Experimental Field "Beyond Cellular": Implementing and Testing 3D/Non-Terrestrial Networks

Dennis Buchberger [1], Luka Kliewe [2], Carsten Bockelmann,[1], Armin Dekorsy [1]

[1]Dept. of Communications Engineering,
University of Bremen, Bremen, Germany
Email: {buchberger, bockelmann, dekorsy}@ant.uni-bremen.de
[2]Center of Applied Space Technology and Microgravity (ZARM),
University of Bremen, Bremen, Germany
Email: luka.kliewe@zarm.uni-bremen.de

Abstract—This paper outlines the plans for an experimental field called "Beyond Cellular", designed to explore and assess the integration of 3D/Non-Terrestrial Networks and new baseband technologies. Spanning terrestrial, aerial, and space segments, the field offers a comprehensive platform for testing deployment scenarios and technologies crucial for the upcoming sixth generation of mobile communications. The setup includes ground-based stations, drones equipped for flight experiments, and "FlatSats" for space segment evaluation. Planned applications include testing of commercial 5G networks, deploying open-source software-defined networks and implementation of satellite engineering models into the network as well as using GNURadio to test new technologies. It is open to partners.

Index Terms—3D network, non-terrestrial network, beyond cellular, experimental field, satellite, testbed

I. Introduction

In the upcoming sixth generation of mobile communications, complementing our terrestrial networks with so-called Non-Terrestrial Networks (NTNs) is being considered [1]. The concept of 3D networks represents a paradigm shift from traditional two-dimensional communication infrastructures. Unlike traditional networks that primarily operate in a horizontal plane, 3D networks encompass connectivity in three spatial dimensions — length, width, and height — effectively expanding the scope and capabilities of wireless communication systems. A 3D network therefore includes different segments: The familiar ground segment (e.g. conventional base stations), the air segment (e.g. drones, aircraft, High Altitude Platforms (HAPs)) and the space segment (e.g. LEO satellites), all of which can contain User Equipments (UEs) and Base Stations (BSs). This vertical integration enables greater coverage, capacity and reliability compared to terrestrial-only networks [2] [3].

This paper presents our experimental field designed to implement and evaluate different deployment scenarios and
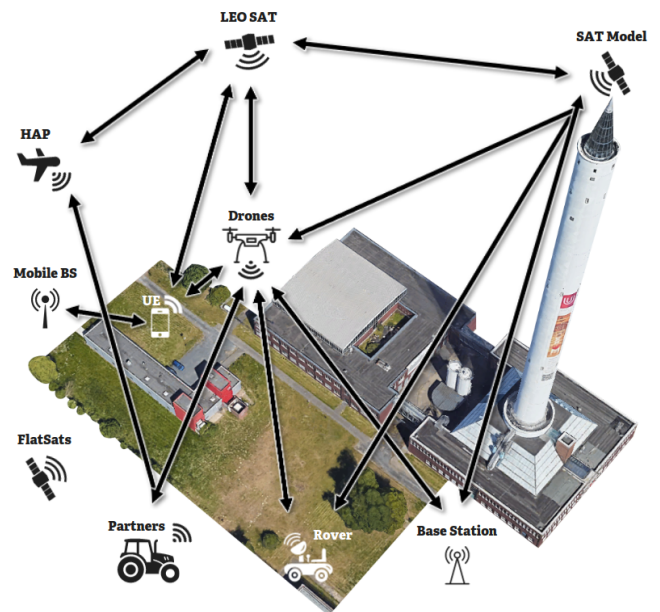
Fig. 1. Testbed "Beyond Cellular"; image: [4], created using [5].

technologies and build a 3D/Non-Terrestrial Network (NTN) covering terrestrial, airborne, and space segments.

II. Open Experimental Field setup

The following sections first introduce the location and the used hardware and software before we show how these components work together in flexible testbed.

A. General data

Figure 1 shows our "Beyond Cellular" testbed of about 7600 m^2, 1400 m^2 are usable for drone flights. It is located next to the Drop Tower of the Center for Applied Space Technology and Microgravity (ZARM) [6] at the University of Bremen. Equipment can be placed in the flight area, on top

	SDR	COTS
RAN	Ettus USRP X410 (3x) Ettus USRP B210 (1x) High-End Workstation (5x) High-Performance Laptop (4x) Intel NUC 13 (3x) Satellite engineering models (3x) Raspberry Pi 5 (3x) [12]	MECSware campusXG® 5G outdoor small cell (2x)
CORE	High-End Workstation	MECSware campusXG® MECS-1204 (1x) MECS-4108 (1x)
UE	Ettus URSP B210 (3x)	5G Smartphones (2x)

of the buildings, as well as at the top of the drop tower (at a height of around $130\,\mathrm{m}$) and in an adjacent server room.

The testbed's location is within the urban part at the border of the populated area. The university and other office buildings are close by, so the testbed is not just an empty field far away, but close to real usage in a city.

B. Network Hardware

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 [7] to partner specific solutions. 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, we use Software Defined Radios (SDRs). The hardware in use are Ettus Universal Software Radio Peripherals (USRPs) X410 [8] and B210 [9]. To have enough processing power even for complex algorithms, needed e.g. by the URLLC demo shown in [7], three of the hight-end workstations use an AMD Ryzen Threadripper PRO 5965WX (24x $3.8\,\mathrm{GHz}$) and two an AMD Ryzen 9 7950X3D (16x $4.2\,\mathrm{GHz}$) with high single-core performance.

Furthermore, we want to include Commercial Off The Shelf (COTS) 5G hardware to evaluate available products in a 3D context. We use a campus network from MECSware GmbH [10] which satisfies 3GPP Release 15 (cf. [11]). It includes 5G outdoor base stations and their core network leading to one network on the drone and another for the ground and satellite segment.

With this in mind, we will have two distinct hardware setups as shown in Table I: One consisting of Software Defined Radios (SDRs) bundled with computing power in the Radio Access Network (RAN) and core network and one of COTS devices. We operate in our 5G campus license from $3.7\,\mathrm{GHz}$ to $3.8\,\mathrm{GHz}$.

C. Rover

In the ground segment, our "Leo Rover" [13] shown in Fig. 2 will carry equipment and drive over the field, either

Fig. 2. LeoRover with Intel NUC and B210 SDR

manually steered or following a pre-defined path. It simulates a mobile user that could profit from the connection to both, the terrestrial BS on the ground as well as the BS carried by the drone. The rover is equipped with localization services Global Navigation Satellite System (GNSS) and will be able to be manually steered as well as follow pre-defined paths. It can carry a payload of $5\,\mathrm{kg}$ at a speed of $0.4\,\mathrm{m/s}$. Its outer dimensions are $45\,\mathrm{cm}$ x $43\,\mathrm{cm}$. We plan to add a custom-built rover using a similar software stack to the one running on the drone.

D. Drone

For the air segment, we chose the Multikopter MK-U25 drone [14] shown in Fig. 3, of which two will be used in the experimental field. With a span of $2.07\,\mathrm{m}$, they can lift up to $10\,\mathrm{kg}$ each. This allows the drones to carry different payloads: A high performance laptop together with an USRP as well as the COTS 5G outdoor base station from MECSware GmbH ($6\,\mathrm{kg}$) together with a mini PC running the MECS 5G CORE and power supply (cf. Table I). Flight time is expected to be more than $30\,\mathrm{minutes}$ without recharging. The drone uses real-time kinematic positioning (RTK GPS). As it is controlled by the open source software ArduPilot [15], we can access and modify it if necessary. Flight data, such as the current position and orientation, are available to the payload. The drone can be controlled manually by the pilot or fly in an autonomous mode, following a pre-defined route for reproducible measurements. The route can be planned offline using software like Ardupilot MissionPlanner [16] as shown in Fig. 4.

E. Satellite models

On top of the drop tower, we will have a satellite model implemented with SDR to investigate the radio aspects. Three more will be in variable positions investigating the implementation of real satellite hardware and software. Accessing a satellite in orbit is planned for future revisions.

Fig. 3. MK-U25 drone with 5G outdoor BS and 5G core
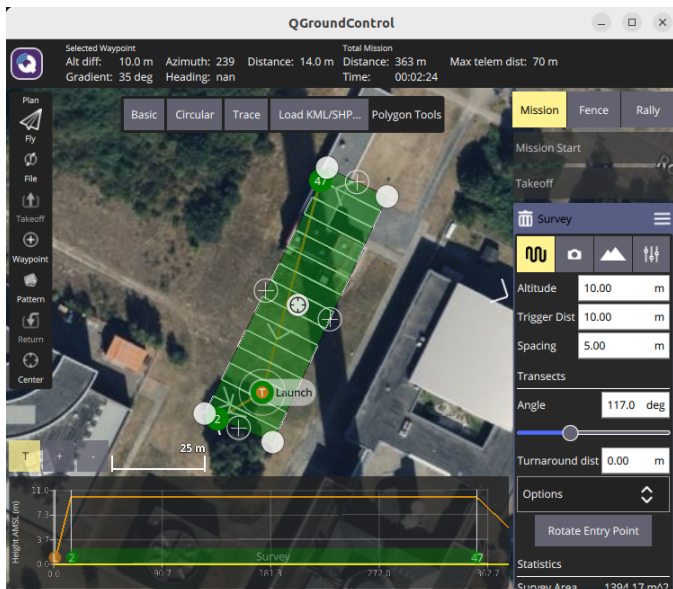
Fig. 4. Screenshot from "MissionPlanner" [16]

	SDR	COTS
RAN	GNURadio srsRAN	proprietary (configurable)
Core	custom 6G core by partner open5GS	proprietary custom containers
UE	GNURadio proprietary (commercial 5G modems)	proprietary
Satellite mockup	custom, using common protocols	-

1) SDR mockup: By using an Ettus X410 on top of the drop tower and one of the high-end workstations, we will simulate satellite coverage from above the experimental field. Aspects like signal delay and Doppler shift will be simulated in software.

2) Satellite engineering models: Different satellite engineering models, in function partly or fully equivalent to real satellites, are implemented into the experimental field. Currently, a model based on several Raspberry Pi 5 is developed, running CubeSat software and protocols. Different hardware for the development of CubeSats is currently under consideration or in the procurement phase.

F. Software

Due to the different approaches and hardware used, the software part of the testbed is diverse as shown in Table II. Whenever useful and possible, we will use containers for the software, e.g. with Docker [17].

The setup with SDRs and high performance computing hardware is especially useful for research on baseband technologies. We plan to use GNURadio [18] for this purpose, because it is a free and open source software-defined radio ecosystem and already in use in our department. Of course, partners are able to use a different software environment.

For further development and tests of 5G systems, implementations from projects like srsRAN [19], providing a 5G radio access network, and Open5GS [20], providing a 5G core network will be investigated.

In the COTS setup, we use the software stack provided by the vendor. It already offers anApplication Programming Interfaces (APIs) and gives the possibility to run custom containers.

The software onboard our satellite engineering models is centered around the widely used Cubesat Space Protocol [21] and additional custom implementations.

III. TESTBED ARCHITECTURE

The testbed aims to provide the infrastructure to research and demonstrate 3D/Non-Terrestrial Networks . It is structured into the three segments ground, space and air as shown in the following sections. The figures 5 and 6 visualize the
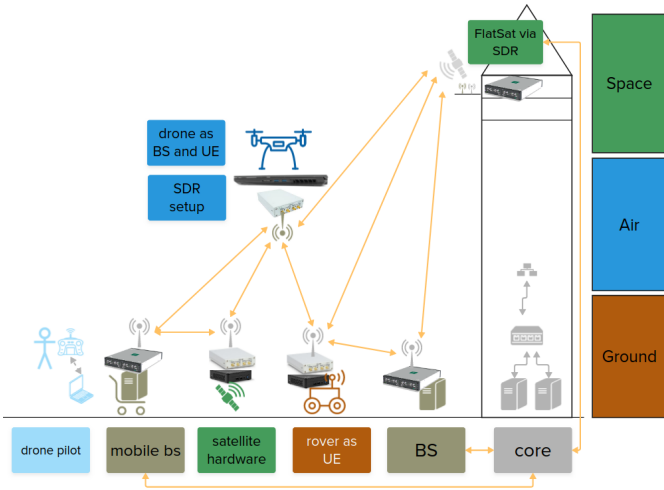
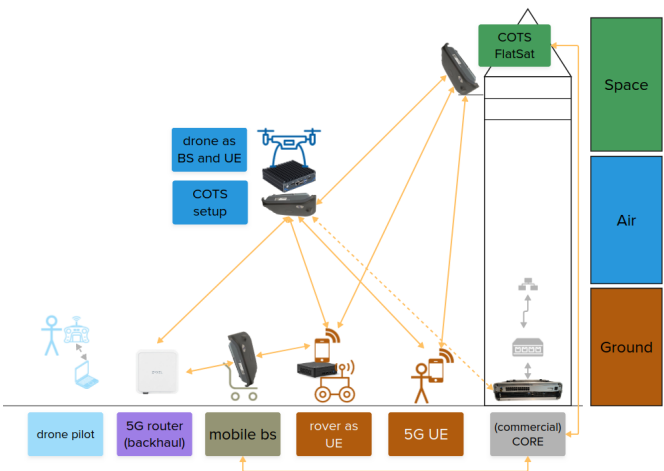Fig. 5. Basic testbed architecture with SDR components; created using [5]

Fig. 6. Basic testbed architecture with COTS components; created using [5]

basic testbed architecture for the SDR and COTS composition, separated only for better readability.

A. Ground segment

On the ground section, several fixed and mobile base stations (manually movable with an equipment cart) will be operating. This gives us a common terrestrial infrastructure. The core will be hosted in the server room of the ZARM with the outside base stations being connected via Gigabit Ethernet.

The rover is used to manually or automatically move UE or act as one by itself. As UE, we use a Intel NUC 13 high performance mini PC with a USRP B210 for the SDR applications. To connect to the COTS setup, we use 5G smartphones equipped with corresponding SIM-cards. As some Smartphones refuses to use private networks without access to the public network, we tried different vendors for our setup. At the moment, we are working with Crosscall-Z5s, which work well for our campus network.

B. Air segment

The air segment consists of our drones described in Section II-D. They will carry a high performance laptop and a B210, a MECSware 5G outdoor base station or other equipment provided by partners. This setup allows us to integrate moving base stations.

For the COTS setup, the backhaul of the drone network is done via a UE on the ground: A 5G router connects to the flying drone network and to the ground infrastructure. The CORE on the drone is setup to forward the outbound traffic of its separate 5G small cell via this UE.

C. Space segment

For the space segment, we use:

1) COTS: One of the commercially available 5G outdoor small cell base stations is placed on top of the Drop Tower. At this location, the base station is positioned at a height of 130 m, thus providing coverage to both ground and air segments. Utilizing hardware designed for terrestrial networks, the functionality as satellite base station is experimental.

2) SDR - satellite mockup: For the space segment, the signal of a communication satellite is simulated with a USRP X410 on top of the Drop Tower, connected to a high performance computer. The satellite hardware is not realistically modeled or replicated in this variant, as the focus is on analyzing the network side.

3) Satellite engineering models: The satellite engineering models form the third variant in the space segment: Integrating actual satellite and flight-proven hardware into the network enables identification of bottlenecks and gives a realistic representation of a satellite system, including payload interfaces and telemetry and commanding structures of onboard software. This setup provides an environment for early satellite communication payload prototypes inside of a 3D network and closes the gap between satellites simulated in SDR and real CubeSats. At least one engineering model is equipped with a USRP B210 and an Intel NUC, together forming the payload and running GNURadio as flexible radio interface. The so-called FlatSat is a testing environment used in space engineering where the satellite's components are laid out flat, allowing easy reconfiguration and access while simulating and verifying the satellite's functionality. The engineering models are integrated into the testbed in the following order:

1) Onboard software structure, protocols and processes running on multiple satellite subsystems that are based on Raspberry Pi 5s. Telecommands are received and telemetry is sent on UHF via an ADALM-PLUTO [22] SDR connected to a dedicated Raspberry Pi 5, forming the satellite's communication subsystem. This engineering model is used to prototype integration into the testbed.

2) Commercial satellite development hardware ("FlatSat") with verified and flight-proven satellite subsystems is additionally used for the first communication tests in the 3D network at ZARM. On this FlatSat, the USRP B210 and the Intel NUC are integrated as payload.

3) Finally, a combination of three different satellite engineering models is fully integrated into the testbed network, each with varying capabilities. These models are able to communicate on an inter-satellite link. A broad range of interfaces, electrically and mechanically, is provided, enabling flexible integration of external communication systems or payloads. The satellite system is controlled from a custom ground station that is running the open source command and control software COSMOS [23].

4) In a future revision, an in-orbit satellite is planned to be integrated into the network.

The overall aim is to combine these variants step by step so that a realistic and versatile communication satellite model - equivalent to a satellite on the software, hardware and network level - is fully integrated into the testbed network.

IV. PLANNED APPLICATIONS

The flexible testbed offers a variety of use cases, that is to be expanded in the future. For now, we plan the steps depicted in the following sections:

A. Measurements of error rate and latency

1) COTS: When building up the testbed, we will first utilise the commercial 5G network to have a functioning environment. Within this campus network, we conduct measurements of quality indicators such as error rates and latency. These measurements will be taken at various angles, positions, and speeds using a drone to carry the user equipment and the base station in different scenarios. Of particular interest will be the scenario with a moving base station.

2) srsRAN: When building up the SDR part of our testbed, we plan to set up a modular 5G network using open source software such as srsRAN and Open5GS. We want to compare their performance to the commercial system.

3) Custom: The SDR testbed offers the opportunity to develop and test new baseband technologies for us. Measuring the error rate and latency, e.g. within our "close to 5G URLL demonstrator" (cf. Section IV-B) will mostly be part of the analysis.

B. Incorporate our URLL demonstrator

In a previous project [7], we developed an ultra-reliable, ultra-low latency demonstrator with Automated Guided Vehicles (AGVs), whose communication system we intend to incorporate into the SDR testbed. The demonstrator shows a joint processing of data from two USRPs at different locations. Expanding this to a joint processing of the base station on the ground and the satellite mockup on top of the tower is of particular interest for us. The communication system was developed in GNURadio. As the AGVs are only for indoor use, the rover (cf. Section II-C) will act a UE in this case.

C. Coexistence and cooperation of terrestrial and non-terrestrial base stations

With the satellite mockup on top of the drop tower and the drones carrying base stations, we want to further study the impact, coexistence and cooperation of terrestrial and non-terrestrial base stations, interference and handovers.

D. Integrated sensing and communication

Integrated (or Joint) Communication and Sensing (ICAS) allows to gather information about the environment while communicating at the same time. Therefore, previously additional sensors like radar with their own spectrum can be integrated together with the communication technology increasing efficiency. [24] In future projects, we will use the testbed to test ICAS algorithms.

E. Demonstrator

One showcase might be the following: The rover moves behind a building on the experimental field and loses connection with its terrestrial base station. The drone takes the loss of connection as a trigger to move into the right position to re-establish the network connection of the rover. This can be used to show research and applications to students and serve as a demonstrator for project meetings and public events when useful.

V. OPENLAB: INTEGRATING PARTNERS

The experimental field is planned as an open lab. Our testbed infrastructure will be open to partners to conduct experiments and integrate their own hard- and software for testing and demonstrations. Our software infrastructure will be containerized wherever possible to make it easy for partners to run code on our modular testbed. We can place various payloads under our drones and on our rover (respecting weight and size limits), so partners can use their hardware setup as well.

VI. OUTLOOK

Currently, most of the hardware is delivered. The drones are functional and regulatory issues like the pilot licenses and the special permission to fly in the urban area of the experimental field are resolved. First flights with the commercial drone setup are conducted.

We will start implementing and testing the SDR setup in the laboratory soon and then move it to the experimental field. First measurements are expected to be taken this year as shown in Table III.

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TABLE III
NEXT STEPS

Year	Quarter	Planned work
2024	Q2	First flights with drone
	Q3	First QoS measurements with COTS Starting SDR setup with open source projects in the lab
	Q4	Integrating satellite models, satellite hardware and the rover
2025	Q1	First data transmission with research SDR setup
	Q2	Integrating URLLC demonstrator
	Q3	6G Event in Belin

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