComs), supporting Store and Forward services, direct UE-to-UE satellite communication, GNSS-independent operation, and improved satellite-based positioning. These upgrades aim to extend 5G connectivity to remote areas. Service requirements from these use cases guide the development of standardized solutions.	**UAV Use cases & NR support for UAVs [TR 22.843]** The upcoming research focuses on enhancing 3GPP support for low-altitude UAV applications, emphasizing improved security, control, and network support. It defines new service-level requirements and KPIs to support various UAV-related use cases, building on TS 22.125. The document also addresses further improvements for UAV operations' safety and integration with the 3GPP system.

TABLE 4. **Pioneering 6G Projects, Programs, and Initiatives Worldwide**

Project Name	Funding Amount	Partners	Goals	Country
6G Flagship Initiative [28]	€2.5 billion	150+ organizations from academia, industry, gov.	Establish Europe as a leader in 6G, develop 6G standards/technologies, foster collaboration among stakeholders.	Finland
H2020 5G PPP 6G Programme [29]	€49 million	33 consortia of European research institutions.	Develop key 6G technologies: terahertz & quantum communications, in-band full duplex transmission.	Europe
EU Horizon Europe FET Programme [30]	€ 95.5 billion	1,500 organizations from academia, industry, gov.	Support high-risk research in emerging technologies including 6G, drive innovation, address societal challenges.	Europe
EU ARTES 4.0 programme (ESA)	€40 million	20 organizations from academia, industry, gov.	Develop next-gen satellite communication systems for enhanced 6G connectivity, coverage in remote areas.	Europe
NGMN Alliance	Membership	200+ telecom companies, tech providers, etc.	Accelerate 6G development/deployment, foster global collaboration, ensure 6G network interoperability.	Global
NIST 6G Initiative	$100 million	National Institute of Standards and Technology in USA	Develop standards, testing for 6G tech to ensure interoperability, compatibility among different 6G systems/devices.	USA
DoD SCI	$200 million	USA Department of Defense - Spectrum Collaboration Initiative	Address spectrum congestion challenges for 6G networks, develop efficient spectrum sharing mechanisms.	USA
NSF 6RCN	$10 million	National Science Foundation - 6G Research Coordination and Networking	Support foundational 6G tech research: advanced materials, AI, quantum computing.	USA
Japan 6G Initiative	Over $450 million	Japanese research institutions, universities, and mobile network operators	Establish Japan as 6G leader, support R&D across academia, industry, gov agencies, develop applications leveraging 6G.	Japan
China 6G R&D Programme	Over $1.2 trillion	Research institutions and Chinese universities and technology companies and mobile network operators led by Huawei and with full support from Chinese government.	Support research on key 6G tech to strengthen China's global position, focus on terahertz comm., network slicing, caching.	China
South Korea 6G Network Vision	$600 million	Korean mobile network operators, universities, and research centers.	Develop comprehensive 6G network vision, foster collaboration among South Korean stakeholders.	South Korea
Australia 6G Initiative	$170 million	Australian Universities and research centers.	Support 6G tech research: quantum comm., in-band full duplex, AI-powered networks to enhance Australia's global position.	Australia
Open 6G Hub [31]	$75 million	17 partners including research institutions, universities, and industrial companies	Contribute to global 6G standardization while adhering to German societal values and promoting the nation's technological sovereignty.	Germany
6G TakeOff [32]	$13 million	19 partners including research institutions, universities, and industrial companies	A novel 3D network will be developed, combining terrestrial and aerial nodes, ensuring seamless connectivity anytime, anywhere, empowering the future of 6G.	Germany
Hexa-X Project [33]	$12 million	26 partners from all European countries including research institutions, universities, and industrial companies.	The Hexa-X project aims to develop an intelligent, connected, sustainable, and globally accessible 6G wireless system that provides extreme experiences.	Europe

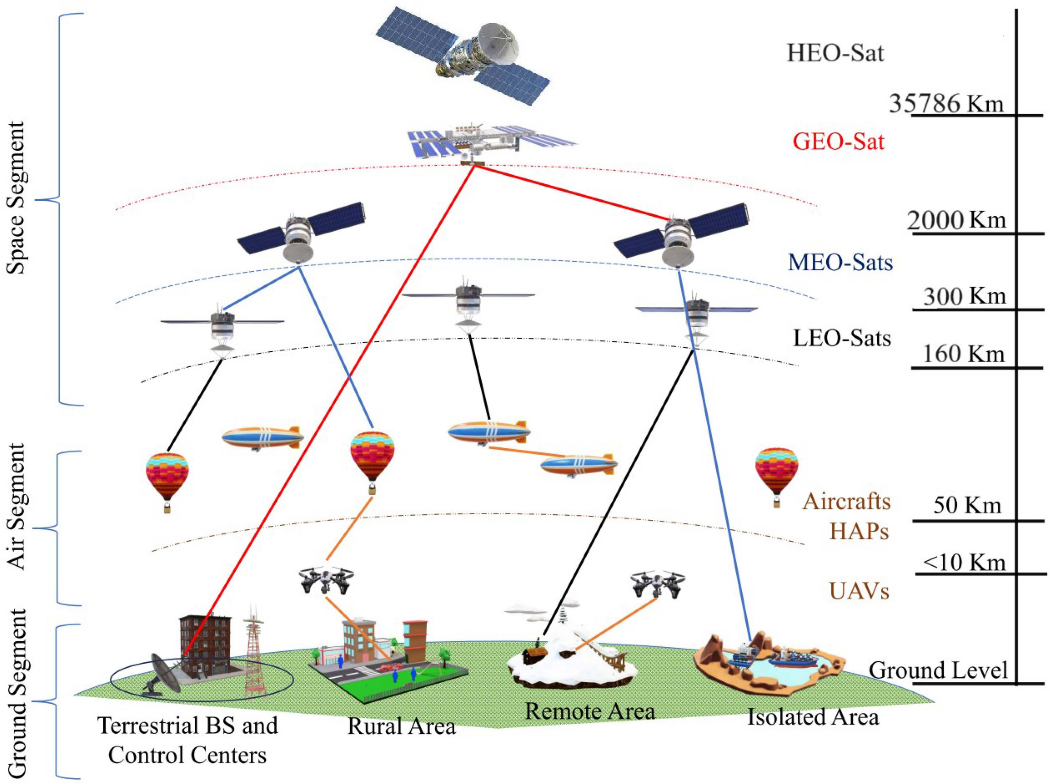


FIGURE 2. A conceptual illustration of a unified 3D network, depicting the integration of space, air, and terrestrial network components.

standardization bodies, are expected to endorse a vertical architecture comprising three distinct layers, as depicted in Fig. 2. This vertical architecture integrates TNs and NTNs, harmonizing them into a cohesive and comprehensive unified 3D network. The integrated layers, from bottom to top, encompass TN, airborne network, and space network layers [4].

The TN refers to the heterogeneous cellular infrastructure, connecting diverse BSs encompassing macro-, micro-, and pico-BSs, while also integrating satellite ground stations. The airborne network contains a swarm of aerial entities, that traverse altitudes ranging from 100 meters to 50 km [2]. This layer is further divided into two categories of communication nodes: UAVs with an operational altitude limited to 10 km and HAPs that orchestrate connectivity within a sphere up to 50 km, predominantly concentrated around the 20 km altitude. The space network layer encompasses a constellation of distinct satellite classes. These satellites are classified based on their orbital altitudes, spanning Very LEO (vLEO), LEO, Medium Earth Orbit (MEO), GEO, and High Earth Orbit (HEO). These categories correspondingly ascend within altitudinal ranges of 50–160 km, 160–300 km, 300–2000 km, 2000–35786 km, and beyond 35786 km [3], [4].

SatComs were formally incorporated into 3GPP Release 17 in April 2022, enabling 5G systems to encompass non-terrestrial components. Furthermore, future Releases 18 and 19 are anticipated to introduce additional enhancements within the "NR_NTN_enh" work item, such as "specifying system enhancements to support satellite discontinuous coverage" and "coverage enhancements." Furthermore, "regenerative payload" and "NR-NTN mobility and service continuity enhancements" are being considered to further advance the technology. 3GPP TR 38.811 comprehensively outlines potential use-cases, scenarios, and classifications of different propagation channel models employed in NTNs [20], [21], [22]. Subsequently, we will briefly discuss the advantages and challenges presented by the three most significant non-terrestrial components of unified 3D networks: satellites, HAPs, and UAVs.

Satcom offers a wide range of services, including mobile broadband and fixed Internet connectivity for ground users in geographically sparse areas, on airplanes, as well as wireless connectivity for Internet of Things (IoT) devices [5], [6]. Recent private non-geostationary satellite orbit (NGSO) constellations, such as SpaceX, OneWeb, and Amazon's Kuiper, have significantly reduced communication delay and yielded higher data rates at a lower transmit power compared to legacy geostationary satellite orbit (GSO) systems [7], [35], [36], [37]. Techniques to enhance data rates of NGSO constellations, such as exploiting higher frequencies, spectrum sharing, user clustering, efficient duplexing techniques, pilot assignment, and handover management, are an active area of research. Mega-constellations like SpaceX and Kuiper have already promised data rates of Terabits per second [8], [38], [39].

However, Satcom systems have limitations in terms of latency and dependability [40]. To meet the future demands of ultra-low latency, reliable communications, and data rates of Terabits per second, Satcom systems need to be complemented by air-borne networks like HAPs and UAVs [9], [41]. HAPs are quasi-stationary aerial vehicles, hovering at an altitude of 17-25 km above Earth. They offer several advantages over satellites, including ease of deployment, low operational costs, and low latency. Some commercially available HAPs include AALTO (a subsidiary of Airbus), Google Loon, and Stratobus. UAVs are unmanned aircraft, that can be deployed rapidly and flexibly, to provide coverage in areas where terrestrial infrastructure is lacking. They can also act as mobile relays for satellite-terrestrial links and facilitate edge computing [1]. By combining the strengths of Satcom, HAPs, and UAVs, unified 3D networks can provide seamless and ubiquitous connectivity to meet the demands of future applications.

Maritime communications play a crucial role in supporting various oceanic activities, including shipping, offshore exploration, and environmental monitoring [42]. Traditionally, maritime communication has relied on radio frequency (RF) technologies such as Very High Frequency (VHF) and Ultra High Frequency (UHF) for basic services like voice calling and messaging. However, the increasing demands for data-intensive applications and the limitations of current systems, especially in offshore environments, have led to the integration of satellite communication, optical wireless communication (like free space optics), and the development of advanced hybrid systems. These new technologies enhance the coverage, capacity, and reliability of maritime communications, enabling more complex applications such as the Internet of Ships (IoS) and maritime IoT [42].

Till now, current maritime communication systems can be considered as part of the TNs. Integrating maritime communications into a unified 3D network that spans space, air, and ground presents significant opportunities. This approach could create a seamless global network that links maritime activities with terrestrial, aerial, and satellite communication systems. Such integration would allow for uninterrupted connectivity for ships, offshore platforms, and other maritime operations, leveraging technologies like LEO satellite constellations, UAVs, and Reconfigurable Intelligent Surface (RIS). The state-of-the-art solutions involve hybrid RF and optical wireless systems, as well as the use of UAVs for relay and disaster recovery applications, offering scalable, low-latency, and energy-efficient networks for maritime users [42].

Recent research has focused on enhancing maritime wireless networks through the use of Unmanned Surface Vehicles (USVs), which are seen as key enablers for next-generation 6G maritime communication. One promising direction is the joint optimization of trajectory and communication resource allocation for USV-enabled networks [43]. This approach focuses on maximizing network performance by optimizing the paths USVs travel while managing communication resources like power, bandwidth, and transmission rates. By adjusting these factors dynamically, USVs can ensure reliable and high-quality links for offshore vessels and platforms, overcoming challenges such as signal blockage and interference. Another significant advancement is in USV-assisted maritime wireless communication toward 6G, where USVs are used to bridge gaps in connectivity by acting as mobile BSs or relays [44]. This enables enhanced communication coverage, low-latency connections, and improved energy efficiency for offshore networks. Additionally, research on MIMO (Multiple Input Multiple Output) USV-enabled maritime wireless networks coexisting with satellite networks has focused on designing beamforming techniques and optimal trajectories for USVs [45]. This approach improves spectral efficiency and minimizes interference, allowing USVs to operate in tandem with SatCom systems, further boosting network performance and reliability in remote maritime environments. These efforts are critical as maritime networks evolve toward 6G, offering new opportunities and addressing challenges in connectivity, coverage, and network management.

III. MOTIVATIONS OF UNIFIED 3D NETWORK

The integration of TNs and NTNs into a unified 3D network is a critical step towards achieving global connectivity and enhancing the user experience [3]. By combining the strengths of ground-based infrastructure with aerial and satellite networks, the network will be able to overcome the limitations of concurrent networks and provide seamless coverage in even the most remote areas [4]. This integration will enable a wide range of new applications and services, from disaster relief and remote monitoring to personalized experiences and immersive entertainment.

A. BROAD COVERAGE AND RESILIENCE

Unified 3D networks provide ubiquitous connectivity, spanning from deep rural areas to remote regions and beyond. This can technically be achieved through:

- *Seamless Handover:* A unified network allows for seamless handover between TNs and NTNs, ensuring uninterrupted connectivity for users as they move between different environments [40].
- *Expanded Coverage:* NTNs can provide coverage in areas where TNs are limited, such as remote areas, disaster zones, and high-altitude regions. This expanded coverage can enable new applications and services [5], [6].

B. IMPROVED SPECTRAL EFFICIENCY AND RESOURCE UTILIZATION

Unified 3D networks can achieve significant improvements in spectral efficiency and resource utilization, providing users with higher data rates, lower latency, and improved quality of service (QoS) [13], [46], [47]. This can be achieved by:

- *Vertical Dynamic Resource Allocation:* A unified 3D network can dynamically allocate resources between NTs and NTNs based on demand, optimizing network performance and reducing costs [13].
- *Network Densification:* By integrating TNs and NTNs, network densification can be achieved without the need for extensive infrastructure deployment on the ground.

This can improve network capacity and reduce latency [47].

C. REDUCED LATENCY IN LEO SATELLITE NETWORKS

Due to their closer proximity to Earth, LEO satellites can help reduce the overall latency in SatComs [48]. This is particularly beneficial for applications where minimizing delay is crucial, such as real-time monitoring, remote operations, and low-latency services in areas lacking terrestrial infrastructure. However, it is important to note that while LEO networks can lower latency relative to traditional satellite systems, they still face higher delays compared to purely terrestrial networks [49]. Optimizing this trade-off is key for applications like critical infrastructure monitoring, augmented reality, and autonomous vehicle control, where balancing coverage and latency is essential.

D. ENHANCED RESILIENCE AND RELIABILITY

Unified 3D networks can significantly improve resilience and reliability, ensuring that critical services remain operational even in the face of disruptions and challenges [50].

- *Disaster Recovery:* Non-terrestrial networks can serve as backup infrastructure to the TNs during disasters or network outages, ensuring critical services remain operational [11].
- *Redundancy:* A unified network provides connectivity redundancy, increasing network reliability and reducing the risk of service disruptions [3].

E. MOBILITY AND AGILITY

Unified 3D networks can adapt to the mobility of users and vehicles by seamlessly switching between terrestrial, airborne, and space-based connections [51]. This is essential for applications involving mobile devices, drones, and autonomous vehicles that frequently change their locations [12].

F. HETEROGENEOUS CONNECTIVITY

Unified 3D networks can integrate different network technologies, including cellular networks, SatComs, and millimeter-wave (mmWave) technologies. This heterogeneity enables optimization for specific use cases and environments, maximizing network efficiency and performance [12], [51].

IV. TECHNICAL CHALLENGES OF UNIFIED 3D NETWORKS ON THE WAY TO 6G

A. LONG PROPAGATION DELAY WITH SATELLITE LINKS

Effective communication latency remains a crucial performance metric for ensuring satisfactory user QoS across wireless networks. From the inception of 1G to the evolving 6G era, network advancements have consistently focused on minimizing latency. Generally, the overall latency experienced by users comprises four main components: transmission delay, propagation delay, processing delay, and queuing delay [12]. While the latter three factors may exhibit comparable characteristics in satellite and TNs, the propagation delay stands out as a significant differentiator. Satellite networks exhibit substantially longer propagation delays compared to TNs due to the extended distances involved. A complete communication process involves at least two satellite-ground links. For GEO satellites positioned at a fixed altitude of 36,000 km, the one-way propagation delay can reach 240 milliseconds (ms), significantly exceeding the 5G end-to-end latency requirement of 1 ms. While the propagation delay in MEO and LEO satellite networks can be reduced to tens of ms, as can be noticed in Table 5, multi-hop transmissions in these systems necessitate additional intra-satellite link (ISL) or satellite-ground link hops, thereby introducing further propagation delays. Additionally, the dynamic nature of MEO/LEO satellite networks, characterized by constantly changing link topologies, can further contribute to latency fluctuations [52].

TABLE 5. Propagation Delay Time for Satellites

Satellite Type	Altitude (km)	One-Way Propagation Delay (ms)
GEO	36000	240.0
MEO	20000	133.33
	10000	66.67
	3000	20.0
LEO	1000	6.67
	600	4.0

The 3GPP acknowledges the diverse latency requirements of different applications within the 5G (and future 6G) network landscape [20], [21], [22]. Real-time interactions, such as remote surgery and autonomous vehicles, demand ultra-low latency to ensure smooth operation, as even minor delays can have significant consequences. Conversely, services like video streaming prioritize overall throughput and can tolerate some delay [20]. To address these varying needs, 3GPP categorizes latency requirements into several groups. Ultra-Reliable Low-Latency Communication (URLLC) aims for round-trip latency below 1 ms, crucial for mission-critical applications. Enhanced Mobile Broadband (eMBB) targets latencies between 1 and 10 ms, catering to high-speed data services. Massive Machine Type Communication (mMTC) focuses on supporting a vast number of devices with less stringent latency requirements, often ranging from 10 ms to several seconds [21]. Achieving these targets involves employing diverse network design techniques. Network slicing enables operators to create virtual networks, tailored to different use cases, prioritizing low latency through advanced techniques like priority scheduling. The introduction of NR features in 5G, such as shorter transmission time intervals and beamforming, reduces signal processing delays. Additionally, deploying edge servers for edge computing brings processing power closer to users, significantly reducing latency for real-time applications [22].

To address these latency challenges and enhance user QoS, several strategies are being explored for 3D unified networks.

For MEO/LEO multi-hop transmissions, strategically placing gateways becomes crucial to minimize the path length from source satellites to gateways with terrestrial connections [53]. The joint placement of controllers and satellite gateways has been investigated to optimize latency in these networks. Furthermore, mobile edge computing (MEC) techniques can be employed to offload processing tasks from remote cloud servers, thereby reducing latency and improving response times [54], [55]. In the integrated satellite-terrestrial context, MEC servers can be deployed at BSs, satellites, or gateways, offering flexibility in selecting the most suitable location for offloaded processing [56]. However, designing effective offloading strategies poses challenges due to the heterogeneity of serving locations in terms of latency and computational capacity. Additionally, managing a large number of users with limited computing and energy resources within the vast network coverage necessitates specialized MEC schemes, tailored to integrated satellite-terrestrial architectures.

Accordingly, latency remains a significant challenge in unified 3D network architectures incorporating satellite links. By optimizing gateway placement, leveraging MEC techniques, and developing tailored offloading strategies, future networks can effectively address latency issues and deliver enhanced QoS for users across diverse geographical regions.

B. COMPLEX CHARACTERISTICS OF SATELLITE CHANNELS

The Earth's atmosphere plays a crucial role in shaping the propagation characteristics of radio waves, introducing various impairments that can significantly impact the performance of SatCom systems. These complexities vary depending on the altitude of the satellite orbit, with unique challenges arising for LEO, MEO, and GEO satellites [10].

LEO satellites, typically positioned at altitudes between 500 and 2,000 km, offer enhanced coverage and latency compared to GEO counterparts. However, the closer proximity to Earth introduces unique channel complexities. Atmospheric attenuation in LEO links is significantly higher due to the higher density of molecules and scattering effects. Additionally, the rapid movement of LEO satellites relative to the ground causes Doppler shifts, which can distort signal waveforms and degrade data transmission. To mitigate these challenges, advanced signal processing techniques, such as adaptive modulation and coding, are employed to compensate for varying signal strength and frequency shifts [5].

MEO satellites, positioned at altitudes between 2,000 and 35,786 km, offer a balance between coverage and latency, providing global connectivity with reduced propagation delay compared to GEO. However, the intermediate altitude of MEO introduces a combination of atmospheric attenuation and ionospheric effects. Ionospheric scintillation, caused by the interaction of radio waves with charged particles in the ionosphere, can introduce rapid fluctuations in signal strength and phase, leading to data loss and link outages. To combat ionospheric scintillation, various techniques, such as adaptive beamforming and space diversity, are employed to counteract the signal fluctuations and improve link reliability [5].

GEO satellites, positioned at an altitude of approximately 35,786 km, offer continuous coverage over a specific region due to their fixed position relative to Earth's surface. However, the extended distance to GEO satellites leads to significant atmospheric attenuation and propagation delay. The one-way propagation delay from GEO to Earth is approximately 240 ms, which can significantly impact real-time applications. To compensate for these long delays, advanced error correction coding is crucial to ensure data integrity. Additionally, techniques such as adaptive modulation and transmission power control are employed to maximize spectral efficiency and minimize link impairments [5], [6].

In the context of terrestrial communication, quasi-static channel models are often assumed, as BSs remain fixed relative to the ground. However, in SatCom systems, the movement of MEO/LEO satellites at high speeds, relative to the ground, introduces significant channel complexities. These dynamic satellite-ground links exhibit rapid time variations, larger Doppler shifts, and larger phase shifts compared to terrestrial links [57]. To accurately capture these dynamic channel conditions, non-stationary channel models are required in the future 3D unified network spanning space, air, and ground. Additionally, obtaining timely and accurate channel state information (CSI) is more challenging in SatComs due to the long propagation delays. Imperfect CSI can negatively impact the performance of various signal processing techniques, such as adaptive modulation and coding, that rely on accurate channel knowledge [58]. Therefore, extensive research is ongoing, to develop robust channel estimation techniques, that can effectively handle the complexities of SatComs.

C. DYNAMIC CONTROL OF INFORMATION FLOWS IN A 3D NETWORK

The dynamic and heterogeneous nature of 3D unified network poses new challenges for the efficient control of information flows. Dynamic control refers to the ability to proactively manage network resources and traffic patterns in real time, to optimize network performance and ensure user satisfaction. This requires a comprehensive understanding of the network topology, link characteristics, and traffic demands. It also necessitates the development of intelligent algorithms, that can adapt to changing network conditions and optimize resource allocation [11].

One key aspect of dynamic control in 3D unified network is the routing of traffic. Traffic can be routed through various paths, including terrestrial links, satellite links, or a combination of both. The choice of path depends on factors such as latency, bandwidth, and cost. Dynamic routing algorithms can continuously evaluate traffic conditions and re-route traffic to optimize performance [59]. Another important aspect of dynamic control is the allocation of resources. Terrestrial and satellite networks have different resource characteristics, and dynamic control algorithms need to take this into consideration. For instance, terrestrial links typically have lower latency but lower bandwidth than satellite links. Dynamic resource allocation algorithms can balance the utilization of terrestrial and satellite resources to meet the demands of different types of traffic [60]. In addition to routing and resource allocation, dynamic control also plays a role in QoS management. QoS refers to the ability of a network to provide a consistent and predictable level of service to its users. Dynamic control algorithms can monitor QoS parameters such as latency, jitter, and packet loss, and take corrective actions to improve QoS if it deteriorates. The dynamic control of information flows in 3D networks is a complex and challenging task, but it is essential to ensure the efficient and reliable operation of the constituting segment networks. By developing advanced dynamic control algorithms, we can harness the full potential of 3D networks, to provide seamless and high-quality connectivity to users worldwide.

D. MOBILITY AND HANDOVER MANAGEMENT

Mobility and handover management are essential aspects of any wireless communication system, ensuring seamless connectivity for mobile users as they move between different coverage areas [61]. In the upcoming 3D unified network, which combines the strengths of TNs and NTNs, mobility, and handover management become even more critical, due to the diverse and dynamic nature of the network topology [12]. In traditional TNs, handovers typically involve switching between neighboring BSs within a single radio access technology [51]. However, 3D unified network introduce the complexity of switching between terrestrial and satellite links, each with its unique characteristics and signaling protocols. Moreover, the dynamic deployment of satellite constellations and the varying signal strengths and delays across different orbits necessitate real-time handover decisions and seamless handover procedures [12].

To cater to the heterogeneity between space-borne, airborne, and TNs, two main types of handovers are typically distinguished in 3D unified network [51], [61]: horizontal and vertical handovers. **Horizontal handovers**, also known as intra-network handovers, and involve switching between terrestrial cells, satellite spot beams, or different satellites within the same network domain. These handovers are relatively straightforward and can be handled using conventional handover techniques, employed in either terrestrial or satellite networks. The decision-making process typically considers factors such as signal strength, interference levels, and channel quality [61]. **Vertical handovers**, also known as inter-network handovers, occur when the connection is transferred between the terrestrial and satellite domains. These handovers pose greater challenges due to the fundamental differences between terrestrial and satellite networks [51]. Handling vertical handovers effectively requires a seamless transition between the two network domains, ensuring minimal disruption to user connectivity. This involves several considerations, including [12]:

- *Network Aware Handover Decision:* The handover decision process needs to consider the characteristics and capabilities of both TNs and NTNs, selecting the most suitable connection based on the user's location, traffic demands, and network conditions.
- *Protocol Translation:* Efficient protocol translation mechanisms are crucial to ensure seamless handover between the TNs and NTNs. This involves adopting signaling messages and data formats to accommodate the different protocols used in each domain.
- *Channel Reconfiguration:* During a vertical handover, the user terminal may need to switch between different frequency bands or modulation schemes depending on the network domain. Efficient channel reconfiguration techniques are essential to minimize service disruptions.
- *Data Transfer Handover:* The handover process must ensure seamless handover of ongoing data transfers. This may involve buffering data until the connection is established in the new network domain, or utilizing protocols that allow for smooth data transfer across different network types.

Addressing these challenges effectively, is essential for enabling seamless and reliable connectivity in the 3D unified network. By developing robust handover management techniques, 3D unified network can provide a unified and flexible connectivity solution for users worldwide.

E. TRAFFIC OFFLOADING AMONG HETEROGENEOUS NETWORK TECHNOLOGIES

In the emerging 3D unified network, data seamlessly flows between TNs and NTNs, offering exciting possibilities for traffic management [3]. One key strategy is traffic offloading, where data is shifted from congested networks to alleviate stress and improve performance [62]. While this concept exists in traditional cellular networks, the 3D architecture introduces unique challenges and opportunities [2], [3]. Satellite networks, with their wide coverage and high capacity, play a crucial role in offloading [63]. They can be especially helpful when TNs are overloaded or unavailable in remote areas. However, their high mobility and long propagation delays create complexities. Offloading schemes need to be dynamic, adapting to constantly changing satellite links, and considering both capacity and latency, to ensure smooth data flow [64].

Existing research explores various offloading scenarios:

- *Backhaul offloading:* Minimizing data delivery time by utilizing satellites for backhaul transmission [65].
- *Multimedia offloading:* Efficiently broadcasting popular content through multicast/broadcast over satellites, reducing congestion on TNs. [66].
- *Reverse offloading:* Shifting computationally intensive tasks from satellites to terrestrial infrastructure, saving energy and resources on satellites [67].

These approaches showcase the potential of combined satellite and terrestrial offloading to optimize network performance [2]. By considering the unique characteristics of each network and employing intelligent offloading schemes, the 3D unified network can unlock its full potential, offering seamless connectivity and efficient data management across diverse terrains and user demands [3]. However, further research is crucial to address challenges like:

- *Resource allocation:* Optimizing resource utilization across different network types.
- *Security and privacy:* Ensuring data security and privacy during offloading between potentially untrusted networks.
- *Standardization:* Developing protocols and standards for seamless interoperability between diverse network technologies.

As research progresses, traffic offloading promises to be a transformative technology for the 3D unified network, paving the way for a truly connected and efficient future.

F. ROUTING IN THE SPACE AND AIR-BORNE TRAJECTORY PLANNING

The convergence of terrestrial, aerial, and satellite networks into a unified 3D architecture paves the way for ubiquitous connectivity and diverse applications. However, managing data flow and optimizing resource utilization in this complex environment requires innovative approaches to routing in satellite networks and trajectory planning for airborne platforms like UAVs and HAPs.

G. EFFICIENT RESOURCE UTILIZATION AND MANAGEMENT IN 3D NETWORKS

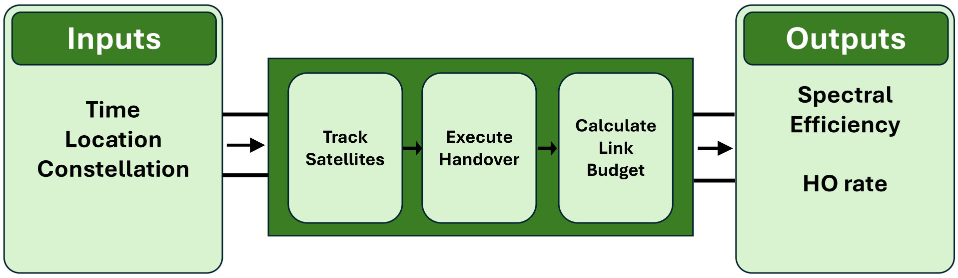
Efficient resource utilization and management in 3D networks, is critical for ensuring optimal performance, high QoS, and scalability. With the convergence of these networks, the challenge lies in dynamically allocating resources, including spectrum, power, and computational resources, while minimizing latency, maximizing throughput, and avoiding interference. State-of-the-art research highlights several approaches and techniques to address these challenges.

- *Dynamic Resource Allocation (DRA):* In 3D networks, dynamic resource allocation is essential to managing the varying demands between TNs and NTNs. Techniques such as vertical dynamic resource allocation (VDRA) have been proposed, which enable efficient spectrum sharing across terrestrial and satellite links. VDRA schemes utilize real-time traffic conditions to allocate frequency, time, and spatial resources based on demand and location, ensuring the efficient use of available bandwidth. For instance, in [13], the authors proposed a VDRA scheme for integrated satellite-terrestrial networks, demonstrating that this approach can reduce latency by up to 35% and enhance spectral efficiency by up to 20% compared to static allocation methods.
- *Network Slicing and Virtualization:* Incorporating virtualization technologies such as network slicing in 3D networks can significantly improve resource utilization by enabling the division of network resources into isolated, virtual slices. These slices can be tailored for different services or applications (e.g., IoT, video streaming, or autonomous vehicles), each with its own QoS requirements. A key advantage of network slicing is its ability to dynamically adjust resource allocation depending on service demand, ensuring that resources are not over-provisioned or underutilized. The results in [46] showed that implementing network slicing in 3D network reduced energy consumption by 28% while maintaining service-level agreements (SLAs).
- *Resource Coordination in Multi-Layer Networks:* One of the significant challenges in 3D networks is multi-layer resource coordination, which involves managing the interaction between terrestrial BSs, aerial platforms (e.g., UAVs), and satellite constellations. Advanced coordination algorithms, such as reinforcement learning-based resource management, have emerged as an effective solution. These algorithms can learn the traffic patterns and adjust resource allocation dynamically to avoid interference between layers. Recent work in [47] demonstrated the potential of deep reinforcement learning (DRL) to improve spectrum efficiency by 17% in multi-layer 3D networks.
- *Joint Beamforming and Power Control:* Another aspect of resource management in 3D networks is joint beamforming and power control, which is particularly critical for NTN links. LEO satellites, in particular, require adaptive beamforming techniques to provide continuous service to moving users while minimizing interference with ground stations. Techniques such as joint beamforming and power control schemes have been shown to optimize the trade-off between interference mitigation and power consumption, improving both spectral efficiency and coverage. According to [68], this approach increased network throughput by up to 15% compared to traditional methods without joint optimization.

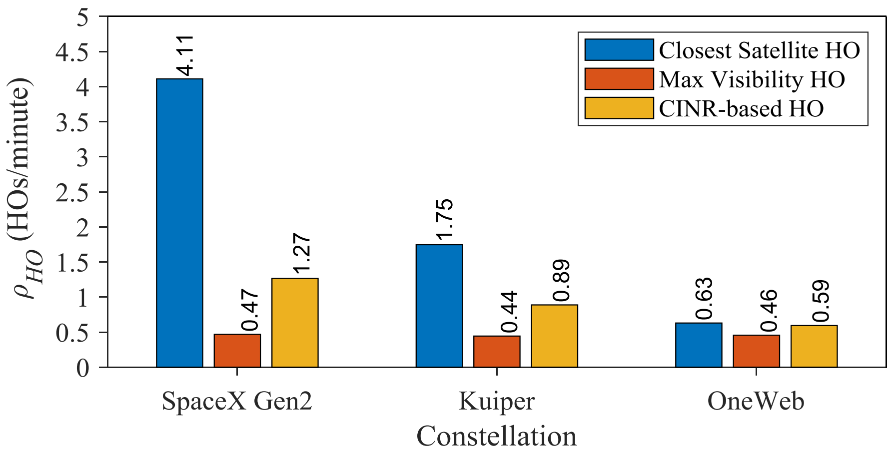
V. TECHNICAL APPROACHES/METHODS AND PERFORMANCES

A. MOBILITY MANAGEMENT AND HANDOVER STRATEGIES

In 3D Multi-Dimensional Multi-Layered Multi-Band (MD-ML-MB) NTN architectures that include satellites, UAVs, drones, and other non-terrestrial network components, mobility management is crucial, especially for NGSO satellite systems, due to their high speeds and frequent handovers. This section discusses key approaches to address these challenges. For GEO constellations, mobility management is similar to terrestrial systems, due to their static nature. However, NGSO constellations require inter-satellite handovers for continuous connectivity, even for fixed users [69]. While other handover types exist, inter-satellite handovers are most essential and generic. Choosing the optimal handover strategy involves selecting the best handover instant and target satellite. Handover instants are typically chosen based on parameters like elevation angle, visibility duration, and Carrier-to-Interference-plus-Noise Ratio (CINR) values, while the best satellite selection considers factors like maximum remaining visibility, minimum distance, Doppler shift, channel availability, and dual satellite diversity [69].



(a) Methodology used in simulation of handovers in private NGSO constellations



(b) Average handover rate ρ_{HO} for three HO strategies, for three major constellations.

FIGURE 3. Methodology and Performance evaluation of different HO strategies.

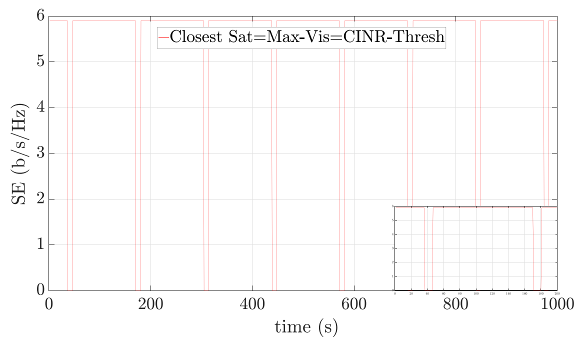
In [70], we showed that the two common handover strategies, "closest sat" and "maximum visibility," suffer from high handover rates and low throughput, respectively, which could lead to link failures in extreme cases. Radio link failures may also arise from high aggregate interference from neighboring constellations sharing the same frequency band, or sporadic invisibility of satellites. Herein we propose a new CINR-thresholding handover strategy, that achieves a balance between handover rate and throughput. The achievable handover rate for three of the major constellations (SpaceX Gen2, Kuiper Constellation, and OneWeb) based on three handover strategies (Closest Satellite, Max Visibility, and CINR-based) is displayed in Fig. 3(b). The simulation parameters, namely effective isotropic radiated power density (EIRPd), measured in dBW/Hz, satellite velocity in km/s, minimum permissible elevation angle $\phi_{\min}$ in degrees, receiver antenna gain in dBi, receiver antenna diameter in metres, and noise temperature T in Kelvin, are listed in Table 6. For our simulation, as can be seen from Fig. 3(a), we used a MATLAB-based simulator, which takes as input the simulation time, location of the ground station, and name of the constellation. It tracks all visible satellites and executes the handover based on the chosen criterion. The link budget is then calculated according to (1):

TABLE 6. Satellite Constellation Parameters

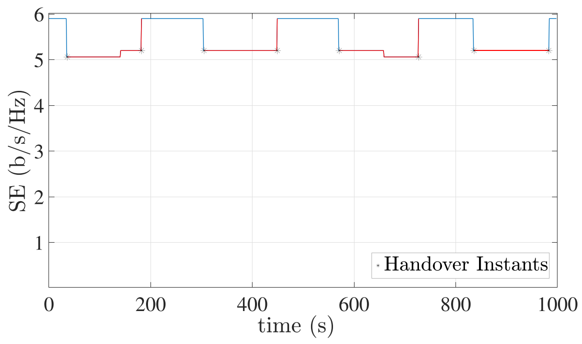
Constellations	EIRP$_d$ [dBW/Hz]	Est. v (km/s)	ϕ_{min}	G$_{RX}$ [dBi]	D [m]	T [K]
SpaceX Gen2	–42.4	7.7	25	48.3	0.48	200
Kuiper	–43.9	7.54	35	38	0.45	200
OneWeb Phase1	–52.0	7.260	55	50	1.80	200

$$\mathrm{CINR} = \mathrm{EIRPD} - \mathrm{PL} - L_{\mathrm{atm}} + G_{\mathrm{RX}} - 10\log(T \cdot k + I_{\mathrm{tot}}), \quad (1)$$

where EIRPD is the effective isotropic radiated power density, PL is the free-space path loss, L_{atm} is the atmospheric attenuation, G_{RX} is the antenna gain of the ground station, T is the noise temperature, k is the Boltzmann constant, and I_{tot} is the aggregate interference from neighboring constellations using the Ka band. The simulator calculates evaluation metrics such as spectral efficiency and handover rate.



(a) Before conditional HO



(b) After conditional HO

FIGURE 4. OneWeb LEO invisibility periods, and Conditional HO from OneWeb LEO to Mangata MEO.

Next, advancements in our handover algorithm require transitioning to a multi-objective optimization approach. This involves simultaneously optimizing multiple performance metrics, such as maximizing throughput, minimizing handover frequency, mitigating interference-induced throughput degradation, selecting satellites with minimal slant-range (Earth Station-satellite distance) to reduce propagation delay, minimize Doppler distortion, and maximize channel bandwidth utilization, while minimizing interference to other users on the same spectrum [71], [72]. Additionally, integrating fast fallback options is crucial, allowing the UE to seamlessly switch to a different satellite or HAP upon failure or congestion. This aligns with the “specifying system enhancements to support satellite discontinuous coverage” feature planned for 3GPP Release 18 [14]. Our ongoing research investigates the implementation of such “conditional handovers,” triggered by radio link failures owing to sporadic satellite invisibility or high interference levels. In these scenarios, the ground station instructs the UE to handover to an alternative NGSO constellation or a stationary HAP. Preliminary results in Fig. 4(b) demonstrate the effectiveness of conditional handovers. Using OneWeb LEO constellation invisibility as a trigger, we successfully shifted to the co-channel and co-located MEO constellation Mangata. The ground station maintained connections to both constellations for an average of 130 seconds, achieving a trade-off between throughput and handover rate. In Fig. 4(b), the portion of the spectral efficiency curve marked in red represents the time connected to Mangata, while the blue section indicates the connection duration with OneWeb LEO.

Beyond handover optimization, improving latency and mitigating Doppler shift are key areas for further advancement in NTN mobility management [14], [73]. The network broadcasts ephemeris information and a common Timing Advance (TA) parameter in each NTN cell. Rel. 17 NTN-enabled UEs leverage their Global Navigation Satellite System (GNSS) capabilities to acquire a valid position, satellite ephemeris, and common TA (information received from the BS (gNB)), before connecting to an NTN cell. This enables them to pre-compensate for timing and frequency shifts autonomously, considering their GNSS position, common TA, satellite position, and satellite velocity. Focusing on latency, research in [14] identifies the total satellite-to-ground link latency as consisting of three components as expressed in (2): waiting time (transmitter waits for receiver acknowledgment), transmission time (function of data rate and packet count), and propagation delay (constant and significantly larger than the other two components). Since the propagation delay dominates, being approximately 4 ms for a 600 km altitude, compared to 0.04 ms per packet transmission and waiting time, exploring alternative approaches like deactivating HARQ or compressing gNB-CU-CP control planes messages might not significantly impact total latency

$$L_{\mathrm{t}}(u, v) = q_{\mathrm{t}}(u, v) + \frac{p}{R_{\mathrm{t}}(u, v)} + \frac{d_{\mathrm{t}}(u, v)}{c}. \quad (2)$$

The integration of HAPs within the unified 3D network framework presents significant potential for enhancing mobility management. Firstly, HAPs offer ease of deployment without the risks typically associated with satellite commissioning, such as the possibility of rocket launch failures. Their reliance on batteries and solar panels renders them fuel-efficient. Additionally, HAPs provide the advantage of a high elevation angle concerning the receiver, as they can hover directly above ground stations or UE. Addressing a major challenge in mobility management of NGSO constellations, HAPs offer reduced latency owing to their non-orbiting nature and lower altitude of 20 km or less, resulting in substantially lower latency, compared to transparent-payload satellites. Furthermore, due to their quasi-stationary nature, HAPs exhibit Doppler distortion comparable to terrestrial communication, simplifying mobility management considerations to focus solely on UE mobility. Unlike satellites, which serve singular missions until decommissioned, HAPs can be commissioned and decommissioned at will, facilitating adaptability to changing mission requirements. Additionally, HAPs can effectively address coverage gaps resulting from sudden satellite invisibility, thereby enhancing network resilience [40]. Moreover, in the context of providing “ubiquitous coverage” as a KPI of 6G networks, HAPs can be conceptualized as “cell towers in the sky,” aligning with the Earth Stations in Motion (ESIM) concept proposed by 3GPP. By acting as base stations, HAPs can overcome limitations of terrestrial cell towers, extending coverage to rural areas and mitigating the near-far problem encountered at cell fringes. With coverage equivalent to multiple terrestrial cell towers and the ability to be relocated swiftly, HAPs offer a versatile solution for providing connectivity directly to devices.

In UAV-based communication systems, handover management poses a significant challenge, particularly concerning UAVs operating at low altitudes. Classification of UAV handovers into hard and soft [15], horizontal and vertical, parallels established cellular network handover frameworks. Additionally, efficient handover techniques based on load and active user counts have shown promise in UAV-aided vertical HetNets, contributing to reduced handover latency [74]. Moreover, in the realm of HAPs, further research is warranted to address challenges associated with HAPs unpredictable displacement due to meteorological factors. This includes mitigating service disruptions during handovers and optimizing trajectory control to ensure seamless operation. In the context of mobility management across various vertical heterogeneous networks, such as HAPs and LAPs, route planning plays a critical role influenced by factors like weather conditions, altitude, and wind direction. Optimization of variables such as energy consumption and coverage area is essential in route planning efforts [75]. Strategies such as globally optimal trajectory planning for UAVs and the implementation of MIMO antenna systems with directional 3D beams for HAPs are integral to mitigating service disruptions and ensuring efficient mobility management [16], [76].

B. INTERFERENCE MANAGEMENT, SYSTEMS CO-EXISTENCE, AND ELECTROMAGNETIC EXPOSURE

1) ELECTROMAGNETIC EXPOSURE IN RELATION TO NON-TERRESTRIAL PLATFORMS

Recent developments in NTN and the emerging quest to bring ubiquitous coverage to end users via direct satellite connectivity to UE may trigger uncertainties with regards to the levels of electromganetic field (EMF) exposure to the humans and environments. It is thus necessary to consider the aspects that are relevant to NTN when assessing EMF exposure levels and how they compare to those of TN. Several international organizations, such as the World Health Organization (WHO), International Commission on Non-Ionizing Radiation Protection (ICNIRP), IEEE-International Committee on Electromagnetic Safety (ICES), and ITU, took on the mission of evaluating the research and studies on human EMF exposure [19], [77], [78], [79]. Based on their assessment of substantiated scientific literature, the safe limits and guidelines, that ensure the protection of the people and environment against any harmful EMF exposure, are derived.

Another aspect to be considered is the assessment methodology, that is adequate to evaluate the EMF exposure levels in 3D networks against the levels set by the ICNIRP's EMF exposure guidelines or other local regulations. This dictates a good definition and understanding of the different scenarios, use-cases, and constellations of a 3D network and its users. At the present time, there is a shortage of measurement studies on EMF exposure near satellite Earth stations [80]. Moreover, the emerging technologies envisioned for the implementation in both TNs and NTNs require additional attention to their implications on the EMF exposure levels. In Table 7, a summary of some of the aspects pertinent to the EMF assessment methods in context of 3D networks is given.

TABLE 7. Considerations of TN vs NTN Properties Relevant to the Evaluation of EMF Exposure

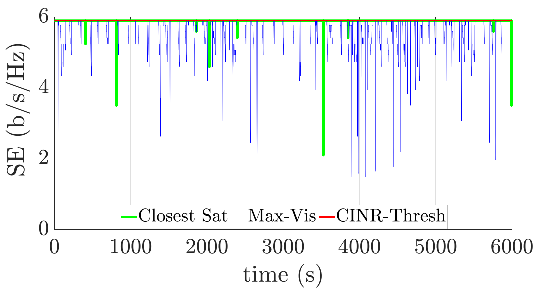
Network	TN	NTN
Antenna type	omni-directional	directional
Cell coverage	stationary	stationary (GEO), mobile (NGSO)
Coverage radius	up to 30km	up to 1000 km (NGSO), up to 3500 km (GEO)
Frequency range (FR)	FR1, FR2	FR1, FR2*
Operation frequencies	up to 7.125 GHz, 24.25-71.0 GHz	1-2 GHz above 10 GHz*
Duplex mode	TDD / FDD	FDD*
Terminal type	UE	UE, VSAT, ESIM
UE power class	class 2, (up to 26 dBm) class 3 (up to 23 dBm)	class 3 (up to 23 dBm)
UEs' density	Medium-High	Low

* NTN specifics are still under development by 3GPP.

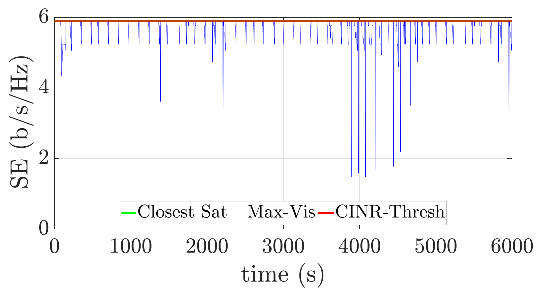
For TN, the International Electrotechnical Commission (IEC) published the latest edition of its technical standard IEC 62232 in 2022 [81] concerned with the evaluation methods of EMF exposure due to RF sources operating in the 110 MHz to 300 GHz frequency range. With the launch of 5G, additional considerations for the assessment of EMF exposure were established to account for the novel technologies in 5G [82]. Inclusion of NTN in future 3D networks necessitates a re-assessment of the current standards, such that they account for the increased number of satellites in space, user terminals on Earth, and any resulting consequences on the EMF levels.

2) INTERFERENCE MANAGEMENT AND SYSTEMS COEXISTENCE

The increasing deployment of broadband satellite constellations, particularly in NGSO, has led to multiple satellite operators competing for bandwidth in Ku, Ka, and V frequency bands. Co-channel interference arises when multiple users share the same frequency channel, while adjacent channel interference occurs when users operate on neighboring frequency bands. The proliferation of multi-beam satellites across various constellations exacerbates interference issues, not only within NGSO constellations, but also between NGSO



(a) Before channelization



(b) After channelization

FIGURE 5. Spectral efficiency for SpaceX, before and after channelization for ground station Miami.

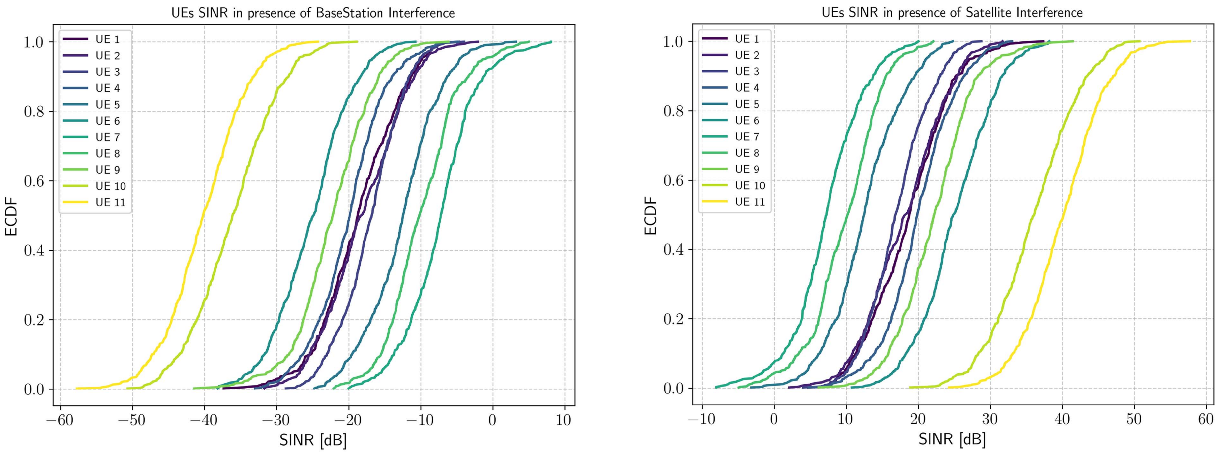
and Geostationary Orbit (GSO) constellations. This interference can severely degrade throughput and, in extreme cases, disrupt services temporarily [83], [84], [85]. Studies, such as [83], highlight the inadequacy of existing spectrum regulations in safeguarding GSO and NGSO constellations from interference. Regulatory bodies are thus prompted to delve deeper into mitigating interference between NGSO-NGSO, NGSO-GSO, and TN-NGSO systems. For instance, the 3GPP-approved satellite operating band n256 overlaps entirely with TN New Radio (NR) band n65 and partially with NR bands n2, n25, n70, and n66. It also adjoins NR bands n1 (FDD) and n34 (TDD) in the S band. The coexistence of TN and NGSO systems is addressed in 3GPP Rel-17 under RAN4: RF & RRM performance enhancements.

Previous work in [86] and [85], has investigated coexistence between GEO and LEO satellites in the Ka band. Similar studies have explored coexistence in the Ka and V bands using parameters from real satellite deployments. Interference mitigation techniques proposed in literature include look-aside methods, band-splitting, channelization, adaptive power control, and polarization techniques. These techniques aim to minimize interference among coexisting systems, particularly crucial for low-altitude mega-constellations like SpaceX [84], [87]. The efficacy of look-aside in mitigating Ka band co-channel interference was studied in [84], while in [40] we showed how efficient channel separation among the various constellations operating in the same frequency band may lead to substantial improvement in throughput (illustrated in Fig 5), and how implementing a CINR-thresholding technique in our handover algorithm can improve its robustness under worst case co-channel interference, e.g. when all constellations are interfering with the studied one, since it takes current channel conditions into consideration and signals a handover as soon as the received CINR falls below a certain threshold. Furthermore, interference management is essential, not only for satellites, but also for HAPs and LAPs, which operate in various frequency bands, allocated by the ITU. While regulations exist to limit harmful interference from these platforms, research on their impact on other aerial vehicles, such as satellites, is still in its infancy. In the realm of UAVs, studies on inter-UAV and UAV-satellite interference mitigation are scarce. For instance, Guo et al. [88] qualitatively analyze UAV interference caused by terrestrial base stations, but no mitigation approaches are discussed. Cross-layer interference mitigation in vertical Heterogeneous Networks (HetNets) emerges as a pertinent research area in the evolving unified 3D ecosystem.

Non-terrestrial communication links have the potential to introduce significant interference to existing terrestrial communication systems, particularly in the S Band frequency range spanning from 2 to 2.5 GHz. This frequency band is notably utilized by Handheld UEs. Handheld UEs, lacking Very Small Aperture Terminal (VSAT) antennas, capable of focusing their main beam on satellites, are particularly susceptible to interference in this working band. Concurrently, users receiving satellite services within the coverage area of a gNB (gNodeB) experience substantial interference from the terrestrial BS, resulting in service outages. In the subsequent analysis, we conducted simulations to assess the received SINR for a group of UEs, situated within a confined area with a radius of 5 km, considering two distinct scenarios:

1) The main service provider is the BS (gNB), while a LEO satellite is the interferer,
2) The main service provider is the satellite, while the BS is the interferer.

The LEO satellite operates at an altitude of 600 km above the Earth's surface, transmitting signals within the 2–2.5 GHz frequency band. The received power from the satellite during its trajectory is fully simulated based on the methodology outlined in incorporating considerations such as flat fading channel effects and the sub-urban environment. Similarly, the received power from the BS is simulated using methodologies detailed in employing the same frequency bandwidth and considering the sub-urban setting. The frequency reuse factor, denoting the number of users sharing the same frequency band between the satellite and the BS, is set at 3. It is noteworthy that the users sharing the band change every second. Initially, 11 UEs are distributed in an area with a radius of 5 km, following a Poisson Point Process centered at a gNB position. These UEs undergo movement in a Random Walk scenario within the designated area, with a velocity of 1 m/s. The studied environment is characterized as an urban area, wherein LoS or NLoS propagation conditions may be encountered from the perspective of the BS. The achievable SNR for UEs during the



(a) BS is Interferer

(b) Satellite is Interferer

FIGURE 6. **UEs achievable SINR in presence of interference, (a) from BS and (b) Satellite.**

passage of two consecutive satellites, spanning approximately 6 seconds, is bounded by 20 and 32 dB. Fig. 6 illustrates the Empirical Cumulative Distribution Function (ECDF) of the received SINR for the scenarios described in 1 (b) and 2 (a). In Fig. 6(b), UEs located further away experience heightened susceptibility to outages, due to weaker signals from the BS, particularly during satellite passes with high elevation angles. Additionally, the interference effect generated by the BS on the UEs-satellite main link exacerbates outage occurrences for a significant portion of UEs.

This emphasizes that interference will inevitably arise in future 3D networks that use both TNs and NTNs. Because of their elevated placements, communication from satellites and HAPS has the potential to produce interference to current terrestrial communication over broader geographical areas. On the other hand, even in limited areas, terrestrial communication presents a considerable source of interference for NTNs. Fig. 7 shows how much of an area can be under the interference of different objects, based on their height and transmission direction. Therefore the higher an object performing a downlink transmission is located, the larger the area in can cause interference towards other objects. The same can be applied for the uplink, in which the transmitters on the ground can create larger interference areas towards the sky, space, and on the ground (due to reflection).

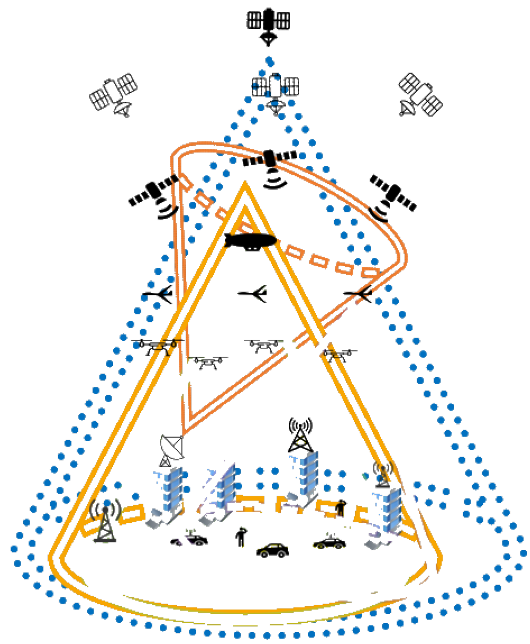


FIGURE 7. **Interfering area of creates by each transmitting object in DL and UL mode. each color represents different frequency band.**

3) MULTIPLE ACCESS AND UES COEXISTENCE

One of the key objectives of the 6G era is to provide massive connectivity, accelerating the transition from IoT to the Internet of Everything (IoE). This requires enabling massive access capabilities in unified 3D networks. Since most IoT devices are located at ground level, multiple access scheme designs are crucial for the final communication hop from the aerial layer (e.g., LAP) to ground devices. LAPs, implemented via UAVs or balloons, may have limited hardware functionality to handle massive connectivity simultaneously. To avoid communication redundancy with numerous ground-deployed devices in 3D networks, network clustering is an efficient approach. By treating clustered devices as a single unit, scheduling overload at aerial base stations can be significantly reduced. This scalability from network clustering enhances massive connectivity services in 3D networks. Additionally, device-to-device (D2D) communication within clusters over shorter distances can reduce communication energy consumption and improve resource utilization efficiency.

To tackle multi-access issues in 3D networks and exploit the benefits of D2D communication, research has been conducted on LAP movement optimization [89], [90], [91], treating the cluster head of a network as a single entity. The

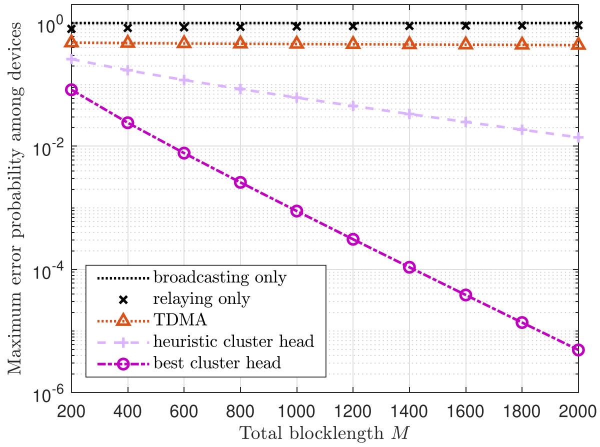


FIGURE 8. Reliability achievements under different scheduling schemes in clustered network [49].

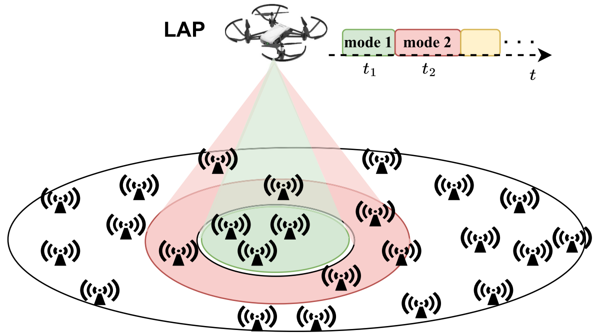


FIGURE 9. LAP-assisted multicasting with multiple analog beamforming modes [93].

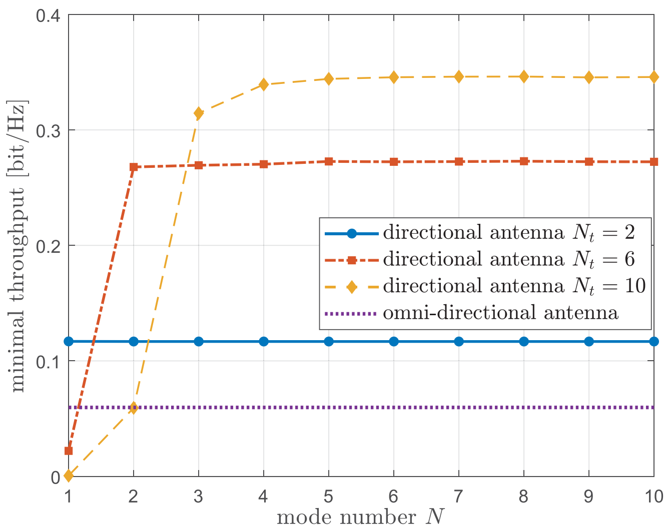


FIGURE 10. LAP-assisted multicasting throughput under different setups [93].

possibility of D2D cooperation within the clustered network to promote sub-network coexistence on a massive scale has been investigated in [49], [92]. Specifically, when serving massive ground devices, the LAP broadcasts data to all clustered users, who then decode the large data packet to extract their own information, albeit with diverse decoding errors. To address the potentially unfair reliability in LAP-assisted downlink communication, cooperative re-transmissions from the cluster head to other users are scheduled, transmitting only the necessary data.

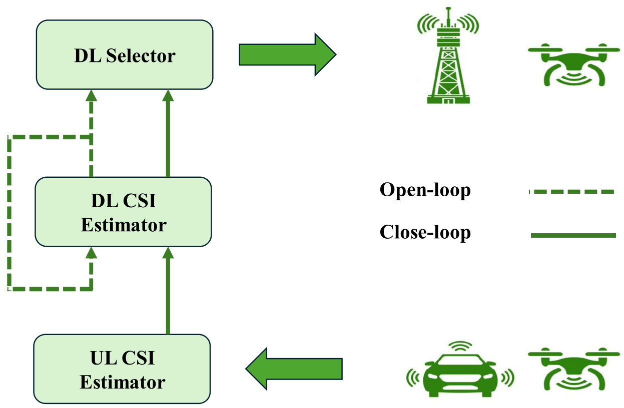
With restricted energy and blocklength resources, efficient joint resource allocation and cooperation scheduling designs have been proposed [49], [92] to minimize the maximum transmission error probability using successive convex optimization technologies. Fig. 8 shows that downlink transmission assisted by D2D cooperation can achieve much higher reliability than other schemes, and that longer scheduled service slot lengths, corresponding to larger blocklength M, allow for a much lower transmission error probability. Additionally, Fig. 8 reveals that cluster head selection significantly impacts the average reliability level, necessitating careful cluster head selection for practical system implementation. Without the scheduling burden at the aerial layer, LAP deployment and movement design can be more flexibly investigated, as shown in [89], [90], [91].

In LAP-assisted downlink communication, multiple ground users may request the same large data packet from the LAP, a common scenario for exploring massive connectivity in massive-access environments. For this multicasting service, the LAP can utilize 3D links for efficient data transfer. An effective analog beamforming strategy for LAP-assisted multicasting, involving the joint optimization of multiple beamforming modes, has been proposed in [93]. As shown in Fig. 9, the LAP operates with different analog beamforming modes in different slots. For each mode, the analog beamforming angle, transmit power, and service slot length are optimized using successive convex optimization techniques. By switching flexibly among multiple beamforming modes, the LAP provides comprehensive service coverage to all ground devices. Assisted by rateless coding schemes, the proposed design significantly boosts throughput performance in LAP-assisted multicasting communications. Fig. 10 illustrates the achieved UAV-assisted multicasting throughput under various antenna setups. Simulation results indicate that more beamforming modes enable more flexible LAP operation, resulting in higher minimum multicasting throughput. Conversely, more antenna elements are beneficial only when the mode number is sufficiently large. This is because additional antenna elements in analog beamforming lead to narrower beamwidths, necessitating more beamforming modes to efficiently cover all ground devices.

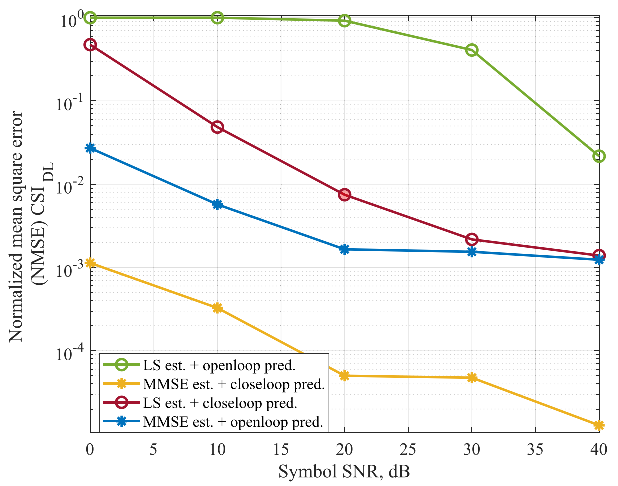
C. DISTRIBUTED PHY CONCEPTS

1) DISTRIBUTED LEARNING FOR LINK RELIABILITY IN 3D NETWORK

Enhancing radio link quality while managing constraints on radio resource availability is pivotal for ensuring high reliability for mobile users, especially in multipath and fading environments. Terrestrial radio access nodes often encounter



(a) Adaptive LSTM assisted DL selection [98]



(b) DL channel information LSTM-based-prediction correctness with high and low accurate estimation methods [98]

FIGURE 11. ML-based Link reliability framework.

NLOS link conditions, leading to areas with poor SNR within coverage zones. To tackle this challenge, research has suggested to employ machine learning (ML) based blind spot detection strategies, along with real-time avoidance techniques at the user end. These approaches aim to mitigate link reliability issues, while maintaining user QoS [94]. On transition from TN to 3D unified network, utilizing radio access via flight nodes offers notable advantages in flexibility, serving as relays or base stations. However, challenges such as energy consumption and flight time constraints persist. Therefore, choosing ATG radio access with high precision becomes crucial in addressing these challenges effectively.

Our system model incorporates Deep Learning-based (DL-based) prediction, using the adaptive Long Short-Term Memory (LSTM) network illustrated in Fig. 11(a), which leverages estimated CSI with or without prior acknowledgment. Our research demonstrates, that a highly accurate link selector is facilitated by an open-loop structure, based on estimated channel states with stochastic acknowledgment. However, in scenarios where prior channel acknowledgment is unavailable or computational resources are limited for high-accuracy estimation methods, like Minimum Mean Square Error (MMSE), we resort to simpler estimation techniques, like Least Squares (LS), with a closed-loop predictor LSTM network. In this case, the predictor operates in a closed-loop fashion, based on previously predicted values to mitigate error accumulation at the selector input, as depicted in Fig. 11(b). This adaptive approach ensures robust link selection and optimization, thereby enhancing the overall performance and reliability of NTN [95]. Consequently, it ensures a resilient and dependable wireless connection for critical applications such as autonomous driving.

To mitigate Inter-User Interference (IUI), beamforming can be utilized to perform Space Division Multiple Access (SDMA) precoding. The performance of common precoding algorithms significantly relies on the accuracy of the CSI. However, acquiring precise CSI is challenging for LEO satellites. On the other hand, the transmission channel in satellite communication is mainly characterized by LoS paths, which highly depend on the positions of satellites and ground users. Successful interference cancellation via SDMA precoding can leverage positional knowledge at the transmitter [96]. However, if this positional knowledge is flawed or unreliable, the transmission performance suffers. There are various approaches researched to combat the influence of unreliable positional knowledge.

In [97], the authors propose an analytical precoding approach, where the precoding performance is optimized concerning the mean Signal-to-Leakage-plus-Noise Ratio (SLNR) in cases of imperfect positional knowledge. In [98], a robust precoding approach using DRL is introduced, and [99] compares both approaches. Robustness can also be achieved by extending common SDMA precoding to Rate-Splitting Multiple Access (RSMA), where each user message is split into a common and a private part, treating the IUI partly as noise. Investigation into scenarios where RSMA outperforms SDMA precoding for LEO satellite downlinks is conducted in [100].

2) DISTRIBUTED BEAMFORMING

Recent advancements in formation flying have garnered significant interest in SatCom. Distributed satellite systems offer advantages in terms of robustness and scalability. Moreover, distributed beamforming among several satellites enables increased spectral efficiency. In [96], satellite swarms have been demonstrated as promising candidates for high data rate communication between satellite swarms and VSAT. Monolithic satellites typically spread the signal energy of a single beam over a region of several tens of kilometers or more, due to their limited antenna array size. However, with the possibility of formation flights, large virtual antenna arrays consisting of multiple satellites can be formed, enabling the creation of very narrow beams, as depicted in Fig. 12. Since the distance between neighboring satellites in a swarm is usually much

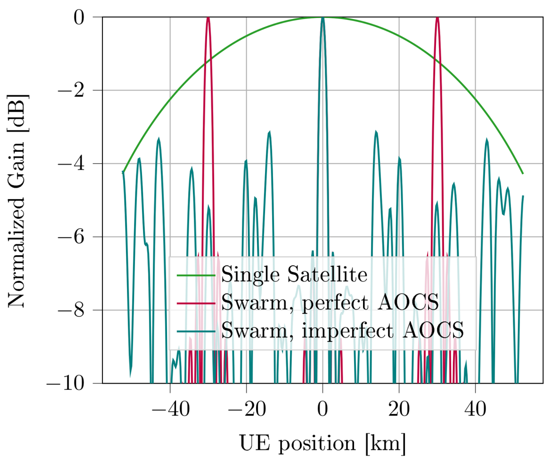


FIGURE 12. Beampattern for traditional MIMO array at a single satellite with 16 antennas and distributed array with 16 satellites.

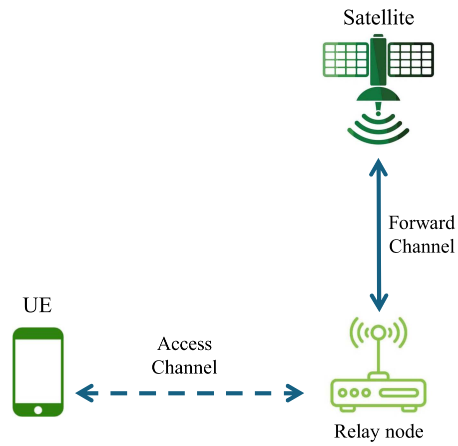


FIGURE 13. A satellite-aided communication system with a relaying aspect. A noisy signal from a UE is received by an on-ground relay node, compressed and finally forwarded to a satellite transponder via an error-prone link.

larger than half of the carrier wavelength, grating lobes might appear in the beam pattern. Nonetheless, as the satellites are not physically connected, small disturbances during flight and imperfect AOCS disrupt any regular structure of the virtual antenna array. This natural behavior prevents the emergence of grating lobes at the expense of an increased average side lobe level. In [101], various swarm geometries are studied in multi-beam satellite communication scenarios.

3) INFORMATION-PRESERVING DATA COMPRESSION

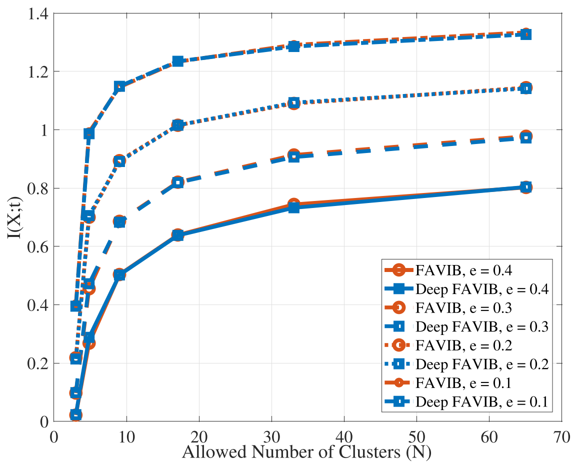
When considering a standard two-hop transmission configuration, wherein multiple UEs necessitate connection to a Remote Processing Unit (RPU) through several intermediary nodes, the meticulous design of data compression schemes emerges as a pivotal concern. The primary challenge lies in devising an efficient method to convey pertinent information across the system without unnecessarily burdening the existing communication infrastructure. For the collaborative design of local compressors at intermediary nodes, the Information Bottleneck (IB) method [102] stands out as an appropriate framework. It adeptly addresses the inherent "complexity-precision" trade-off, by directly incorporating the source/UE signals into the design problem. In [103], the original point-to-point (remote) source coding framework of the IB method has been extended to encompass the domain of Joint Source-Channel Coding (JSCC). This extension accounts for an error-prone link between the intermediary node and RPU, integrating its ramifications into the design formulation. Furthermore, [104] and [105] introduce the (distributed) multi-terminal Remote Source Coding (RSC) and JSCC extensions of the IB framework, respectively.

The aforementioned model-based IB algorithms necessitate prior knowledge of the joint statistics of input signals, rendering their application in highly dynamic environments challenging. Continuous estimation of the joint statistics of input signals becomes necessary, adding complexity. To circumvent this requirement, one viable approach involves developing model-free and entirely data-driven schemes rooted in established data compression principles within the realm of (generative) Latent Variable Models (LVMs) in Deep Learning theory. In particular, [106] presents a derivable objective function that extends the Evidence Lower-Bound (ELBO) of Variational Auto-Encoders (VAEs) [107]. Additionally, it introduces a learning architecture enabling optimization of the derived lower-bound through standard training procedures of encoder/decoder Multi-Layer Perceptrons (MLPs). This introduced scheme, referred to as Deep FAVIB, offers a promising avenue in this direction.

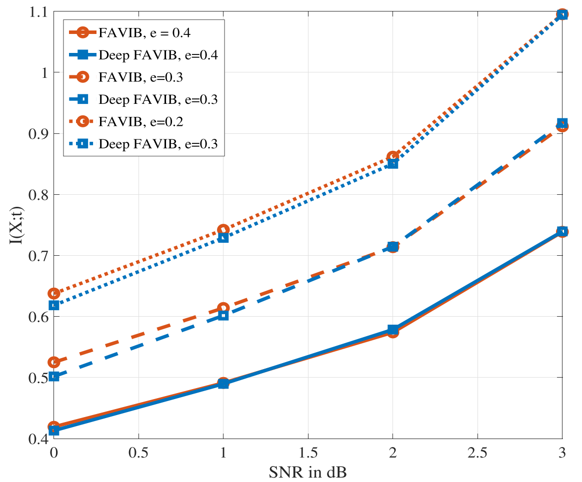
In [108], the applicability of Deep FAVIB has been showcased in a satellite-aided communication scenario that is illustrated in Fig. 13, wherein a noisy source signal should be compressed at an on-ground relay node before getting forwarded over an error-prone and rate-limited channel to a satellite transponder. Specifically, by considering an AWGN access channel that is characterized by the noise variance, σ_{n}^2, and a symmetric forward model that is characterized by the error probability, e, as can be readily observed from Fig. 14, irrespective of the certain choice of model parameters, the devised Deep FAVIB scheme performs on par with the SotA model-based methods, without requiring the prior knowledge of the joint statistics of input signals.

4) ENERGY OPTIMIZED COMPUTATION OFFLOADING

As the UAV has a limited battery capacity that can sustain few hours, a careful offloading decision needs to be made to minimize the energy consumption at the UAV. The UAV are within the LoS of a terrestrial BS equipped with sufficient computation power. Depending upon the channel conditions, the UAV can offload the computation data to the terrestrial BS based edge cloud. In case of a bad channel condition or coverage holes the data should be processed locally in the UAV, as transmitting the data will consume more power [109],



(a) Transmission rate versus number of output clusters, $\sigma_n^2 = 0.4$.



(b) Transmission rate vs access channel SNR, $N = 32$

FIGURE 14. **The performance comparison of the model-free Deep FAVIB [106] with the SotA model-based FAVIB [103] for an equiprobable Quadrature Phase Shift Keying (QPSK) source signaling.**

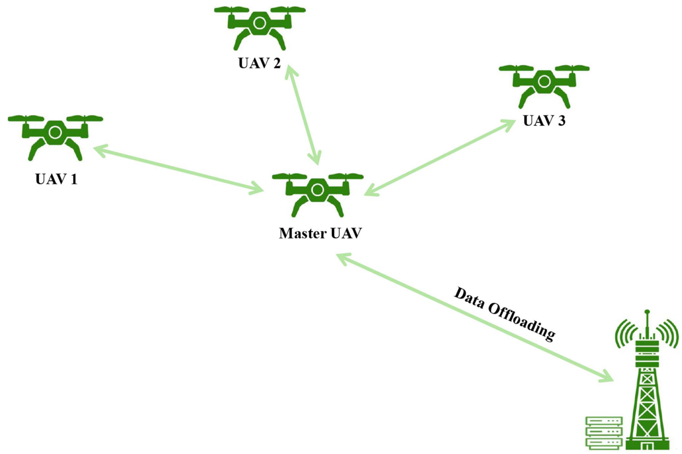


FIGURE 15. **UAV computation offloading.**

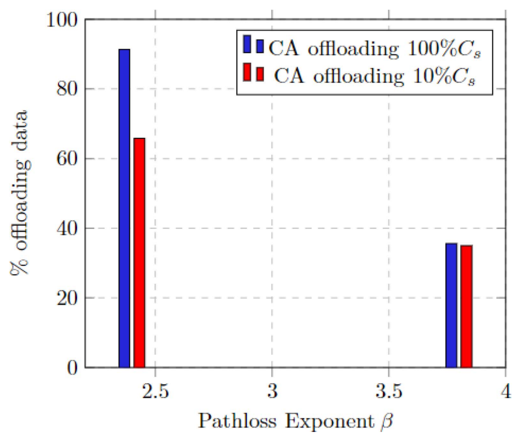


FIGURE 16. **ATG offloading, $f_c = 4$ GHz, NLoS (UAV height range 0–11 [m], $\beta = 2.4$), LOS (UAV height range 11–24 [m], $\beta = 3.8$).**

[110]. Unlike the terrestrial devices where the UE movement is limited to on-ground movement and gradual altitude change, the UAV are high velocity drones reaching different altitudes in short time span. This may lead to loss of connectivity, as the channel is highly uncertain and unpredictable link conditions exists due to high velocity movement in 3D. In case of centralized controlled UAV, connectivity loss or consecutive packet loss may result in loss of information flow, hence leading to control failure as presented for terrestrial case in [111]. The channel-aware (CA) offloading decision for TN is presented in [109]. Therefore, we proposed a CA computation offloading algorithm for UAV to minimize the energy consumption while simultaneously satisfying the latency constraints. In this scenario shown in Fig. 15, we considered the offloading from ATG communication link. A system of UAVs offloading the computational data to an edge cloud co-located with BS is assumed. Analyzing the energy consumption trade-off between in-device execution and transmission of data to obtain an optimal decision is made. The optimal offloading percentage varies with the availability of an edge cloud server capacity C_s Cycles/s. A UAV can offload more data if the cloud server is free. In case of limited cloud server capacity, the offloading percentage decreases as shown in Fig 16. In ATG link, the channel conditions vary with the altitude of aerial vehicles and the 3D distance between BS and the UAV. As the UAVs attain higher altitude, the LoS communication link and the pathloss exponent is lower. The UAV experience near to free-space pathloss [112], [113]. Therefore, taking into account the altitude and the pathloss experienced by the UAV, we determine the energy consumption to offload the processing data. At lower altitudes the energy consumption is higher to successfully transmit the data, as NLoS channel is experienced and the pathloss exponent is higher, $\beta = 3.8$. Therefore, the offloading percentage is reduced as shown in Fig. 16 and the energy consumption is higher as shown in Fig 17. With no-offloading case, all the data processing is

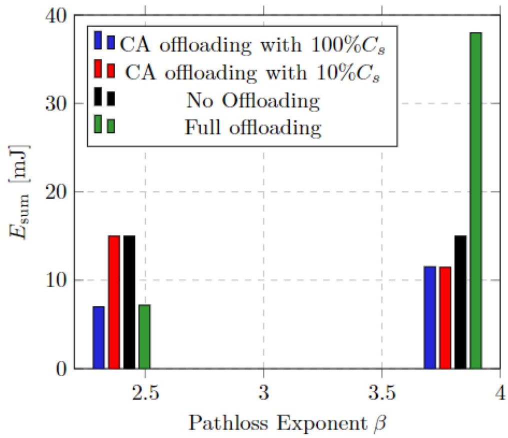


FIGURE 17. System energy consumption for ATG Channel Aware(CA) offloading.

done in the UAV, therefore the energy consumption is constant. In case of full-offloading scenario, the UAV offloads all the data without considering the channel conditions, therefore, the energy consumption increases. In CA offloading the energy consumption is minimized as the partial data is offloaded considering the pathloss. The minimum energy consumption is seen with CA offloading with sufficient edge cloud server capacity, i.e. 100% C_s. If the cloud server is pre-occupied and have limited capacity for processing, less data is offloaded to the cloud, therefore the offloading percentage is lower in Fig. 16. The energy consumption is also higher at $\beta = 2.8$, refer Fig. 17 for C_s i.e. 10% C_s compare to 100% of C_s. As the optimal amount of data cannot be offloaded to the cloud due to longer waiting times, the UAV process the data, increasing the total energy consumption.

VI. EMERGING USE-CASES AND FUTURE RESEARCH DIRECTIONS

A. USE CASES

3D unified networks require suitable application scenarios in order to justify the need for further investigation and research on the one hand, and to be able to define realistic evaluation criteria and KPIs on the other. In the following, various applications are described which are made possible by the unified 3D networks, as backhaul problems can be solved or flexible topologies can be realized, for example.

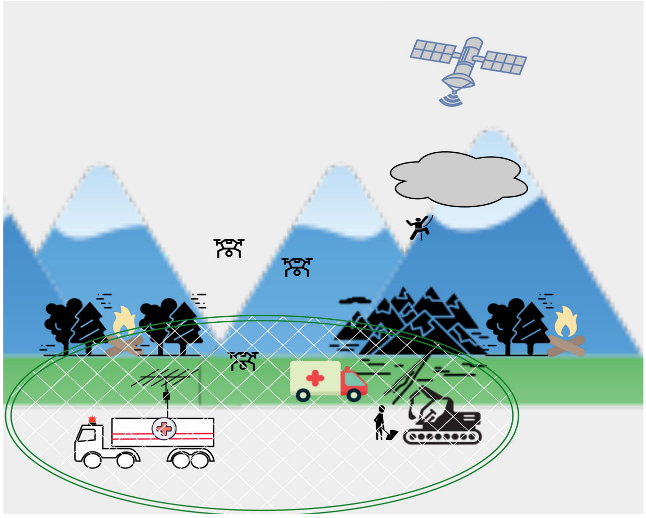
1) NOMADIC NETWORKS

On-demand and nomadic functionalities are able to revolutionize private 6G networks, offering a dynamic and cost-effective approach to network resource management. Imagine a factory that can instantly scale its network bandwidth up or down based on real-time production needs. This eliminates the need for pre-provisioning excess capacity, leading to significant cost savings and improved efficiency [114]. The concept extends beyond static locations. Nomadic functionality allows network slices to seamlessly hand-off between private operators [115]. This is a game-changer for applications in logistics or agriculture, where devices constantly move between coverage areas. Nomadic 6G ensures uninterrupted connectivity and eliminates connection drops as devices transition, fostering applications like autonomous farm equipment or connected logistics fleets. However, unlocking the full potential of nomadic 6G requires innovative solutions. Here's where the concept of demand-driven operation with spatial mobility comes in. This approach not only reduces costs for operators in both infrastructure (CapEx) and operational expenses (OpEx), but also significantly contributes to sustainable information and communication technologies.

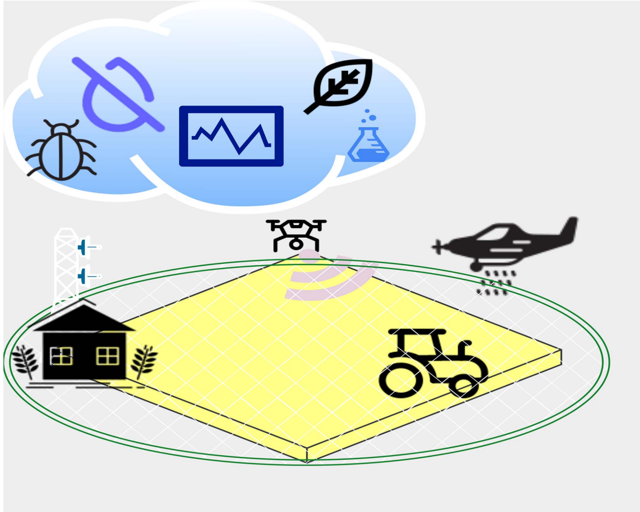
AI plays a crucial role in this vision. It goes beyond applications in agricultural automation and extends to orchestration of on-demand network provisioning, like the post-disaster solution shown in Fig. 18(a). AI can handle communication within the nomadic network (intra-nomadic) and between nomadic networks and other infrastructures (inter-network), optimizing resource allocation and mitigating interference. Developing an architecture and mechanisms for automated interaction between the nomadic on-demand network and existing terrestrial or non-terrestrial networks is essential. Questions like frequency allocation between nomadic networks, trusted data exchange, and time-limited licensing need to be addressed. A pay-as-you-go paradigm for nomadic networks can provide communication customers with a dynamic and resource-efficient model. This, coupled with a simple network infrastructure with minimal reliance on wired connections, benefits both service providers and users. Here, technologies like Non-Public Networks (NPN) and NTN become even more relevant in the 6G research landscape. Let's consider a specific use case in agriculture, see Fig. 18(b). A farmer can rent communication resources realized with a nomadic network, operating it with spatial mobility or as an on-demand network in specific geographic zones [116]. This enables precise planning of crop cultivation with on-site provisioning orchestrated through a central node. This strategic node hosts a variety of field nodes, optimizing resource utilization and minimizing complexity. The field nodes themselves are deliberately streamlined and rely on wireless connectivity for rapid deployment and lower costs. This dual approach not only enhances flexibility and cost-effectiveness but also contributes to energy savings, furthering the vision of sustainable information and communication technologies.

2) 3D EARTH OBSERVATION SYSTEM

The 3D unified 6G network, comprising a seamless integration of terrestrial and non-terrestrial sensors and platforms, holds the potential to revolutionize Earth observation and climate monitoring, see Fig. 19. To achieve the goals of this unified 3D Earth observation system, different nodes within this ubiquitous network including satellites, HAPs, airplanes, drones, IoT devices, and UEs, will meticulously gather measurements of various environmental parameters such as greenhouse gases (Carbon Dioxide, Methane, Nitrous



(a) Public protection disaster relief with 3D unified network.



(b) Smart agriculture with airborne platforms.

FIGURE 18. **NNPN Use-case: (a) Public protection disaster relief with 3D unified network, (b) Smart agriculture with airborne platforms.**

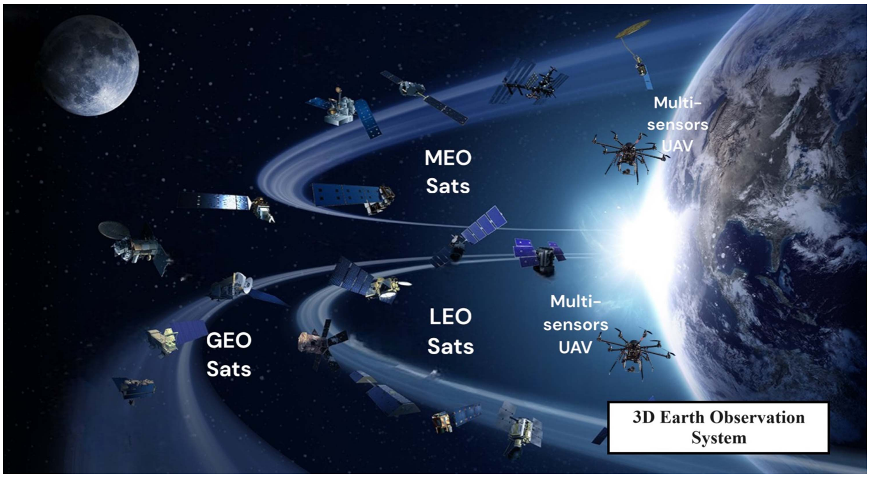


FIGURE 19. **3D Earth observation system that comprises terrestrial and non-terrestrial sensors and platforms.**

Oxide, Ozone), temperature, air pressure, humidity, solar energy reaching Earth, and light reflected from its surface. Precise but distributed monitoring of biological and/or physical processes such as emissions caused by plants and consumers will enable continuous tracking of process parameters allowing to gain insights into timely varying process properties, e.g., pollution fluxes. These amassed sensory insights will serve on a short-time scale for disaster monitoring such as volcanic eruption or, on a rather long-time scale, as an invaluable foundation for comprehending Earth's climate dynamics, offering unprecedented insights that will inform global strategies to mitigate climate-related challenges. Moreover, the "3D Unified Earth Observatory System" will facilitate seamless data exchange among scientists and climatologists, fostering unprecedented collaboration and enabling much more accurate forecasts and analysis across the globe in a timely manner.

6G network with its 3D unified network architecture enables a 3D Earth observation system that stands out against existing ones, in several key aspects:

- *Unified data collection:* The system seamlessly integrates terrestrial and non-terrestrial sensors and platforms, encompassing a wider range of data sources than traditional systems. This comprehensive data collection approach provides a more holistic understanding of Earth's climate and its dynamic processes.
- *Real-time data transfer:* The system utilizes advanced 6G communication technologies to enable near-real-time data transfer between sensors and fusion centers. This real-time data flow ensures that scientists and decision-makers have access to the most up-to-date information, enabling rapid responses to climate events and informed decision-making.

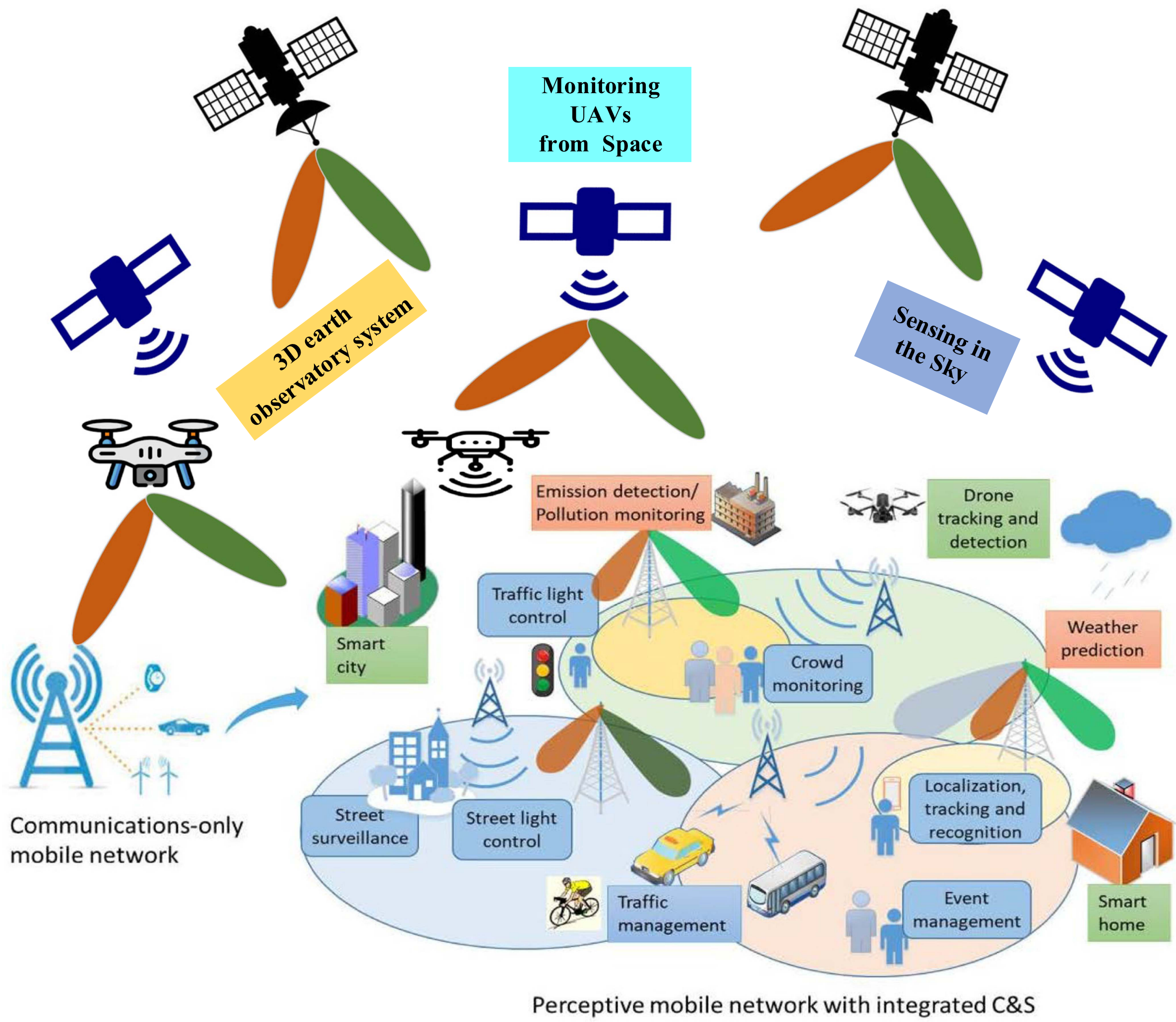


FIGURE 20. **3D Perceptive mobile network.**

- *Centralized fusion centers:* The system incorporates centralized fusion centers equipped with sophisticated data analysis tools and algorithms. These fusion centers process the vast volumes of data collected from the network, extracting valuable insights and generating actionable information for scientists, policymakers, and the public.
- *Enhanced data accuracy:* The use of advanced sensors, 6G communication, and centralized fusion centers leads to significant improvements in data accuracy and consistency. This enhanced data quality underpins more reliable and informed decision-making related to climate change and its impacts.
- *Seamless data sharing:* The system facilitates seamless data sharing among scientists and climatologists from around the globe. This collaborative environment fosters knowledge exchange and promotes the development of advanced climate models and predictive analytics.

The 3D unified Earth observatory system represents a significant advancement in Earth observation and climate monitoring. Its unified data collection, real-time data transfer, centralized fusion centers, enhanced data accuracy, and seamless data sharing capabilities will revolutionize our understanding of Earth's climate and enable more effective responses to climate-related challenges.

3) 3D PERCEPTIVE MOBILE NETWORK

The future of mobile networks is moving toward a transformative leap with the integration of sensing and communication functionalities. This convergence, known as Integrated Sensing and Communication (ISAC), when applied to large-scale mobile networks with a unified 3D network architecture, has the potential to revolutionize how we interact with our surroundings. This paves the way for the emergence of a 3D Perceptive Mobile Network (PMN).

This novel network architecture transcends the limitations of communication-only networks. The 3D PMN seamlessly integrates communication and radio sensing capabilities, transforming it into a ubiquitous radio sensing network. Imagine a network that not only keeps you connected but also gathers real-time information about its environment. Fig. 20 illustrates the vast potential of 3D PMN sensing applications.

Several key features enable the efficient functioning of 3D PMNs:

- *Shared signal optimization:* A single, intelligently designed transmitted signal serves the dual purpose of communication and sensing. This eliminates the need for separate signals, maximizing efficiency and spectral utilization.
- *Bi-directional sensing:* Both uplink (user to network) and downlink (network to user) signals can be harnessed for communication and sensing (C&S). This expands the data gathering potential of the network.
- *Hardware and processing synergy:* A significant portion of the hardware and signal processing modules within network transceivers are leveraged for both communication and sensing tasks. This translates to cost savings and a more streamlined network infrastructure.
- *Flexible sensing deployment:* Sensing can be implemented in various configurations: within a single node (base station or user equipment), or even across a network of nodes. This adaptability caters to diverse sensing applications.
- *Cooperative network-wide C&S:* All network components, including terrestrial infrastructure and NTN platforms, can participate in cooperative C&S activities. This collaborative approach enhances both communication and sensing KPIs.

The 3D PMN signifies a paradigm shift in mobile network design. It promises not only seamless communication but also unlocks a treasure trove of environmental data, paving the way for innovative applications across various sectors. From smart cities and environmental monitoring to industrial automation and connected transportation, the possibilities are truly boundless.

4) RESILIENT 3D NETWORK

Resiliency is one of the main concerns in current TN, and in upcoming integrated NTNs. A unified 3D-Network can provide resiliency by its own due to its architecture. In case of natural disasters that cause failure of communication of TN, or turn the backhaul network down, non-terrestrial communication links can play role of backup in case of direct service to users or provide backhaul links between down links and the core.

Resiliency in a 3D network comes from the co-existence of more than one communication layer. The main challenges facing such resiliency can be listed as:

- The space segment can cover a wide area, but the main limitation is the relatively low data rate that can be achieved. In the event of natural disasters, which disrupt communication for many users, relying solely on SatCom may not be enough. For example, in the S-band, the maximum available bandwidth for each cell is around 30 MHz. A potential solution involves integrating both air and space segments, where HAPS can cover smaller, more concentrated areas, while the space segment provides extended coverage for nomadic users or serves as a backbone for air communication links.
- Durability is another limiting factor when it comes to the resilience of flying objects, especially LAPs like drones or UAVs, as their operational time as service providers is limited. For LEO satellites, this issue translates into limited visibility for each user on the ground or in the air. A possible solution to this challenge is the use of LEO mega-constellations, along with separating communication services between GEO or MEO satellites for delay-tolerant services.
- Managing radio resources to avoid interference is another challenge when relying on both air and space segments for service. When transferring the traffic from a downed ground network to non-terrestrial links, ensuring reliable service for the backhaul network requires large-scale radio resource management for each group of services.

B. FUTURE RESEARCH DIRECTIONS

1) FUTURE HANDOVER STRATEGIES

Promising future directions in handover within 3D unified networks incorporating non-terrestrial platforms include the development of seamless and ultra-reliable handover mechanisms, which necessitate exploring triggering strategies based on factors beyond signal strength such as mobility prediction and real-time channel quality assessment [70]. Additionally, predictive and proactive handover approaches leveraging ML to anticipate handover needs based on user mobility patterns and network conditions could significantly reduce latency [117]. Joint optimization of network selection and handover algorithms considering user equipment capabilities and service-specific requirements is vital for enhancing network efficiency and user satisfaction. Standardization efforts focusing on defining common handover protocols and ensuring inter-operability across different non-terrestrial platforms and terrestrial networks are crucial. Security considerations, including secure key exchange and data encryption during handover procedures, are paramount [118]. Integration with network slicing for tailored service provisioning and leveraging AI/ML for real-time network assessment and handover path selection are avenues for further exploration. Lastly, cognitive radio technology holds promise for dynamic spectrum management to optimize handover procedures in congested non-terrestrial platform environments.

2) FUTURE INTERFERENCE AND PEACEFUL COEXISTENCE STRATEGIES IN 3D NETWORKS

Future directions for interference management and peaceful coexistence in unified 3D networks entail dynamic adjustments based on real-time context such as user location, mobility patterns, and network traffic to enhance interference mitigation strategies beyond static models [119]. Proactive interference prediction and management leveraging ML algorithms trained on network data represent a promising avenue for optimizing resource allocation and minimizing interference [120]. Cognitive radio technology emerges as a pivotal enabler for dynamic spectrum sharing, with research focusing on intelligent spectrum management algorithms to identify available spectrum bands while mitigating interference [121]. Furthermore, optimizing resource allocation strategies tailored to network slicing requirements and developing efficient coordination mechanisms for inter-slice and inter-network communication are crucial for ensuring seamless coexistence. Standardizing interference management techniques across vendors and technologies and exploring joint optimization strategies for handover and interference management are imperative for interoperability and smooth service continuity in unified 3D networks.

3) FUTURE DIRECTIONS FOR DISTRIBUTED LEARNING APPROACHES, MEC, AND DISTRIBUTED BEAMFORMING

In advancing distributed learning approaches, MEC, and distributed beamforming within unified 3D networks, several promising future directions emerge [122]. These include developing federated learning algorithms resilient against malicious actors to ensure data privacy and security, seamlessly integrating MEC with distributed learning frameworks for on-demand training at the network edge, and jointly optimizing learning and beamforming techniques to enhance network performance [123], [124]. Exploring the incorporation of non-terrestrial platforms like LEO satellites into distributed learning architectures, alongside efforts to develop energy-efficient algorithms and ensure explainability in AI models, will further augment network capabilities. Addressing security concerns in distributed beamforming, designing scalable protocols, and leveraging federated learning for anomaly detection and network slicing optimization represent crucial avenues towards creating intelligent, adaptive, and secure unified 3D networks capable of delivering superior performance and user experience.

4) INTEGRATION OF AI IN UNIFIED 3D NETWORKS

The integration of AI in unified 3D networks represents a pivotal evolution in modern communication systems [125]. As 3D networks become increasingly complex, AI will play a critical role in automating and optimizing various network functions, from resource allocation to mobility management [126]. The future of AI in 3D networks promises not only enhanced performance but also smarter, more adaptive networks capable of responding in real-time to changing conditions, traffic demands, and user behavior [127]. One of the most promising directions is the use of ML and DL techniques for dynamic resource management. AI-powered algorithms can predict traffic patterns, user mobility, and network load, enabling proactive resource allocation and load balancing across terrestrial, aerial, and satellite links. This will be particularly important in scenarios involving large-scale satellite constellations and autonomous aerial networks, where real-time decision-making is essential. Furthermore, DRL models can continuously learn and adapt from network interactions, optimizing performance metrics such as latency, throughput, and spectral efficiency. This will make 3D networks more resilient and capable of providing uninterrupted, high-quality service even in highly dynamic environments.

Another future direction for AI in 3D networks lies in the development of self-organizing networks (SONs) [128]. By leveraging AI, 3D networks will be able to autonomously configure and reconfigure their parameters in real time, minimizing the need for manual intervention. AI-driven SONs could significantly reduce operational costs while enhancing reliability by detecting and mitigating network faults, interference, or bottlenecks before they impact service. Additionally, AI will play a crucial role in security management, where intelligent algorithms can identify and respond to emerging threats or anomalies, safeguarding the unified 3D network infrastructure from increasingly sophisticated cyber attacks.

VII. CONCLUSION

This paper has presented a compelling vision for a unified 3D network architecture as the cornerstone of future 6G networks. By leveraging the combined strengths of space, air, and ground network segments, this transformative architecture presents a solution to meet the ever-growing demands for capacity, data rates, latency, mobility, and seamless heterogeneous connectivity. We have addressed the technical challenges inherent to this paradigm shift, proposing strategies for mobility management, handover optimization, interference mitigation, and the integration of distributed physical layer concepts. The potential of federated learning, advanced beamforming, and energy-efficient computational offloading holds immense promise for enhancing network performance and resilience. Furthermore, we have explored compelling use cases that showcase the transformative potential of this architecture. We believe that continued research efforts, drawing upon standardization initiatives and cutting-edge advancements, will pave the way for the realization of a unified 3D network, ushering in a new era of ubiquitous, intelligent, and hyper-connected experiences.

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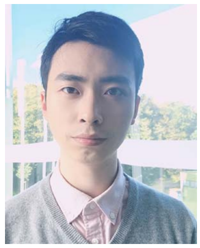

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