Open6GHub

3D Networks

Unify Ground – Air – Space Communications

Position Paper

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The work presented is part of the BMBF project “Open6GHub” and contains views of industrial members of the BMBF project “6G-TakeOff”, both part of the 6G-Platform Germany. The views expressed herein can in no way be taken to reflect the official opinion of the BMBF.

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1 Executive Summary

The term "3D network" has emerged from the joint efforts of the academic community, industry and standardization bodies working towards the integration of different network layers to achieve ubiquitous connectivity. As an important milestone, 3GPP standardized the integration of non-terrestrial networks (NTNs) into a terrestrial 5G network under the label 5G-NTN. To create a "fully connected smart world", the vision of 6G further develops the 5G integration approach by aiming for a unified 3D network. This unified 3D network combines technologies from three spatial segments – space, air and ground – into a single, interconnected network.

This position paper of the BMBF project "Open6GHub" describes the activities on unified 3D networks of the German 6G program of the BMBF, underlines the necessity of these R&D activities for Germany and Europe by describing the societal and economic importance of unified 3D networks and reflects both their international embedding in government-funded R&D programs and industrial aspects such as market potential and industrial activities. The paper also highlights the key achievements and results of the Open6GHub activities on RAN and Core topics and naming first steps towards harmonization and consolidation of 3D network use cases and technologies to be provided to 3GPP standardization. Based on this stock of accumulated expertise, future skilled workforce and global impact, examples of R&D elements that need to be addressed in the near future are shown in order to continue the path taken so far towards a successful positioning of the German and European industry on the global 3D network market. This is the only way to guarantee technological sovereignty in 6G technology, which is of central importance for German and European society and the economy.

2 Problem Statement

The vision of 6G aims to create a "fully connected intelligent world" that overcomes limitations of terrestrial networks through a unified 3D infrastructure. A unified 3D network refers to a communications infrastructure that combines technologies across three spatial segments – space, air and ground – into a single, interconnected network. This network facilitates the seamless delivery of services by incorporating both terrestrial and aerospace components, each with different communication characteristics such as coverage, latency, data rates, link budgets and processing capabilities. The comprehensive design of a unified 3D network enables optimal access and connectivity for a variety of subscribers, including government, private and individual customers, and requires research and development of innovative communication solutions for all three segments. This unification enables global connectivity and supports advanced use cases (applications), shown in Figure 1, that promise to revolutionize global communications and data processing. For example, unified 3D networks facilitate the following advanced use cases, including several socially and economically important use cases:

1) **Connecting Rural Areas**: Delivering internet connection to remote and rural regions, enabling access to digital services and economic opportunities.
2) **Resilience Communication Infrastructure**: Providing robust communication channels during disasters, ensuring continuity of operations for emergency services and disaster response teams.
3) **Autonomous Driving and Transportation:** Enabling seamless operation of autonomous vehicles and providing uninterrupted connectivity for transportation.

4) **Fast Train Support**: Ensuring stable connectivity for passengers on high-speed trains.
5) **Intelligent Farming**: Supporting precision agriculture through Internet-of-Things (IoT), improving crop yields, and reducing resource wastage.
6) **World-wide Logistics**: Enhancing global supply chains with real-time tracking and management of goods.
7) **Maritime Connectivity**: Ensuring reliable communication for cargo and cruise ships, enhancing safety and operational efficiency.
8) **Airline Connectivity**: Enabling uninterrupted connectivity for in-flight passengers.
9) **Health-support**: Support in uncovered areas ensuring immediate accident responses.
10) **Earth Observation and Environmental Monitoring**: Enhanced monitoring capabilities for climate change, natural disasters, and environmental conservation through global IoT networks.
11) **Governmental Services**: Facilitating secure and reliable communication for government operations, enhancing national security and public administration.
12) **Stock Exchange Networks (Security)**: Ensuring secure and fast transactions across global financial markets, enhancing the stability and efficiency of financial systems.

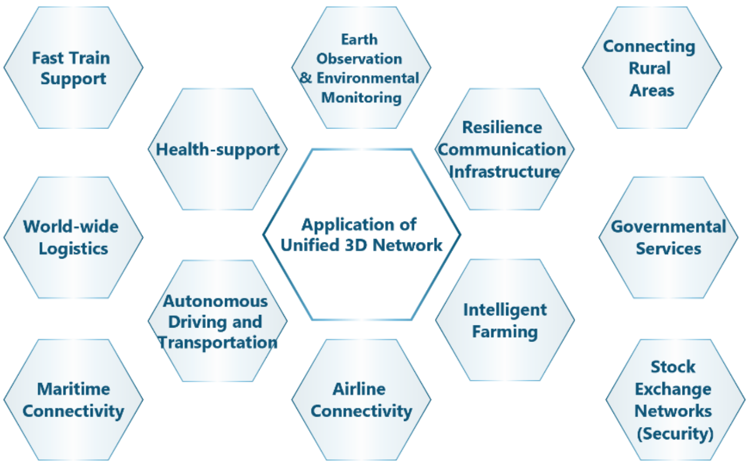

Figure 1: Use cases of unified 3D network

Unified 3D Networks – crucial for Germany and Europe?

Table 1 provides information on the social and economic significance of unified 3D networks for Germany and Europe.

Table 1: Significance of unified 3D networks for Germany and Europe

Measure	Impact
Comprehensive Coverage & Connectivity	Unified 3D networks ensure ubiquitous connectivity, extending internet access to remote and underserved areas that terrestrial networks alone cannot reach. This is crucial for rural regions and geographically challenging areas in Europe, promoting digital inclusion and bridging the digital divide.
Economic Growth & Competitiveness	By enabling advanced applications such as intelligent farming, autonomous transportation, and world-wide logistics, 3D networks drive economic growth and enhance competitiveness. For Germany, a leader in manufacturing and technology, this infrastructure supports Industry 4.0 initiatives, optimizing production and supply chains. In addition, it enables new competitive use cases and services to be offered worldwide.

Enhanced Resilience & Security	Integrated networks provide robust and resilient communication channels, essential for disaster response and emergency services. In times of crisis, non-terrestrial networks can maintain connectivity when terrestrial networks are compromised. This resilience is vital for national security and public safety.
Technological Sovereignty	Developing and deploying 3D networks reduce dependence on foreign technologies and services, enhancing technological sovereignty. For Germany and Europe, leading in 6G technology development ensures control over critical infrastructure and aligns with strategic interests in maintaining independence from non-European providers.
Innovation & Leadership	Unified 3D networks represent the forefront of innovation in communication technologies. By investing in and leading the development of these networks, Germany and Europe can influence global standards, foster innovation ecosystems, and maintain leadership in the next generation of mobile communications.
Environmental & Societal Benefits	These networks support applications like environmental monitoring and smart city initiatives, contributing to sustainable development goals. They also enable secure and efficient government services, enhancing the quality of life for citizens.
Collaboration & Harmonization	Unified 3D networks necessitate international collaboration, aligning with Europe’s goals of harmonizing standards and regulations across member states.

International collaborations

The realization of unified 3D networks requires solid international cooperation to effectively address the technical, financial and regulatory challenges. LEO satellites providing base station functionalities are crossing borders and operate globally. International managed satellite constellations are expected which requires collaboration of all stakeholders involved. Partnerships can accelerate innovation, harmonize standards and ensure interoperability, while pooling resources for large-scale projects reduces costs and risks for development and deployment. International alliances also improve geopolitical stability and create a stable global communications network that promotes an inclusive digital ecosystem. For Europe and Germany, strategic alliances are crucial to maintain leadership and competitiveness in 6G technologies.

3 Setting the Scene

The term "3D network" has emerged from the collective efforts of the academic community, industry stakeholders, and standardization bodies as they have worked towards integrating different network layers to achieve ubiquitous connectivity, see Figure 2 below. Key milestones in the development of this idea include the 3GPP standardization activities on 5G-NTN – the integration of NTNs as part of its releases for 5G and beyond – academic conferences and journals exploring the technical challenges and potential solutions for creating integrated 3D networks, and national and international research programs such as the European Union's Horizon and the German Federal Ministry of Education and Research (BMBF) 6G program that have funded projects specifically aimed at developing 3D network technologies.

In its essence, a 3D network comprises three distinct segments visualized in Figure 2:

- Ground Segment: terrestrial base stations (BS) and network entities
- Air Segment: Aircrafts and Unmanned Aerial Vehicles (UAVs) comprising Low Altitude Platforms (LAPs) and High Altitude Platform Stations (HAPSs)

- Space Segment: Constellations of satellites in Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationary Earth Orbit (GEO)

This segmented architecture forms the backbone of the unified 3D network, offering a comprehensive and versatile communication infrastructure for the 6G era.

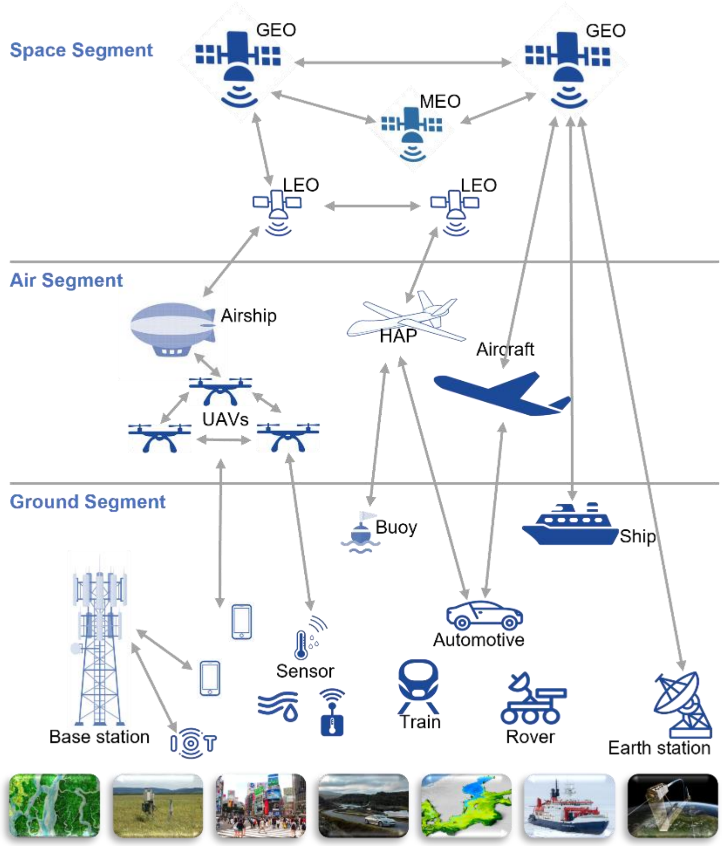

Figure 2: A conceptual illustration of a unified 3D network

3GPP standardization work on NTN and UAV communications

The 3GPP has been actively standardizing NTNs and UAVs communication since 2017, focusing on NTN enhancements and terrestrial network support for UAVs.

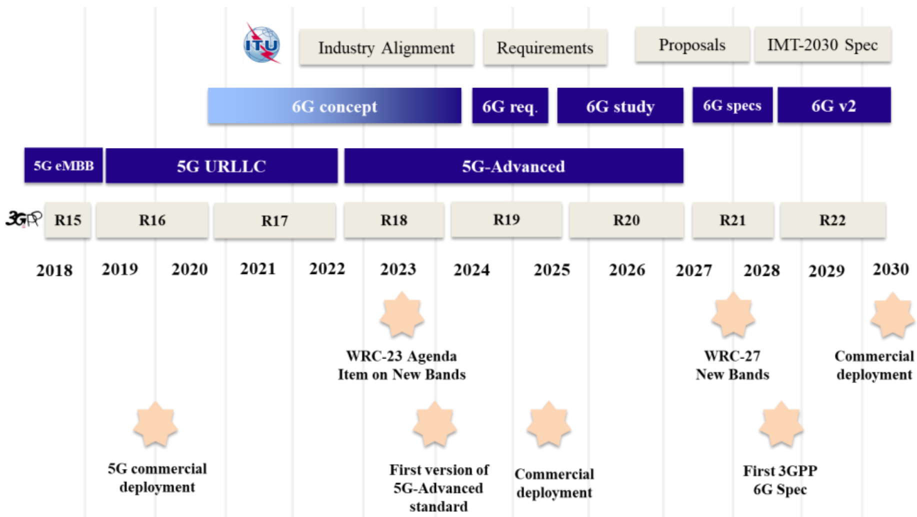

Figure 3: 3GPP standardization activities related to communications involving non-terrestrial platforms

From Release 15 to Release 17, 3GPP developed standards addressing various aspects such as frequency bands, antenna types, and mobility management for NTNs, and improved UAV interference management, connectivity, identification, and tracking. Release 15 introduced foundational studies and scenarios for NTN and UAVs, while Releases 16 and 17 provided solutions and enhancements for integrating satellite access in 5G and improving UAV operational support. Release 18 will further refine NR NTN coverage and support for UAVs, ensuring compatibility with handheld terminals and addressing mobility and service continuity challenges. The 3GPP 5G-NTN laid the foundation for integrating components of the air and space segment, paving the way for the 6G track to advance toward unified 3D networks. Both the 5G-NTN and 6G roadmaps are illustrated in Figure 3.

International 3D Network programs

Several pioneering research programs and projects on satellite communications (SatCom), NTN and 3D Networks are underway worldwide. Figure 4 shows examples of research projects funded by the EU and ESA, while the three projects of the BMBF 6G Program in Germany addressing unified 3D networks, Open6GHub, 6G-TakeOff, and 6G-Plattform are highlighted subsequently.

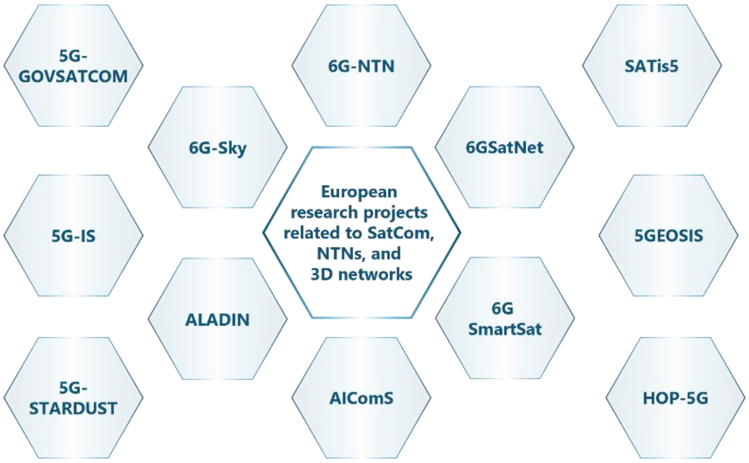

Figure 4: European research projects that are related to SatCom, NTNs, and 3D networks

BMBF 6G Program Germany – unified 3D Networks

The BMBF's 6G program has produced innovative concepts and technical solutions for 3D networks over the last three years, starting with the Open6GHub project. In the academically staffed Open6GHub, the focus is on the theoretical and isolated design of basic concepts, their analysis with the help of specially developed simulation platforms and initial rudimentary verifications in newly established testbeds.

The industry-oriented research project 6G-TakeOff further develops promising approaches and findings from the Open6GHub, but primarily pursues an end-to-end approach. The focus is on the design of a unified 3D architecture, the development of further new technological solutions and their analysis in an end-to-end approach. The results are partly validated and tested using the 6G-TakeOff end-to-end simulation platforms and testbeds (proof of concept). Both projects pursue a comprehensive design approach with the aim of a unified 3D network.

The 6G-Platform Germany is the umbrella organization of the BMBF 6G program and it promotes harmonization with international regulations and standardization as well as the involvement of society and industry. It further manages liaisons and collaboration with other international 6G programs being crucial for 3D networks. As a first results of the 6G-Platform Germany for 3D Networks, the "3D Networks" working group, led by the University of Bremen, has taken the first steps towards harmonizing and consolidating technological 3D approaches. The goal is to anchor the developed approaches as standards in the upcoming 3GPP standardization process. Furthermore, its working group “Roadmap and Vision”, led by FAU Erlangen, has consolidated use cases for 3D networks and coordinated them with the European projects, and is currently contributing the consolidated outcomes to the 3GPP SA1 standardization group via the European format EU-SNS. Both activities are crucial for achieving technological sovereignty in the field of 3D networks.

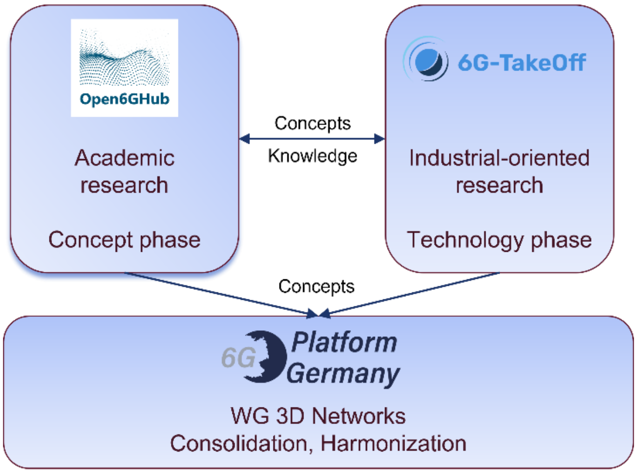

Figure 5: 3D-projects of BMBF 6G-Program

The individual focal points and the interaction of the three projects Open6GHub, 6G-TakeOff and 6G-Platform Germany are visualized in Figure 5.

4 Open6GHub – research results

This chapter outlines the research conducted thus far within the Open6GHub on 3D networks, emphasizing the most significant findings.

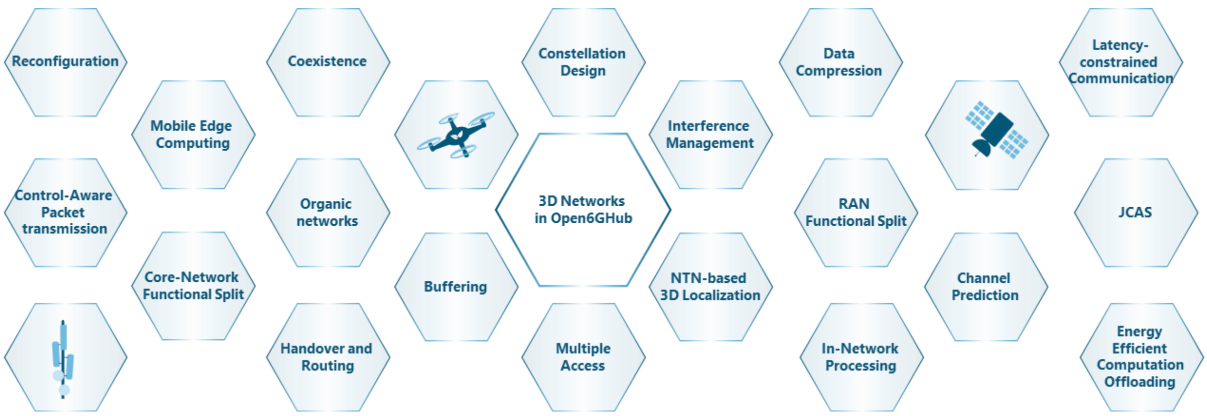

Figure 6: Topics of 3D Networks of the Open6GHub

Figure 6 shows the main topics that have been investigated, while Table 2 and Table 3 describe the topics in detail and highlight the achievements by listing the publications. Table 2 is on technologies of the radio access network (RAN) and Table 3 lists results that can be assigned to the Core. It is not always possible to make an assignment to RAN and Core unambiguously. For detailed information on the achieved results the reader is referred to the publications listed in section 9.

Table 2: Radio Access Technologies - Results

Technology	Description
Satellite Constellation Design	Satellite constellation design for 5G and 6G involves deploying satellites in specific orbits (mainly LEO) to provide global coverage and utilizing inter-satellite links for efficient data routing and improved connectivity. Advanced algorithms manage dynamic resource allocation and traffic, ensuring seamless integration with terrestrial networks and scalability for future demands [1].
Interference Management	Beamforming for interference management involves directing signal transmission in specific directions using MIMO antenna arrays enhancing signal strength to intended users while minimizing interference to others. • Model-based dynamic beam pattern design optimizing network performance and ensuring efficient use of the spectrum [2, 3, 4]. • ML-based precoding strategies achieving high sum rates for varying training points and fulfilling robustness requirements [5, 3].
Joint Comm-unication and Sensing (JCAS)	The joint operation of communication and sensing together in one system and frequency spectrum asks for mutual • Joint optimization of beamforming and 3D array-steering [6] as well as 3D trajectory design [7, 8] to maximize sensing performance while ensuring communication QoS for wireless-based JCAS enabled by UAVs. • Exploitation of the spatial correlation inherent in sensing data to optimize UAV’s trajectory design, aiming to maximize the sensing information collected by an energy-constrained UAV [9].
Latency-constrained communication	Communication latency is a critical service metric in 6G wireless networking. • In [10], the optimal LAP trajectory design has been achieved UAV-assisted latency-constrained communication with targeted reliability threshold. • Efficient joint resource allocation and reliability maximization has been proposed in [11, 12] for clustered network with constrained latency requirements.
Channel and Interference Prediction	Predicting information of channel and interference for link adaptation and resource allocation • Distributed ML-based interference prediction approach [13, 14]. • Development of a two-dimensional downlink link selection scheme used for accurate forecasting of forthcoming channel frequency responses based on geometry-based stochastic channel [15].
Data Compression	The efficient data exchange between the 3D network nodes requires design of adaptive data compression concepts • Model-based design of information-preserving data compression schemes for uniterminal [16] and multiterminal scenarios [17] facilitating reduced fronthaul rate requirements. • Data-driven design of information-preserving joint source-channel coding schemes for two-hop transmission setup [18] adapted to 3D networks [19]. • Decoder implementations with minimum bit-resolution [20, 21].

Handover and Routing	Design of handover algorithms for private non-geostationary orbit (NGSO) constellations like Starlink and Kuiper with improved performance for high interference scenarios [22].
Coexistence	Ensuring coexistence between terrestrial and non-terrestrial networks as well as the interworking between satellite mega-constellations, e.g. 3GPP interworking, is essential for global coverage and efficient spectrum use. The interference among various satellite constellations in the Ku and Ka bands and efficacy of effective channelization in mitigating co-channel interference was studied [23].
RAN Functional Split	Adopting a RAN architecture with functional split enhances flexibility, scalability, and cost-efficiency. The fronthaul data rates for NTN platforms reveal trade-offs between data rate and complexity, particularly given the power and complexity limitations of flying nodes [24, 25].
Multiple Access	To support massive connectivity in 3D network, the application of multiple-access schemes is necessary. • In [11, 12] clustered ground users requesting different data packets are considered and an efficient data transfer strategy is proposed with the assistance of D2D communication enabling massive connectivity at LAPs. • For LAP-assisted massive-device multicasting scenario, analog beamforming design has been conducted for maximizing multicasting throughput [26].
UAV Control Aware Packet Transmissions	The energy consumption of UAVs can be minimized by efficient data transmission techniques. Therefore, optimal resource allocation and control requirements dependent packet transmission techniques are proposed. • The control requirements aware dynamic resource allocation is proposed that increases resource efficiency considering control error thresholds [27]. • The impact of Age of Information and Value of Information on the optimal packet transmission strategy for control applications is evaluated [28].
NTN-based 3D Localization	To address the issue of unreliable GPS localization, NTN can support 3D localization with cooperative localization. Localization and security challenges have been analyzed and investigated in [29, 30].

Table 3: Core Network Technologies - Results

Technology	Description
Buffering	Buffer-aided relaying with UAVs was proposed to enhance communication throughput on both the source-to-UAV and UAV-to-destination links within UAV-enabled two-hop wireless communications [31].
Mobile Edge Computing	A two-layer iterative algorithm was proposed to jointly optimize communication and computing for fast updating of digital twin (DT) models [32]. This approach can reduce the time required for DT synchronization by over 40%.
Reconfigu-ration	Unified 3D networks involve three levels of reconfiguration: extrinsically given, uncontrollable movements like satellites requiring continuous and predictable topology reconfiguration; controllable components like UAVs, coordinated with terrestrial networks to adapt to user movements and workloads; and innovatively adapting both network topology and workload through integrated in-network processing (as demonstrated for optical networks [33]).
In-network processing	Future networks (6G and others) will process data already inside the network, for both network-facing functions (e.g., firewalls) as well as user-facing functions (e.g., machine-learning inference). 3D networks provide widely distributed, reconfigurable, closer-to-the-user processing at low latency. The challenge lies in harmonizing processing, data transport, and power supply, taking advantage of moveable processing.

Core Network Functionality Split	Similar to the RAN, also the Core network can be deployed across the network nodes. Three distinct models were defined for how the core network could be deployed on top of the mega-constellation system in order to be able to offer the expected reliability, security and service delays. • For the data plane in space an optimization named “shortcut” was defined enabling the reduction of the end-to-end communication between two satellite connected user devices by providing a no-satellite gateway data path similar to the DVB mesh mode. This optimization drastically reduces the end-to-end communication delay between two satellite connected devices [34]. • For the data plane, a low footprint cross-layer optimization between the mega-constellation routing control and the 3GPP control plane has been proposed. The cross-layer enables the reservation of end-to-end QoS resources and the adaptation to the momentary network capacity not only on the user link, but also to the feeder links, recognized as the potential second bottleneck due to their varying capacity influenced by weather [35]. • For the control plane an integrated solution was proposed based on the Organic 6G Core concept where the core network functionality is integrated following a full software paradigm in which network services interact through optimized interfaces instead of the 5G service Based Architecture. With this mechanism it is possible to deploy a comprehensive core network as part of the satellite payloads complementing and running on the remaining resources from the RAN [36].

5 Verification and testing activities

In addition to the design of innovative concepts, Open6GHub also strives for intensive verification and performance testing these concepts. Table 4 describes the SW simulators developed within Open6GHub and the testbed activity is described afterwards. The testbeds are currently still under construction, meaning that only the first simple implementations of technologies can currently be tested.

Software simulators

Table 4: Software simulators

Technology	Description
Channel Modeling	For the simulative evaluation of communication concepts, software realization of realistic channel models for the various transmission channels in 3D networks comprising satellites, HAPs, LAPs, terrestrial base stations, ground station and UEs are required. To this end, channel models have been implemented based on ITU-R [37] and TR 38.811 [38] models accounting for atmospheric gases, rain, clouds, scintillation, water vapor, sky noise, etc.
Mobility Simulator	Software tools have been realized to capture the mobility of the various 3D network elements. The tools allow for tracking the mobility of real private NGSO constellations (Starlink, Kuiper, etc.) with ephemeris data taken from FCC and a time granularity of 1s to enable simulation of mobility management protocols.
Link Level Simulator	For link-level evaluations the open-source software toolbox Sionna® has been extended for NTN communication link. A second simulator allows the calculation of link-budgets for satellite-to-ground links enabling easy evaluation of interference mitigation techniques and handover algorithms.
Orbital Simulator	The UB/DLR Hybrid Platform for Space Systems (HPS) is a modular orbit propagation tool that creates digital twin spacecrafts with realistic interaction in space environments. It utilizes high precision methods for non-gravitational forces and

	gravitational field models to generate precise mock data for various satellite scenarios, including constellations and swarms. These scenarios can be coupled with channel models, enabling realistic coverage and uplink/downlink analysis.
Network Simulator / Emulation	• Extension of ContainerNet/FaultyNet emulation framework (Mininet + Docker containers) for 3D capabilities. 3D simulation capabilities have been integrated in DEFIANCE (HPI extension to NS/3 & NS/3-AI) for distributed ML training and inference in 3D networks.
OpenLanes	Fraunhofer FOKUS OpenLANES toolkit aims to bridge the gap in real-time emulation tools for real-world networks. It emulates a large number of network nodes and their dynamics, providing a robust environment for building new functional features on top of Linux available stacks, and facilitates their easy testing and validation in complex environments. • OpenLANES automates the testing across a large number of out-of-the-box diverse network topologies and network evolution scenarios using a large number of relevant terrestrial operators and mega-constellation networks. With this, experiments can be easily run across many networks, automatically validating innovative technologies in complex environments. • OpenLANES emulates large-scale satellite networks and their inherent dynamicity providing a network level emulation for the inter-satellite links, for the ground-space user and feeder links as well as for the terrestrial support network. It provides information on link availability, bandwidth capacity, packet loss and transmission delay induced from space specific emulation of links as well as weather impact or other space-specific phenomena. • OpenLANES can bring hardware in the loop enabling the testing of real devices in comprehensive environments, automatically validating their software features against a large number of deployment scenarios and topologies.

Testbed Activity

As part of the Open6GHub the experimental field „Beyond Cellular“ for testing components of 3D networks is established at the University of Bremen. As shown in Figure 7, we build a comprehensive and flexible platform based on SDRs and commercially available 5G hardware. The testbed contains ground base stations, drones, satellites and user devices, e.g., rovers and IoT devices. The goal of this platform is to run different proof-of-concept experiments to demonstrate the effectiveness of 3D networks in expanding the coverage and ensuring diverse QoS requirements. This testbed has a flexible structure to cover a wide range of deployments representing different applications, e.g., seamless and multi-link connectivity, and to explore different technical aspects, e.g., resource management, data compression, and interference prediction.

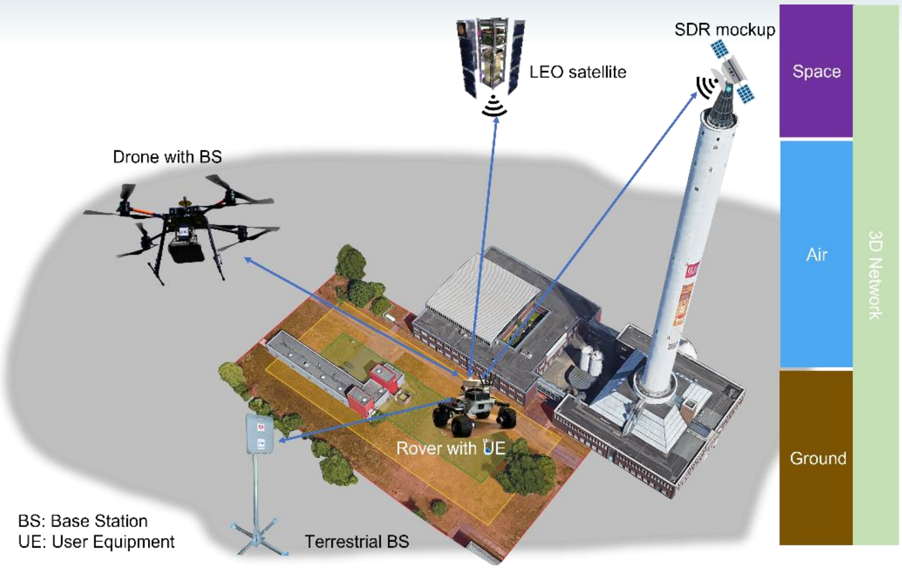

Figure 7: 3D Experimental Field at Universität Bremen

6 Industrial aspects

Strategic considerations

According to analyst companies including GSMA and NSR/Analysis Mason [39], the medium-to-long-term perspective of the satellite market is estimated to be around $45B by 2032 (see Figure 8).

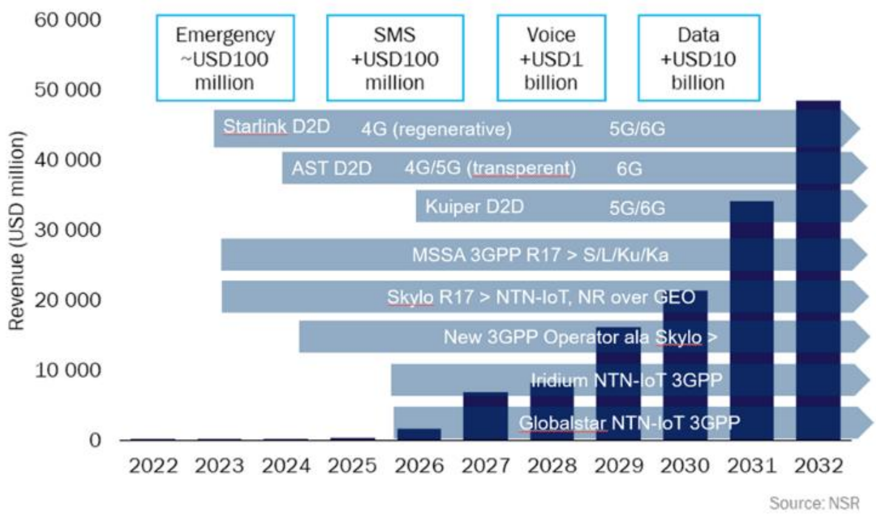

Figure 8: Satellite market potential

This market estimate comes from NSR and is overlaid with a subset of NTN satellite operators and their service introductions using different strategies to tap into the 3GPP market. We foresee that, over time, even companies like Starlink will acquire L/S band assets and provide 3GPP NTN Release 17 and beyond type of service. In addition to develop modified eNB and gNB versions to connect to unmodified 4G and 5G mobile phones, there is a trend where traditional satellite operators are implementing new 4G/5G core technologies and providing hybrid NTN services while retaining their existing terminals, such as those operating over DVB-S2X, alongside new 3GPP NTN terminals.

Furthermore, almost all of the main SatCom operators and service provider have developed a multi-orbit strategy and are taking actions of collaborations with NGSO partners summarized by major market analysts like Euroconsult [40]. Examples of collaborations are Eutelsat-OneWeb, SES-Starlink, Orange-SES, TeleSat-Lightspeed. These strategies are supplemented by the development of chipset modems to enable ultra-low power and superior connectivity for IoT devices across satellite and cellular networks, making connectivity available globally and providing easy device setup and orientation. For reference, see Qualcomm's press note [41] or the statement by MediaTek’s wireless communications business unit [42]: "Two-way satellite communications on smartphones and other devices will usher us into a new era of connectivity and open up new possibilities across many different verticals".

The IRIS² programme (Infrastructure for Resilience, Interconnectivity, and Security by Satellite) started by the European Union is an ambitious initiative to create a satellite internet constellation that provides high-speed internet and secure communications for both governmental and private entities, addressing connectivity dead zones and enhancing European strategic autonomy in space. Following the call for tender, a consortium was formed, led by Airbus Defense and Space, Eutelsat, Hispasat, SES and Thales Alenia Space and complemented by a core team of Deutsche Telekom, OHB, Orange, Hisdesat, Telespazio and Thales. Future developments of IRIS² will offer additional commercial services based on 5G and 6G technologies. German companies can contribute their strengths in telecommunications and satellite communication services, security solutions, 3D end-to-end networks and systems engineering, as well as providing satellite subsystems and equipment.

HAPS (airborne platforms), like the Airbus Zephyr, fly at lower altitudes and will make it possible to provide customers with communication services of the usual quality in large, otherwise unserved regions. It is projected that the global HAPS market will reach a value of EUR 3.5 billion by 2029, with the EU accounting for 21% of the total market and experiencing significant market growth and technological developments, refer to [43]. Deutsche Telekom expects that airborne platforms can play a complementary role to its terrestrial network to ensure service continuity. The mobility of airborne platforms is particularly beneficial to temporarily provide additional network capacity. Future improvements in solar cell efficiency are expected to enable 24/7 operations of stratospheric airplanes and to open up new deployment opportunities.

How can Germany participate?

3D networks will significantly influence the next generation of mobile networks and establish digital services in key areas of society that are quickly becoming indispensable. Against this background, politics and business must find a strategy for dealing with such systems that both counteracts the trend towards market dominance by technology groups outside Europe and maximizes the economic opportunities for the export-oriented supplier industry.

By supporting R&D activities in this area, the German/European aerospace industry will be able to remain technologically leading and commercially successful. Although 3D applications for the mass market are currently served by US and China-based companies, 3D networks will be an enabler for high-tech products and thus represent an important and attractive niche market for European companies. In addition, SMEs can serve niches very well. Examples of R&D

elements in which the German aerospace industry should aim for strong market participation are as follows [44]:

- Routing
- Multi segment dynamic resource management
- Mobility management
- Mobile edge computing
- (Optical) Inter-satellite links
- Antenna technologies
- Access technologies
- Multi-segment user terminals
- HW/SW platforms including processor technologies
- Satellite-based control modules
- Position navigation and timing services
- Joint communication and sensing
- Cyber security

From the perspective of terrestrial mobile network operators in Europe, harmonized spectrum usage conditions, especially at national borders, are essential. The main objective for continuous, high quality mobile connectivity is to protect terrestrial IMT networks from harmful interference from new technologies while creating new service opportunities for mobile satellite services (MSS) as part of a comprehensive mobile network. For satellite operations, the corresponding frequencies for both mobile satellite services and fixed satellite services (FSS) as well as the rights to the orbit must be secured in a timely manner and on a larger scale than before, as these are strategic resources. When revising the regulatory framework for enabling 3D network architectures, the differences between terrestrial and satellite-based services as well as the different business models have to be considered, e.g., LEO satellite constellations require a global business model, while terrestrial mobile communications and HAPS operate in national markets. The resulting regulatory principles should allow for concerning the same use-cases and markets.

7 Positioning and Conclusion

The concept of 3D networks has evolved over time due to advances in various technologies and the increasing demand for ubiquitous, fast and reliable connectivity. In particular, the vision of a unified 3D network with all its various components connected across all three 3D segments – ground, air, space – requires a comprehensive design approach with completely new R&D problems and new strategic and technological approaches.

As part of the BMBF's 6G program, innovative concepts and technical solutions for unified 3D networks have been developed over the past three years, starting with the Open6GHub project. The results achieved include new concepts and initial technological approaches, the development of testbeds, initial simple tests and verifications as well as initial findings in the implementation of individual concepts. The industry-oriented research project 6G-TakeOff has already further developed promising approaches and findings from the Open6GHub, but is primarily pursuing an end-to-end approach. Work to date has focused on the design of a unified 3D architecture, the development of further new technological solutions and their analysis in an end-to-end approach. Numerous new topics and problems beyond technology have been identified, such as the regulation of a unified 3D architecture and frequency regulation, with problems such as base stations flying across national borders.

The task now is to continue both the basic conceptual research and the application-oriented R&D work that has already begun in order to develop technologies that can then be developed into products in a subsequent pre-development phase. At the same time, test activities must be further expanded. This involves the further development of testbeds by incorporating new applications and integrating the HAP level (aircraft, aerostats). Another important step is the testing of 3D technologies on SW-based satellite test platforms in orbit. The window of opportunity for 3GPP is open, and an extension of 6G funding will support the direct transfer of these technological approaches into standardization. In addition, an expansion of testbed activities to support 3GPP work is essential in order to review and test initial technological approaches. These preparatory activities are a necessary prerequisite for the successful positioning of German and European industry in the global 3D network market and the guarantee of technological sovereignty in the 6G technology that is central to German and Europe society and economy.

8 List of Acronyms

3GPP	3rd Generation Partnership Project
BMBF	German Federal Ministry of Education and Research
BS	base station
DT	digital twin
eNB	4G Node B (base station)
ESA	European Space Agency
FSS	Fixed-satellite service
GEO	geostationary Earth orbit
gNB	5G Node B (base station)
HAPS	high altitude platform systems
IoT	internet-of-things
IRIS²	infrastructure for resilience, interconnectivity, and security by satellite
LAP	low altitude platform
LEO	low Earth orbit
MEO	medium Earth orbit
MSS	mobile satellite service
NGSO	non-geostationary orbit
NTN	non-terrestrial network
PNT	position navigation and timing
PoC	proof of concept
RAN	radio access network
SiS	server in space
UAV	unmanned area vehicles

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