6G-TakeOff: Holistic 3D Networks for 6G Wireless Communications

Marko Andjelkovic[1)], Nebojsa Maletic[1)], Nicola Miglioranza[1)], Milos Krstic[1,9)]
[1)] IHP – Leibniz-Institut für innovative Mikroelektronik, Frankfurt (Oder), Germany
[9)] University of Potsdam, Potsdam, Germany
{andjelkovic, maletic, miglioranza, krstic}@ihp-microelectronics.com

Enrico Koeck[2)]
[2)] EANT, Leipzig, Germany
ekoeck@eant.de

Jan Buchholz[3)]
[3)] IMST GmbH, Kamp-Lintfort, Germany
jan.buchholz@imst.de

Maike Taddiken[4)]
[4)] DSI Aerospace GmbH, Bremen, Germany
maike.taddiken@dsi-as.de

Markus Fehrenz[5)]
[5)] Creonic GmbH, Kaiserslautern, Germany
markus.fehrenz@creonic.com

Shaden Baradie[6)]
[6)] John Deer European Technology Innovation Center, Kaiserslautern, Germany
BaradieShaden@JohnDeere.com

Dirk Wübben[7)]
[7)] University of Bremen, Bremen, Germany
wuebben@ant.uni-bremen.de

Markus Breitbach[8)]
[8)] Deutsche Telekom AG, Bonn, Germany
m.breitbach@telekom.de

Abstract—**The unified 3D communication networks, integrating standard terrestrial mobile communication networks and non-terrestrial networks (NTNs), are seen as the key enabler for global connectivity in the next generation (6G) wireless communications. To achieve this goal, new technologies and components are needed in order to meet the requirements for the 6G networks in terms of higher data rates, and enhanced reliability, security and network reconfigurability. This work introduces the German project 6G-TakeOff, aimed at the design of solutions for unified 3D networks for 6G wireless communication systems. The project consortium brings together academic and industrial partners from Germany and Europe, covering the entire value chain from design of electronics to applications. This work presents the key hardware components required for 3D networks and the concept for demonstration of their functionality.**

Keywords—6G wireless communications, 3D networks, Non-Terrestrial Networks (NTN)

I. Introduction

The terrestrial wireless (mobile) communication networks have undergone tremendous advancements over the past decades, bringing new capabilities and applications. However, conventional Terrestrial Networks (TNs) are not capable of providing a global coverage, due to a lack of network infrastructure to cover rural, non-inhabited and sea/ocean regions. According to the International Telecommunication Union (ITU), around 2.7 billion people in the world still had no access to the Internet in 2022 [1]. Moreover, TNs may be unreliable or non-functional in the case of natural disasters or attacks [2 - 5]. In addition, TNs cannot meet the increasing needs for ubiquitous and continuous connectivity services that require high bandwidth.

It is widely recognized that a significant enhancement of resilience and functionality of wireless networks, together with the global coverage, could be achieved only by combining TNs

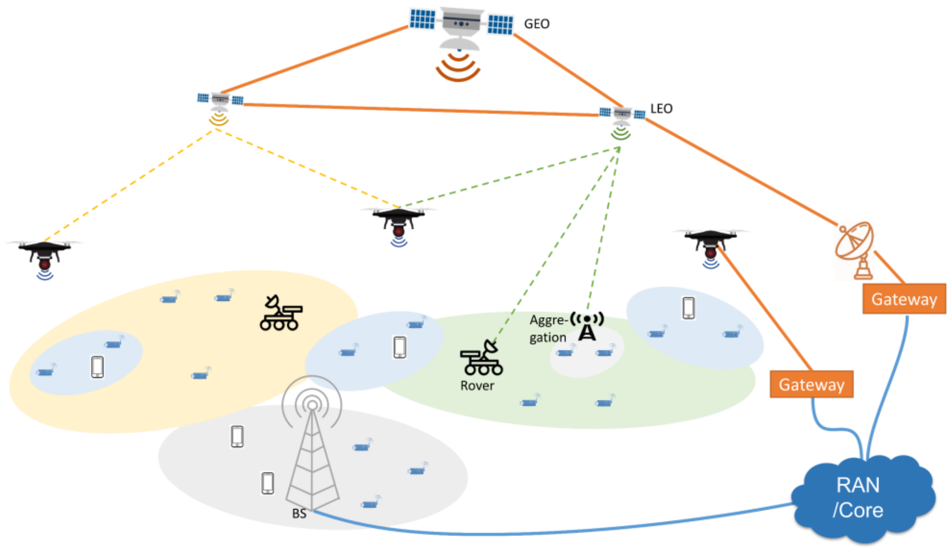

Fig. 1: General architecture of 3D network integrating ground, air and space communication segments.

and Non-Terrestrial Networks (NTNs). According to the releases of the 3rd Generation Partnership Projects (3GPP), an NTN is defined as a network or a segment of network that employs flying vehicles for data transmission [6]. The flying vehicles could be manned and/or unmanned platforms, such as drones, helicopters, balloons, planes, and satellites. While in TNs only the end devices are mobile, in NTNs the individual network nodes move relative to each other.

Although they are still in the development phase, the NTNs are showing a strong economic potential. According to market analysis reports, the global NTN market size has been valued at USD 4 billion in 2023, and is projected to reach almost USD 63 billion in 2031 [7]. This market potential stems from the fact that the NTNs could enhance significantly the performance of numerous existing applications, as well as introduce new ones. In addition, a reduction in the launch costs has attracted new players in space industry, opening opportunities for expanding the space communication infrastructure. As a result, the number of satellites is increasing every year, with currently over 9 000 orbital satellites, and it is estimated that this number will exceed 40 000 in the next ten years.

The NTNs have been initially introduced as a part of 5G systems, and the next generation (6G) wireless communication networks are expected to bring a more heterogeneous network infrastructure, with an increasing integration level of communication infrastructures at ground, air and space. In general, a communication system that integrates TNs and NTNs is referred to as a 3D network. The new 6G 3D networks are expected to support higher data rates, and provide enhanced reliability and security, compared to 5G networks. The 3D networks will have reconfigurable hardware components and organic structure, allowing individual networks nodes to dynamically join or leave the network. To support space-to-ground data transmission, completely new antenna systems with high gains and new data processing electronics will be needed. Additionally, the functionality of 3D networks will be further enhanced with the introduction of advanced technologies such as Multi-access Edge Computing (MEC) and Artificial Intelligence (AI) [8, 9].

An architectural concept of a 3D network with three main communication layers is illustrated in Fig. 1. The first layer is the ground segment composed of terrestrial network components, such as base stations, respective core network, gateways, etc. The second layer is the air segment, consisting of the flying vehicles that can be classified into Low Altitude Platform Stations (LAPS), such as drones, and High Altitude Platform Stations (HAPS), such as balloons and gliders. Finally, the third segment is the space segment, which consists of satellites in different orbits, such as the Low Earth Orbit (LEO), Medium Earth Orbit (MEO) and Geostationary Earth Orbit (GEO). The integration of LAPS/HAPS and satellites into a 3D network would provide higher flexibility in terms of coverage. Namely, while satellites follow a predefined trajectory, HAPS and LAPS have more freedom in movement and thus can be redirected to satisfy the coverage demands.

However, the realization of fully functional 3D networks will require to overcome a number of technical challenges [2, 10 - 13]. For example, satellite systems experience much larger propagation delays than terrestrial systems, which will likely impact the overall performance of a 3D network. Moreover, unlike terrestrial transmission equipment, satellites are moving fast, and hence create Doppler effect (particularly the LEO satellites). Additionally, satellites may be required to operate in constellations to best serve target areas while guaranteeing service continuity, thereby raising synchronization issues. These issues are further exacerbated considering mmWave transmissions due to the severe path loss experienced at those frequencies. The problems that also need to be solved are related to power supply (duration of the possible downtime, which currently ranges from a few days to around one year), the maximum payload that such stations can carry, and the connection to terrestrial ground stations. Moreover, reliability and security will become even more important requirements in 3D networks, due to increased network complexity. The LAPS and HAPS are generally vulnerable to attacks, while the orbital satellites are exposed to intense ionizing radiation that may affect the functionality of electronic systems.

The aforementioned challenges have led to a significant increase in research efforts towards integration of TNs and NTNs. Some examples of previous and running European projects addressing the 3D communication networks are 5G-ALLSTAR [14], 5G-STARDUST [15], 6G-NTN [16], and 6G-SKY [17]. Along with the rise in the number of multi-partner research projects, the number of related scientific publications is also increasing every year. According to Google Scholar, the number of publications addressing the NTNs has increased from around 130 in 2020 to over 700 in 2023.

In this work, we present the German 6G-TakeOff project, bringing together academia and industry with the aim to develop novel solutions for unified 3D networks for 6G wireless communications. The rest of the paper is composed of five sections. Section II introduces the goals and concept of the project. In Section III, the common application scenarios for 3D networks are presented. An overview of the key components developed in 6G-TakeOff project is given in Section IV. The conceptual design of the demonstrators is presented in Section V. Finally, Section VI concludes the paper.

II. 6G-TakeOff Project: Objectives and Concept

The 6G-TakeOff project [18] is a German project funded by the German Federal Ministry of Education and Research, running from 01.08.2022 to 31.07.2025. The project consortium consists of 19 partners from both academia and industry, with Deutsche Telekom as the project coordinator. The involved partners cover the whole value chain relevant for 3D communication networks, combining the competences in electronics, wireless communications, security, aerospace, network service provision and application industries. The general structure of the consortium is depicted in Fig. 2.

The ultimate objective of 6G-TakeOff project is to provide technological advancements for the “anytime and anywhere” 6G wireless connectivity. To this end, 6G-TakeOff will strive for a 3D communication network with a uniform design approach, where flying network nodes together with terrestrial network components provide functionalities dynamically and organically as required. The holistic approach required for this enables innovations that go beyond the 5G NTN approaches by using the potential of flying network components much more comprehensively and profoundly. A 6G system will connect network components flexibly, autonomously, where necessary independently of the infrastructure and in accordance with current requirements. 6G-TakeOff will develop a unified 3D network architecture and the necessary technologies, and demonstrate their feasibility using experimental platforms. In addition, 6G-TakeOff pursues the integration of AI technologies at all levels and brings forth approaches with low energy consumption and use of network resources that guarantee network resilience and security.

Specifically, the 6G-TakeOff project aims to address the following objectives:

a) **Holistic 3D architecture:** Our main goal is to establish a uniform network architecture that includes TN and NTN nodes. Specifically, we aim to implement the MEC concepts in TN and NTN elements, in order to support higher Quality of Service (QoS) requirements for Internet of Things (IoT) and Enhanced Mobile Broadband (eMBB) services. In addition, we plan to develop reliable multicast methods, which use the large coverage areas of satellite-supported communication.

b) **Flexible relocation of network functionalities:** We will analyze the integrated orchestration of hardware and software mobility, and dynamic migration of core network and network management functions (adapted to load, requirements and resources). To ensure flexible networking, we will analyze the Next Generation Radio Access Network (NG-RAN) function split, both in the access link between space and ground segment and within the space segment. We will also study the AI concepts to adapt Physical (PHY) and Medium Access Control (MAC) layers, to enable resource- and energy-efficient information flow, while complying with QoS requirements.

c) **Mobility management in 3D networks:** We will investigate various AI methods for mobility management for dynamic network nodes and coordination of simultaneous connections. In addition, we intend to investigate the methods for agile monitoring of spectrum and communication between dynamic spectrum utilization with low interference.

d) **Dynamic control of information flows in a 3D network**: We will analyze the applicability of AI algorithms to control communication relationships between network nodes, given the complex requirements regarding move-

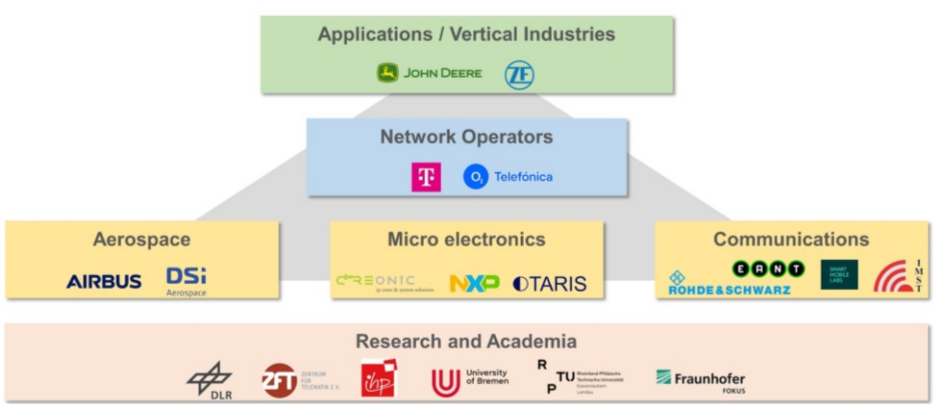

Fig. 2: 6G-TakeOff consortium structure.

ment dynamics, data volume and latency. Novel concepts for data security and authentication between the varying communication platforms, aimed to secure highly dynamic communication relationships, will be investigated. In addition, resilience concepts for network nodes (enabling that they can temporarily operate independently without connectivity to the terrestrial core network), as well as for non-terrestrial backhaul links, will be studied.

e) **Antennas and backhaul hardware:** We aim to develop novel antenna, beamforming and beam tracking concepts to meet the complex requirements regarding spectral extensions (new frequency bands and higher bandwidths) and larger distances between ground stations and network nodes. In addition, we will develop novel signal and data processing architectures with improved tolerance to harsh radiation conditions in space.

f) **Verification:** The developed hardware solutions (new antennas and data processing systems) will be validated with simulations and measurements. Besides validation of individual solutions from each partner, it is also planned to validate the interactions between different solutions through unified testbeds involving flying stations, imitating LAPS and HAPS.

In order to achieve the aforementioned objectives, the workplan is organized into five technical work packages (WP1 to WP5), networking and exploitation work package (WP6) and project coordination and communication work package (WP7). The relation between work packages is shown in Fig. 3. WP1 is focused on defining the technical requirements and use cases for 3D networks. In WP2, the architecture of 3D network, with detailed specification of links between different network components, will be defined. In WP3, the key technologies (e.g., MEC, AI, etc.) for 3D networks are explored. WP4 addresses the development of key hardware components for 3D networks, and WP5 is focused on setting up the demonstrators for validating the components and technologies.

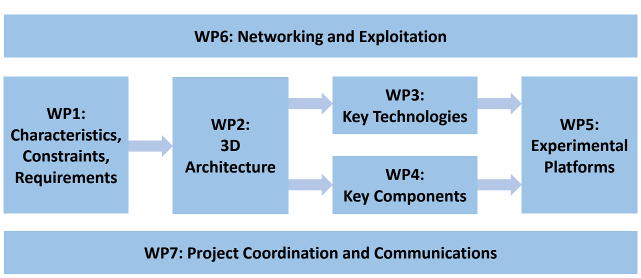

Fig. 3: Relation between 6G-TakeOff work packages.

III. Typical Applications

The 3D communication networks have a strong potential to enhance existing applications and support new disrupting applications, leveraging the unique capabilities offered by air- and space-based communication technologies. Based on the analysis in 6G-TakeOff project, as well as the published reports from other projects and research papers, the following are the most promising applications of 6G 3D networks [19, 20]:

- *Global Internet Connectivity*: NTNs can provide seamless global wireless connectivity, particularly in remote areas where terrestrial infrastructure is limited or does not exist. This could enable internet access, communication services, and IoT connectivity in regions where traditional TNs are impractical or non-economical. As a result, a significant performance boost could be achieved in applications such as smart cities, environmental monitoring, asset tracking, supply chain management, autonomous driving, etc.
- *Disaster Response and Emergency Communication*: Terrestrial communication infrastructure may be damaged during natural disasters (e.g., floods or earthquakes) or humanitarian crises. Use of NTNs can provide reliable communication channels for emergency responders, enabling coordination, rescue operations, and transmission of information to affected population.
- *Maritime and Aviation Communications*: NTNs can improve communication capabilities for maritime vessels, aircraft, and other mobile platforms operating in remote regions where terrestrial coverage is limited or does not exist. This could enhance safety, navigation, and operational efficiency for maritime and aviation industries.
- *Environmental Monitoring and Earth Observation*: Space-based sensors and satellites equipped with 6G technology can enable advanced environmental monitoring, including climate observation, deforestation detection, pollution tracking, and disaster monitoring. This data can be used for scientific research, environmental protection, and resource management.
- *Precision Agriculture*: Farms are usually situated in rural areas, where mobile connectivity is either weak or does not exist. In recent years, the general trend is to provide high level of automation in agriculture. NTNs can support precision agriculture by providing real-time monitoring of crop health, soil moisture levels, and environmental conditions. This data can help farmers optimize irrigation, fertilization, and pest control strategies, leading to increased crop yields.
- *Remote Sensing and Exploration*: NTN-enabled satellites and spacecraft can support remote sensing and exploration missions, including planetary exploration, asteroid mining, and space colonization. These networks can facilitate communication with robotic probes, collect scientific data, and support human presence in space.
- *Secure and Resilient Communication*: NTNs can offer secure and resilient communication channels for military, government, and critical infrastructure. Space-based networks are less susceptible to terrestrial disruptions, electromagnetic interference, and cyber-attacks, providing a secure communication backbone for strategic operations and national security.
- *Telemedicine and Remote Healthcare*: NTNs can facilitate telemedicine and remote healthcare services, enabling remote consultations, medical diagnostics, patient monitoring, and even remote surgery using robots. This can significantly improve access to healthcare services and support medical emergencies in remote locations.
- *Space Tourism and Commercial Space Activities*: With the rise of commercial space exploration and space tourism, NTNs can support communication and navigation services

for spacecraft, space stations, and lunar habitats. This could enable commercial space activities, tourism ventures, and scientific research in space.

- *AR/VR-Assisted Police*: Police can use Augmented Reality (AR) / Virtual Reality (VR) headsets and remotely operated drones to capture views from areas that are normally not visible to police (behind walls, far distance, etc.).

IV. Key Components

One of the main goals of 6G-TakeOff project is to develop new components capable to support the requirements of the 6G communications. In the following, the major functionalities and design characteristics of components under development are briefly introduced.

A. Ground Station Antenna (EANT)

To support a wide range of services on the ground, flying nodes need a robust connection to the core network. Since the weight and power consumption of equipment installed on a LAPS or HAPS is critical for the mission time, one approach is to offload as much as possible to the ground station. Therefore, EANT designs a ground station based on a 60 cm parabolic tracking antenna.

The key features of the ground station antenna are:

- High gain (>41dB @ 40GHz): lower requirements for antenna gain and RX/TX power on flying node,
- High directivity (<1° @ 40GHz): high immunity to interference and low source of interference,
- Mechanical tracking (<0.02° angular resolution): reliable tracking of HAPS/LAPS for a stable link and high Signal-to-Noise Ratio (SNR).

The antenna, together with its integrated controller unit, can be mounted in a fixed position or nomadically, for example on a trailer to be deployed in different scenarios, such as disaster relief. Since the antenna itself presents only a transparent link, i.e., it takes a baseband signal as input and converts it to the transmission frequency and vice versa for reception, it supports a bent pipe approach as well as a regenerative approach.

In the bent pipe approach no signal processing happens on the LAPS/HAPS. The signal to the User Equipment (UE) is fed into the antenna, converted to a higher frequency band, received by the LAPS/HAPS, converted back to its original frequency range and radiated through a different set of antennas on the flying node towards ground, and the same way back. A regenerative payload in contrast means that the node is placed on the HAPS/LAPS and has a dedicated high throughput data connection to the core net through the ground station.

B. LAPS/HAPS Phased Array Antenna (IMST)

The phased array antenna, planned to be placed onboard LAPS or HAPS, is key to enable long distance communication while maintaining a compact form factor. It is built up by a matrix of antenna elements, each able to set amplitude and phase to modify the resulting overall antenna beam. For 6G-TakeOff project, an innovative brick structure has been developed, placing the antenna elements in a trigonal lattice. This way it is possible to maintain the optimal 0.5 λ between antenna elements, even though chip dimensions make it difficult at mmWave frequencies. To enable circular polarization in both directions along with linear polarization if needed, each antenna element is built up of two orthogonal antennas sharing the same element center. Efficient software is required to set phases and amplitudes of the individual antenna elements precisely, to ensure an antenna pattern with a small beam width that is steerable along all solid angles. Though, a compromise has to be made between scan loss and beam width. By using an intelligent beam steering algorithm, the antenna is able to locate the direction in which the link should be established. For this, depending on the distance between both terminals, a conical scan analysis can be used. Here, the antenna beam is steered in a circular motion around the received power maximum indicating the exact alignment of both terminal antennas. As long as the measured power does not vary over time, the beams are aligned. Otherwise, the maximum must have moved out of the center. For less critical distances, positional coordinates of HAPS and ground station can be used. The same applies to the initial pointing of the antenna, regardless the link distance, where positional coordinates help to avoid a lengthy scan of the whole hemisphere.

The array built for this project is scalable, i.e., the array itself can be stacked again so that one can build an array with multiple hundreds of antenna elements allowing ultra-high link distances. This way it is easy to build up arrays depending on the specifications needed for the use case, i.e., GEO, LEO, HAPS or even a low altitude demonstrator. For this project, one antenna block consists of eight layers, each with eight antenna elements which again, as stated before, are built up of two orthogonally polarized antennas, totaling in 64 antenna elements or 128 antennas per block. The structure of the antenna is shown in Fig. 4.

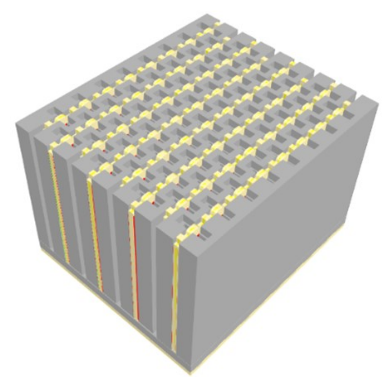

Fig. 4: mmWave Phased Array Antenna consisting of 8 layers each with 8 antenna elements per polarization.

C. mmWave RF Frontend (EANT, IMST)

For the project, the frequency ranges of 38.0 GHz – 38.3 GHz (air to ground) and 39.2 GHz – 39.5 GHz (ground to air) will be used. The RF frontend part of transceiver on the ground and in the air will be developed using off-the-shelf-components to keep the costs low and allow for easy modifications. The goal is to have a link with at least 25dB SNR over 25 km to support QAM256 modulation. Such high order modulations require a very low EVM. This in return requires an excellent (phase-) noise of the entire signal chain and a sufficient back-off of the amplifiers. Crucial for the overall phase noise is primarily the phase noise of the frequency synthesizer and its oscillator, whereby the latter dominates at mmWave frequencies by $20\log_{10} N$, where N is the multiplication factor.

D. Single-Carrier Baseband Processor (IHP)

The baseband processor serves as a core processing unit in wireless communications, being responsible for managing the transmission and reception of data. It performs tasks such as modulation, demodulation, encoding, decoding, error correction, and signal routing. A basic block diagram of a baseband processor, illustrating interfaces with MAC processor and RF frontend, is shown in Fig. 5.

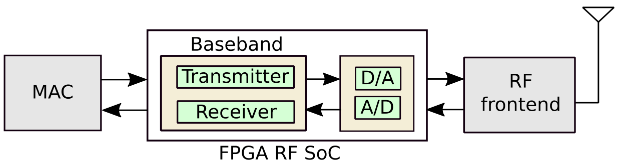

Fig. 5: Typical wireless communication system with MAC processor, baseband processor and RF frontend.

IHP will design a reconfigurable baseband processor for satellite-ground link, supporting a single carrier signal and 8 different modulation schemes: BPSK, QPSK, APSK16, APSK32, APSK64, QAM16, QAM32, and QAM64. The selected modulation schemes support the data rates from 1 bit/symbol (BPSK) to 6 bits/symbol (APSK64 and QAM64). The system will have the capability to select autonomously the optimal modulation scheme based on application requirements and channel state. Low order modulations will be selected when noisy channel is detected, while high order modulations will be used when the channel state is good.

For the initial prototype, the baseband processor will be implemented on a Xilinx Zynq UltraScale+ RFSoC ZCU111 evaluation board. The selected board contains 8 12-bit RF ADCs and 8 14-bit RF DACs. Since the development of MAC processor is out of the scope of this project, the MAC functions and other high-level processing functionalities will be implemented in software that will be run by the processor available on FPGA board.

In addition to standard error correcting techniques used in wireless communications, the baseband processor for space should also be radiation-tolerant. Electronics employed in space may experience various radiation-induced effects such as Total Ionizing Dose (TID), Single Event Upsets (SEUs) and Single Event Transients (SETs). These effects may lead to data corruption, malfunction or even system failure. The primary focus will be on mitigating the SEU and SET effects, which are the most critical radiation-induced effects for electronic systems designed in scaled technologies (selected FPGA platform is implemented with scaled process).

To evaluate the radiation hardness of the baseband design, we will adopt the fault injections at two levels: at the Register-Transfer Level (RTL), using the commercial fault injecting tool Cadence Incisive Functional Safety Simulator (IFSS), and at the level of FPGA configuration memory, using the Xilinx Soft Error Mitigation (SEM) IP tool. The fault injection will enable to identify the most critical blocks in the design, as well as the most critical elements in each block. Based on this information, appropriate fault-tolerant measures will be selected.

Regarding the fault-tolerant solutions, both static and dynamic (reconfigurable) fault-tolerance techniques will be investigated. As transistor-level fault-tolerance techniques are not applicable to FPGAs, our focus is on circuit- and system-level approaches, such as dual- and triple-modular redundancy, SET filtering, and error detection and correction codes. For FPGA configuration memory, the Xilinx SEM IP tool will be used. We are investigating the possibilities to combine different approaches, depending on the soft error sensitivity of individual functional blocks. We are also considering to implement the error detection in all functional blocks, in order to enable the self-awareness of the system. The self-awareness is essential for achieving the online reconfiguration, allowing for a trade-off between performance, fault-tolerance and power consumption, which is essential in space applications.

E. Computing Platform for Satellites (DSI)

NTNs require advanced high-performance processing platforms that can handle significant computational demands and data management in space. Such platforms are key to reducing latency, optimizing bandwidth, and improving the reliability of satellite operations. However, space electronics are faced with several challenges imposed by the harsh environment they are exposed to, such as extreme temperature variations, high radiation levels and mechanical stress.

Radiation-tolerant hardware typically compromises performance relative to Commercial Off-The-Shelf (COTS) devices. To counteract this, critical time-sensitive functions have been traditionally accelerated using programmable logic.

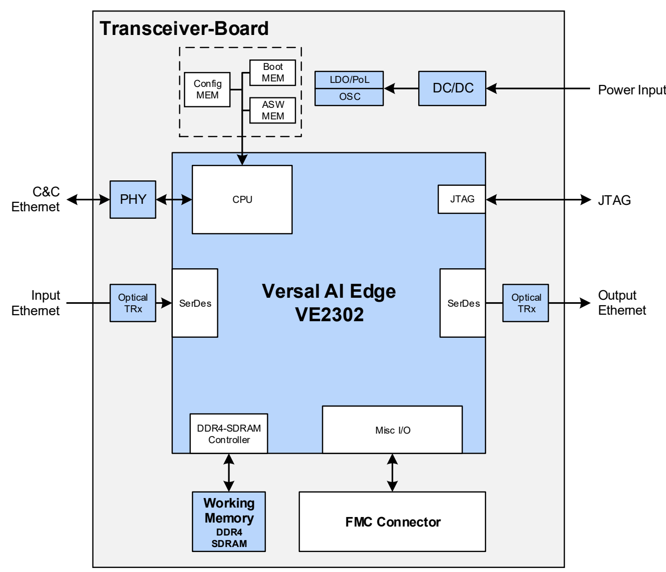

Fig. 6: Architecture diagram of the demonstrator for the satellite transceiver board based on AMD's Versal AI Edge.

In this context, DSI will design and develop a transceiver board for satellites based on a high-performance computing platform, as shown in Fig. 6. The AMD Versal AI Edge VE2302 device is part of AMD's Adaptive Compute Acceleration Platform (ACAP) line-up. These devices are designed to merge the performance advantages of various processor types, such as scalar and vector processors, with the adaptable processing capabilities offered by programmable logic. This enables distribution of various computational loads, as they are found in advanced signal processing, to be performed either in software by the CPU, accelerated in hardware by customized processing cores in the programmable logic, or to be processed by the already integrated, high-performance accelerators. The programmable logic further allows for flexible adaptation of interfaces for development, testing, or extension purposes. The presented demonstrator offers an FMC connector to connect to possible extension or interface devices.

The VE2302 will be available as a space-qualified, radiation tested version and offers multiple accelerators that can be used for advanced signal processing. While the architecture of the presented demonstrator is based on COTS components, it has been designed to ensure that space-grade versions or suitable replacements of the main components are available to facilitate a possible future development of a flight model.

V. DEMONSTRATORS

In order to validate the developed components, appropriate demonstrators will be set up. Since the testing in space is beyond the scope of the project, the experimental validation will focus on ground and aerial communications. Each partner will develop individual demonstrators to test their hardware components (described in Section IV). The individual solutions will be tested with simulations, in-lab measurements, and in-field tests. After verification of individual designs, the solutions from all partners will be integrated into unified testbeds that will allow testing the developed functionalities under realistic scenarios. Three testbeds are planned, as follows:

- Testbed I focuses on the implementation and evaluation of backhaul hardware components for LAPS and HAPS.
- Testbed II focuses on demonstration of multi-access edge computing.
- Testbed III focuses on the interaction of different technology components of various partners, with the aim to demonstrate the 3D networking.

Testbed I is essential for validating the functionality of hardware components developed by different project partners in WP4. The general concept of Testbed I is illustrated in Fig. 7. The main idea of Testbed I will be to demonstrate a link between the core network and UE via the bent pipe of a flying node. As a development of a complete HAPS is out of scope for this project, demonstration of the backhaul link capabilities in Testbed I will be done by means of a heavy lift drone, able to carry up to 10 kg of payload.

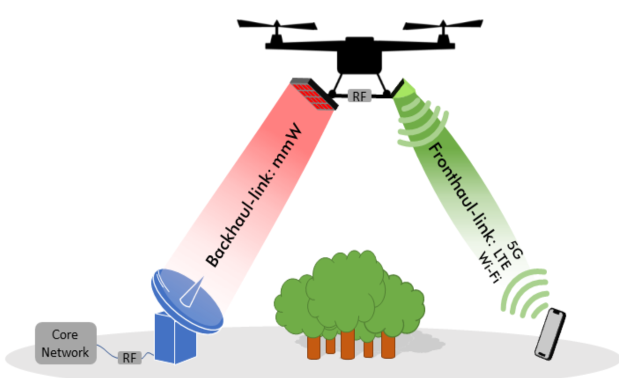

Fig. 7: General concept of Testbed I

The bidirectional link in Testbed II is built up as follows. A base station (preferably 5G-NR, LTE or Wi-Fi) will be connected via the RF-Frontend to a dish antenna which generates a mmWave wireless link. Onboard the drone, the link is terminated by the phased array antennas (one for each link direction) and converted back to the baseband by a second RF-Frontend module. From there, the signal will be distributed to clients' UEs on the ground with a traditional (mostly) isotropic antenna. In this testbed, the ground station antenna developed by EANT, the phased array antenna developed by IMST, and the mmWave RF frontend developed by EANT and IMST, will be used. For data processing on the ground, the baseband processor developed by IHP will be used, while the processing platform developed by DSI and communication system from Creonic will be installed on the drone.

An important aspect of Testbed I will be to assess the interaction (compatibility) between the components developed by different partners. This preliminary assessment is important to define the required specifications for the unified 3D network, which will be tested through the Testbed III, as well as to define the realistic test scenarios.

For demonstration in Testbed I, several commercial drones have been considered. One of the possible choices is the drone MK-U25 shown in Fig. 8. The MK-U25 is a multicopter drone designed to meet the needs of surveying and inspection. With a payload of up to 10 kg and a modular system, the MK-U25 is one of the most versatile drones on the market. Specially designed container for communication payload will be connected to the bottom of the drone.

Fig. 8: Drone MK-U25 with payload connected to its bottom

A visualization of Testbed III is shown in Fig. 9. The testbed hardware was chosen to provide the flexibility to run various kinds of implementations, ranging from open source 5G implementations over advanced RAN implementations to partner specific solutions [21]. Hence, the testbed enables measurement campaigns in a 3D environment using stable available solutions, to test new functions in existing frameworks and to try completely new PHY or MAC layer algorithms. In order to have this flexibility, the Software Defined Radios (SDRs) will be applied.

Furthermore, to evaluate available products in a 3D context, COTS 5G hardware will be included by integrating a 5G campus network from MECSware [22], satisfying the 3GPP Release. It includes 5G outdoor base stations and their core

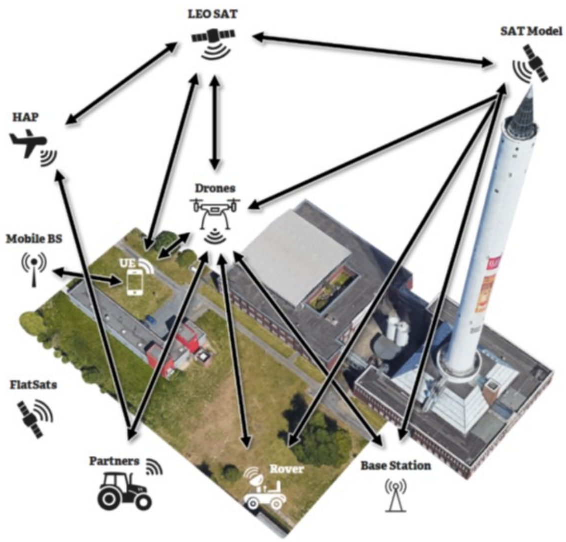

Fig. 9: Testbed III located at the University of Bremen Drop Tower

network leading to one network on the drone and another for the ground and satellite segment.

With this in mind, Testbed III will have two distinct hardware setups: one consisting of SDRs bundled with computing power in the RAN and core network, and one composed of COTS devices. This setup allows for flexible integration of hardware developed by different partners.

VI. Conclusion

The main goal of the German 6G-TakeOff project is to develop and test novel solutions for unified 3D communication networks that will integrate conventional terrestrial networks and non-terrestrial networks. The project consortium consists of 19 partners, including academic and industrial players with expertise in electronics, aerospace, communications and security, as well as network operators and application industries.

In this work, the initial design concepts for antennas, RF frontend, and processing electronics that could be applied in the future 3D networks are presented. For the validation of developed components under realistic scenarios, the concepts for an end-to-end LAPS/HAPS testbed and a 3D network testbed are introduced.

We strongly believe that the 6G-TakeOff project will establish the necessary understanding of future requirements for unified 3D communication networks. Thus, the key ambition of the 6G-TakeOff project is to lay a foundation for long-term securing of Germany's and Europe's technological sovereignty in the field of future 3D networks.

Acknowledgement

This work has been done in the framework of 6G-TakeOff project, funded by the German Federal Ministry for Education and Research (BMBF – Bundesministerium für Bildung und Forschung), under the grants 16KISK057, 16KISK058, 16KISK060, 16KISK068, 16KISK071.

References

[1] International Telecommunication Union (ITU) Press Release, 2022, Available online: https://www.itu.int/en/mediacentre/Pages/PR-2022-09-16-Internet-surge-slows.aspx.

[2] A. Durembekova, H. Schotten, "Opportunities and Limitations of Space-Air-Ground Integrated Network in 6G Systems," in Proc. Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), 2023. DOI: 10.1109/PIMRC56721.2023.10294000

[3] C. T. Nguyen et al., "Emerging Technologies for 6G Non-Terrestial-Networks: From Academia to Industrial Applications," arXiv, 2024. DOI: 10.48550/arXiv.2403.07763

[4] F. Feltrin et al., "Potential for Deep Rural Broadband Coverage with Terrestrial and Non-Terrestrial Radio Networks," Frontiers in Communications and Networks, vol. 2, 2021. DOI: 10.3389/frcmn.2021.691625

[5] F. Rinaldi et al., "Non-Terrestrial Networks in 5G and Beyond: A Survey," IEEE Access, vol. 8, pp. 165178 – 165200, 2020. DOI: 10.1109/ACCESS.2020.3022981

[6] https://www.3gpp.org/technologies/ntn-overview.

[7] https://www.insightaceanalytic.com/report/5g-non-terrestrial-networks-market-/1921.

[8] A. Iqbal et al., "Empowering Non-Terrestrial Networks with Artificial Intelligence: A Survey," IEEE Access, vol. 11, pp. 100986 – 101006, 2023. DOI: 10.1109/ACCESS.2023.3314732

[9] M. Mozaffari, Q. Lin, S. Hayes, "Toward 6G with Connected Sky: UAVs and Beyond," IEEE Communications Magazine, vol. 59, no. 12, pp. 74 – 80, 2021. DOI: 10.1109/MCOM.005.2100142

[10] S. Kota, G. Giambene, "6G Integrated Non-Terrestrial Networks: Emerging Technologies and Challenges," in Proc. International Conference on Communications Workshops (ICC Workshops), 2021. DOI: 10.1109/ICCWorkshops50388.2021.9473743

[11] A. Vanelli Coralli, A. Guidotti, T. Foggi, G. Colavolpe, G. Montorsi, "5G and Beyond 5G Non-Terrestrial Networks: Trends and Research Challenges," in Proc. 5G World Forum (5GWF), 2020. DOI: 10.1109/5GWF49715.2020.9221119

[12] M. M. Azari et al., "Evolution of Non-Terrestrial Networks from 5G to 6G: A Survey," IEEE Communication Surveys and Tutorials, vol. 24, no. 4, 2022. DOI: 10.1109/COMST.2022.3199901

[13] S. Mahboob, L Liu, "Revolutionizing Future Connectivity: A Contemporary Survey on AI-empowered Satellite-based Non-Terrestrial Networks in 6G," IEEE Communication Surveys and Tutorials, vol. 62, no. 2, pp. 1279 – 1321, 2024. DOI: 10.1109/COMST.2023.3347145

[14] https://5g-allstar.eu/project/.

[15] https://www.5g-stardust.eu/.

[16] https://www.6g-ntn.eu/about-6g-ntn/.

[17] https://www.6g-sky.net/.

[18] https://www.6g-takeoff.de/.

[19] "Use Case Deliverable (D2.1) in 6G-NTN Project," Available online: https://www.6g-ntn.eu/public-deliverables/.

[20] Y. Hokazono, H. Kohara, Y. Kishiyama, T. Asai, "Extreme Coverage Extension in 6G: Cooperative Non-Terrestrial Network Architecture Integrating Terrestrial Networks," IEEE Wireless Communications and Networking Conference (WCNC), 2022. DOI: 10.1109/ICCWorkshops50388.2021.9473743

[21] D. Buchberger, L. Kliewe, C. Bockelmann, A. Dekorsy, "Experimental Field "Beyond Cellular": Implementing and testing 3D/NTN-Networks," 28. VDE-ITG-Fachtagung Mobilkommunikation, Osnabrück, Germany, May 2024.

[22] https://www.mecsware.com/.