6G-TakeOff: Holistic 3D Communication Networks for 6G

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***Abstract*—Terrestrial, air- and space-borne networks need to be integrated in a holistic manner to achieve optimum service performance for customers. The present study investigates a unified architecture and the key technologies and components required for 3D networks.**

Keywords: 6G, Non-Terrestrial Networks, unified 3D network

I. Introduction

A. Motivation

Digital communication is indispensable for modern societies in both business and private contexts. This requires mobile connectivity that is available everywhere and at all times. However, this is a challenge for today's cellular mobile communications networks with ground-based base stations with antennas on more or less high masts: Obstacles such as hills, buildings or vegetation can shadow radio signals transmitted from these base stations and lead to gaps in coverage, and maritime areas can only be covered near coastlines.

To overcome these limitations, the current two-dimensional infrastructure can be extended with altitude as a third dimension: drones, stratospheric aircrafts, and satellites in various orbits can cover large areas independently from geographic conditions, thus creating the basis for innovative solutions in digitized agriculture, logistics, maritime, or environmental and climate sciences. In addition, network nodes in flying platforms are flexible in terms of location and time: Temporary provision of additional network capacity at major events, e.g., cultural or sporting events, would thus be just as possible as short-term mobile communications coverage in disaster situations, especially if there is disruption to service from the regular terrestrial infrastructure.

3GPP has already taken an important first step with the inclusion of Non-Terrestrial Networks (NTN) in Rel. 17. However, terrestrial, air- and space-borne network elements differ significantly in terms of their possible coverage ranges, user data rates and capacities. Therefore for optimal coverage of communication subscribers, it is necessary to go beyond the functionality of 3GPP Rel. 17/18 and combine TN and NTN elements in a unified overall architecture to optimize them jointly and to benefit from the different strengths provided by these systems.

The inclusion of NTN elements in cellular mobile radio networks leads to a paradigm shift: In today's mobile communications networks, terminals are the only mobile elements, making static network topologies the only considered option in standardization and industry. NTN elements (except GEO satellites), however, are mobile, leading to a network structure in which neighborhood relationships between network elements and, thus, the paths of communication links through the network change constantly.

B. Project "6G-TakeOff"

6G-TakeOff [1] is a joint activity of partners from vertical applications (John Deere, ZF Friedrichshafen), space (Airbus, DSI Aerospace), microelectronics (Creonic, IHP), security (NXP, OTARIS) and communications (EANT, IMST, Rohde & Schwarz, SmartMobileLabs) industries, network operators (Deutsche Telekom, Telefonica) and academic partners (DLR, Fraunhofer FOKUS, RPTU Kaiserslautern Landau, Univ. of Bremen, Zentrum für Telematik). We will investigate the consequences of this paradigm shift and work out an architecture for 3D networks and develop the necessary technologies and components for its realization. 6G-TakeOff started in mid-2022 for three years. It follows three main goals:

- At application level, it aims to provide an optimal connectivity service by integrating terrestrial, airborne and space-based network elements.
- At the functional level, architecture and technology concepts shall be contributed into standardization bodies and industry associations.
- At an enterprise level, aerospace industry and communications industry shall be brought together, as the topic of 3D communication networks requires the expertise of both.

Investigations in 6G-TakeOff have begun with an analysis of use cases, and the resulting requirements will be incorporated into the architecture development. Further work packages are dedicated to the key technologies and core components required for the implementation of 3D networks. The results of all work packages will be tested in several testbeds and a simulator.

II. Applications and Requirements

The change from flat terrestrial to 3D networks will act as enabler for a variety of new application scenarios, beyond providing coverage in unserved areas: By combining the specific capabilities and availability of terrestrial and non-terrestrial systems, more sophisticated use cases and scenarios can be addressed, such as maritime coverage with terrestrial broadband connectivity in harbors, while satellite communications take over at sea. Another scenario is temporary peak-loads beyond the limits of only one available system, which can be handled by joining capacities of terrestrial and airborne systems.

In addition to choosing the most suitable path, a 3D hybrid connectivity can be provided by, e.g., backhauling a HAPS simultaneously via a (v)LEO and GEO satellites and splitting the traffic depending on the requested requirements, e.g. use (v)LEO for low latency traffic (see *Fig. II.1*). This approach can be extended by actively steering the network capabilities to the location needed, e.g., by moving airborne platforms or by antenna beam pointing of satellites with larger coverage. We call this approach of leveraging the mobility of flying objects a dynamic 3D-aware traffic optimization.

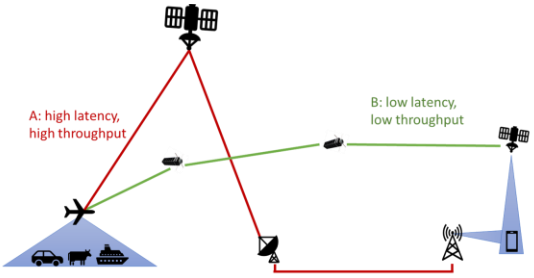

Figure II.1: 3D hybrid connectivity

III. Considerations on Architecture, Technologies and Key Components for 3D Networks

6G-TakeOff will work on extending the 5G state-of-the-art architecture through dynamic 3D networks in 6G. The envisioned 3D network architecture is designed to support the use-cases described in the previous section.

The heterogeneity of the 3D networks needs to be embraced to get the full potential of the three dimensions and meet the diversity of future communication needs. Flying aerial and space-borne nodes join and leave the network dynamically, thus changing the available RAN and backhaul links for each user terminal's end-to-end transmission. Also, the movement of user terminals can change the best suitable radio link, as in legacy terrestrial networks. By continuous assessment of available transmission paths, a user terminal can influence the service quality delivered to the application. Furthermore, we envision flexible deploy-ment of network functionality among 3D network components. This may be combined with network slicing, such that multiple services can be provided with different performance characteristics. Moreover, we investigate providing edge computing on flying nodes to obtain its benefit of low latency combined with the high coverage and resilience of a 3D network and to enable network condition aware applications.

Network operations are becoming more challenging for several reasons: The dynamic changes in the network topology as well as the flexible deployment of network functionality require fully automated network operation. AI / ML methods are regarded as promising enablers for this. Furthermore, NTN capacity is likely to be shared by multiple mobile network operators and operation of NTN platforms done by third-parties.

A unified network architecture for terrestrial, airborne and spaceborne network elements in a fully interconnected 3D network poses several additional challenges that must be addressed such as interference management and handovers. Some techniques may become inapplicable, e.g., carrier sensing, but other novel aspects can be of advantage like extended coverage and path diversity. The presence of flying nodes creates specific requirements like profound adaptation and possibly re-design of waveforms to fully reap all the additional capacity of the network. Transmission delay and path loss of NTN links are much higher than those of TN systems, which results in differences in the waveform, modulation, channel coding designs etc. The movement speeds of spaceborne and airborne platforms are higher than terminal movement speeds in terrestrial networks, thus causing larger Doppler shifts and leading to deviations in carrier frequency as well as a deformation of the received signals. Data loss, due to the mentioned factors, and obstacles obstructing the links in such a dynamic network, require an adaptable use of reliability techniques such as error correction coding and interleaving.

The flying nodes deployed in stratosphere and space experience adverse environmental conditions. Communication systems operating in space are exposed to ionizing radiation, which may cause transient and permanent hardware errors, eventually resulting in data corruption or even system failure. Therefore, it is mandatory to apply various radiation hardening techniques (e.g. dual or triple modular redundancy) to enhance the robustness of the critical system elements.

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References

[1] 6G-TakeOff project homepage; https://6g-takeoff.de