OpenLab "Beyond Cellular": First Results and Planned Scenarios

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***Abstract*—This paper describes the OpenLab "Beyond Cellular" at the University of Bremen. This OpenLab is designed to explore and assess the integration of 3D networks and new baseband technologies. It will also be available for external researchers to execute different measurement campaigns and to test newly developed technologies and algorithms. Spanning terrestrial, aerial, and space segments, the OpenLab offers a comprehensive and flexible platform for testing deployment scenarios and technologies developed for the upcoming sixth generation of mobile communications. In the paper, we show the testing capabilities the OpenLab can offer by considering different implementation tracks using commercial off-the-shelf 5G and SDR-based equipment. We further outline the current status and further plans for the OpenLab. Initial results from recent testing activities using the "Beyond Cellular" OpenLab are also demonstrated.**

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

I. Introduction

Non-Terrestrial Networks (NTNs) as a key element of 3D networks are considered in every Release since Release 15 by 3GPP [1]. Expanding our terrestrial networks into 3D is a paradigm shift from traditional communication infrastructures. A 3D network is expanding the scope and capabilities of wireless communication systems by including the familiar ground segment (e.g. conventional base stations), the air segment (e.g. drones, aircrafts, 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 paper gives an overview and presents the current state of our OpenLab for 3D networks shown in [2]. This includes a description of the different tracks we follow as well as our satellite engineering models. Furthermore, first measurement results are shown.

II. Architecture

Fig. 1 shows the general infrastructure of the 3D OpenLab at the university of Bremen, in which multiple BSs are used to build the ground, air and space segments. The BSs are connected to a common core network and provide connectivity to UEs, which can be either stationary or mobile, including flying. The airborne BS is mounted to a drone with a payload capacity of 10 kg. To realistically represent satellites in this 3D network, two different types of small-satellite engineering models (EMs) (cf. Fig. 2) are implemented in the OpenLab: One is a so-called RasPi-Sat, based entirely on a Raspberry Pi platform and developed at ZARM. The other type is an EnduroSat DeskSat with fully space-qualified hardware and subsystems with space heritage. They are installed on the top of the Bremen Drop Tower at the Center of Applied Space Technology and Microgravity (ZARM) in Bremen as well as flexibly placed in the experimental field.

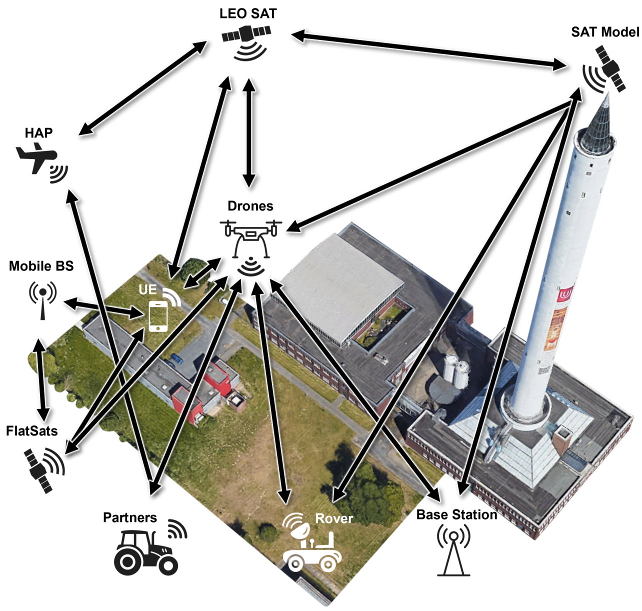

Fig. 1. General 3D experimental setup [2]

The BSs are implemented using different technology approaches, such as an SDR implementation and commercially available 5G hardware. While the ground and simulated space

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Fig. 2. RasPi-Sat (left) and EnduroSat DeskSat (right) [3] Satellite Engineering Models.

BSs can be connected to the core network via a cable, either Ethernet or fiber optic, the drone BS needs a wireless connection to the core network. It is worth mentioning that a tethered drone setup is also envisioned in our experimental setup, but we initially focus on the layout shown in Fig. 1.

III. Experimental Field: Current Status

To facilitate different implementation and testing capabilities, we offer multiple implementation tracks using different hardware and software components to realize the BSs and UEs in Fig. 1, e.g. commercial or SDR-based equipment. In this section, we provide a detailed description of the considered implementation tracks and corresponding capabilities and exemplary testing scenarios. Afterwards, we give more details about the status of our satellite engineering models. To avoid repetition, we refer to [2] for more details about the used hardware components and architecture.

A. Commercial 5G Equipment

In this track, we use 5G standard-compliant commercial off-the-shelf hardware. The goal of this track is two-fold. First, using already-existing 5G hardware enables the capability of running immediate proof-of-concept demonstrations to show the feasibility and benefits of employing the 3D networks, in addition to executing measurement campaigns in initial scenarios deploying 3D networks. Second, using standard-compliant hardware has the advantage of providing standard interfaces that can easily be used by external researchers to run their own measurement campaigns or testing certain developments especially at the UE side. This supports our vision of building an OpenLab for 3D network testing that is easily accessible.

To this end, the OpenLab is equipped with a hardware platform consisting of a 5G core network and an outdoor 5G campus network, here referred to as base stations, from the vendor MECSWare. This platform is 5G standard-compliant following the 3GPP Release 15. One main aspect of this platform is that the core network can be connected to multiple base stations, making it suitable for the 3D network implementation. If a UE receives signals from two BSs, e.g., ground and air BSs, both connected to the same core, an automatic handover is triggered and the UE is connected to the BS with the best signal quality.

Planned Scenarios: For example UAV-BS for range extension: In this scenario, the air BS, attached to the drone, is used to provide coverage when the ground BS goes down, e.g., in a disaster scenario, or in areas not covered by the ground BS.

Current Status: The complete setup is implemented and usable. The simulated space BS, in this track a common outdoor BS, is installed at the top of the ZARM Drop Tower, and the flying BS on the drone is connected through a WiFi bridge to the common core network. It can be used as an autonomous network with its own core as well. First tests on the scenario "UAV-BS for range extension" have been successfully executed incorporating the ground, flying and simulated satellite BSs. For more details on this setup and the implemented scenario, we refer to Section IV. In summary, this track is implemented, functioning, and ready to be used by interested researchers.

B. 5G Compliant with SDR

While the commercial setup offers a reasonable proof-of-concept capability, it is not suitable for research and development activities, in which new communication services or features should be integrated and tested. For this purpose, we consider a more flexible implementation using software defined radio and (high power) computers for both BS and UE realizations. The SDR track offers extensive control over the hardware and communication aspects, e.g. to try out new algorithms, waveforms and channel codes.

As RF front-end devices, we use Ettus USRP X410 for the ground and space BSs, while we use the USRP B210 for the drone BS and UE. Note that the use of different USRP models provides different hardware capabilities, allowing the technology/algorithm testing under different hardware conditions.

On the software side, we use the open-source platform OpenAirInterface, which provides an implementation for the 5G core network and the 5G full stack. However, any other software platforms that can be supported by the hardware platform can be easily and directly integrated into our OpenLab. For instance, the open-source platform srsRAN can also be used without any further modifications or extensions. On potential advantage of using the OAI is that the latest OAI branch has many features from the 3GPP standard Release 17, particularly the NTN support considering both GEO and LEO payloads on both gNB and UE sides, including the conditional handover.

At the time of writing this article, only OAI provides support of NTN features on both gNB and UE side. In this regard, notice that the handover between the terrestrial and non-terrestrial networks, i.e. TN-NTN handover, is one of the main topics towards realizing practical and effective 3D networks, which is one of the scenarios planned for this track. Therefore, we decided to use the OAI in our OpenLab.

For the space BS, a USRP with an antenna is installed on the top of the drop tower, with a fiber connection to the core network. The satellite engineering models are also integrated to mimic realistic satellite payloads, while the channel characteristics, mainly delay and frequency offsets, will be generated through software, e.g. using GNURadio.

Planned Scenarios: TN-NTN handover: In the current OAI branch, only inter-DU (distributed unit) is supported, meaning that the handover is executed among multiple DUs that are all connected to the same central unit (CU) and core network. In our scenario, we have three DUs reflecting the three BSs, i.e., ground, air, and space, which are all connected to the same core and CU, which can be running on the same machine. The drone BS is again connected through a WiFi bridge to the CU and core. The main challenge of this scenario is that the terrestrial handover is triggered based on the quality of signals from different BSs, while the non-terrestrial handover is mainly a conditional handover, usually time-based.

Current Status: The SDRs and computers are all available. Implementing the TN-NTN handover scenario is ongoing in the laboratory. Moving to the experimental field is under preparation.

C. Research with SDR

While the 5G-compliant SDR setup offers a 5G-compliant but open platform for development, it has a lot of overhead created by the large software implementations like OpenAirInterface, Open5GS or others. Therefore, it is great for later stages of development and investigations on the system level, but for first tests of new algorithms or waveforms, we want to offer an even more flexible approach: We use GNUradio [4] for a research-oriented setup. For research on behaviour of a 5G communication payload on a satellite, an SDR with a mini-PC running GNUradio is implemented on the satellite engineering models. This enables the analyses of the interface, limited power supply, operational sequences and satellite modes, as well as command-timing, line-of-sight simulations, and general operational flow.

Planned Scenarios: This setup is for flexible research. Gathering data from practical outdoor scenarios, e.g. under different weather conditions or for live-tests, is planned. We plan to incorporate our ultra reliable low latency communications (URLLC) demonstrator developed in a previous project [5]. In the laboratory, we have a Hardware-In-The-Loop setup that we could extend to the outside world of the experimental field.

Current Status: The hardware is available (see Sec. III-C). We use GNURadio in several research applications and demonstrators in the laboratory. The integration in the experimental field is planned later this year. A live test with the QUBE satellite by Zentrum für Telematik (ZfT) [6], [7] was successfully performed on 06.03.2025, confirming the capability to receive telemetry of a satellite in orbit with our ground station. Tests with the satellite as a repeater will follow.

D. Professional Setup

In this track, this OpenLab provides the possibility to build and test scenarios using custom software on hardware provided by industry partners. Hence, the experimental field offers extensive control over the software setup, being executed on industry-used hardware with its resources, e.g. in computing capability. For instance, we are currently working on integrating two hardware platforms from our industry partners NXP, namely the Layerscape platform, and DSI Aerospace GmbH, namely High Performance Data Processing Unit for Artificial Intelligence Application (HPDPU) [8]. The later hardware platform is designed mainly for a high-performance processing platform as a demonstrator for Machine-Learning-based onboard baseband processing for 5G NTN.

The hardware platforms are available and the work on integrating then into the OpenLab is ongoing. For the NXP Layerscape, we plan to implement the O-RAN 7.2 split in which the Layerscape is serving as the CU/DU unit while a remote unit (RU) will be installed on the top of the drop tower. Such an implementation can be interesting in the current discussions regarding the possible functional split options for the NTN deployments towards regenerative payloads. This is also one of the scenarios planned for the DSI platform. It is worth mentioning that different functional split options and machine learning techniques in the physical layer for satellite 5G communications have been intensively investigated by the University of Bremen, see e.g., [9], [10], within the scope of the project AIComs (AI for Satellite 5G Communications) [11]. The developed algorithms will be further implemented and tested on the Layerscape and HPDPU platforms.

E. Satellite Engineering Models

The RasPi-Sat, in use for early prototypes of subsystem and hardware developments, teaching, and student projects, connects to an ADALM-PLUTO or a bladeRF 2.0 micro xA4 SDR as communication subsystem. One of the Raspberry Pi 5s is running GNUradio [4] to implement the SDRs for communication over ultra high frequency (UHF) for telemetry and telecommands and for inter-satellite links. The subsystems on the RasPi-Sat communicate with each other using the Cubesat Space Protocol [12].

The DeskSat is a sophisticated small-satellite development platform. Its On-Board Computer (OBC) and UHF subsystems are flight-proven in space on multiple missions and serve as a realistic representation of a small satellite in both operation and development. The UHF subsystem serves for communication with our satellite ground station (see Section III-F) and inter-satellite communication. An external satellite payload consists of an Ettus USRP B210 with an Intel NUC, serving as interface to the 3D network of the OpenLab. Software like OpenAirInterface for the 5G compliant SDR research and development activities (see Sec.III-B) and GNURadio for a more research-oriented setup (see Sec.III-C) can be implemented there. By using Software Defined Radio (SDR), effects of orbiting base stations, like the Doppler shift, will be simulated. An in-depth look into the satellite models and their capabilities is given in [13]. For a more realistic hardware approach, a NXP Layerscape processor can be used instead (cf. Section III-D).

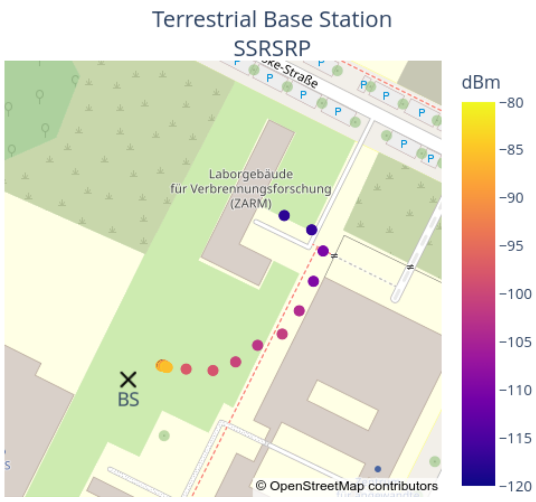

Fig. 3. Signal strength between a terrestrial user and a terrestrial base station at different positions, partially blocked by a building.

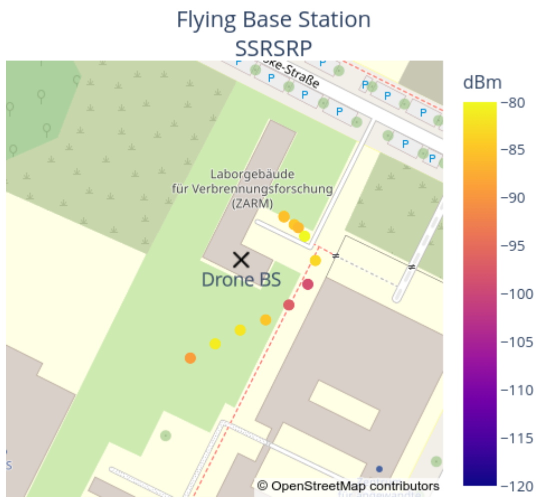

Fig. 4. Signal strength between a terrestrial user and a flying base station at different positions, not blocked by the building.

F. Satellite Ground Station

A realistic implementation of the commanding and telemetry signal paths is achieved with our amateur radio satellite ground station. Based on a bladeRF 2.0 micro xA4 SDR with additional filters and amplifiers and two Cross-Yagi antennas for UHF and VHF bands, a full satellite ground station setup is included in the OpenLab. It includes tracking and pointing capabilities to follow the orbital path of satellites and optionally drones (with external drone telemetry input) and has a transmission power output of 40 W to 60 W. The antenna is installed on a mobile platform and can be positioned flexibly. The ground control center software, used for processing of telemetry and telecommands, is the open-source OpenC3 COSMOS [14]. Signal processing takes place in GNUradio. An S-Band antenna for reception of higher-bandwidth downlink signals like images and payload data is under development.

IV. First Measurements

With the fully operational commercial 5G setup (cf. Sec.III-A), we have conducted first measurements and a first showcase described in the following sections.

A. Showcase: Extended Coverage

One possible use case of a 3D network is coverage extension. To investigate this in a first experimental setup, we implemented the following scenario: A rover is carrying a smartphone (Crosscall Core-Z5) as UE. It is initially located close to the terrestrial base station. When the experiment start, the UE moves away from the BS, reaching a position behind a building. We measure the signal quality with the app Open Mobile Network Toolkit (OMNT) from Fraunhofer Fokus [15]. As expected, the building blocks the terrestrial signal as soon as the UE is behind it. The experiment and the measurement results are visualized in Fig. 3.

After the UE has reached its position behind the building, the drone takes off and creates a 3D network with its attached base station. It is connected to the same core as the terrestrial one using a WiFi-bridge. As soon as the drone flies above the building, the UEs connectivity is restored as shown in Fig. 4. This showcases how a drone could be used to deploy a 3D network with a flying base station on demand to enhance the connectivity of users.

B. Measurement: 3D Measurement of a Terrestrial BS

In this measurement series, we used a terrestrial base station and two Crosscall Core-Z5 smartphones as UEs. The smartphones are connected to our 5G non-terrestrial campus network and measure two things:

- SSRSRP (Synchronization Signal-RSRP (Reference Signal Received Power)) in dBm among other network information using the App ”OpenMobileNetworkToolkit” [15], and
- Bi-directional throughput using iPerf3 .

One of the UEs is mounted on our Rover, the other on our drone for measurement payloads (Holybro X500 v2, 1.5 kg payload capacity). For independent performance measurements, only one UE performs an active measurement (like throughput) at a time. They are controlled by our ground stations as shown in Fig. 7. Our software on the ground station computer is attached to the rover's or drone's telemetry respectively. This gives access to the position data from the flight controller, which is significantly more accurate than a smartphone's GPS. It starts a throughput measurement by sending a request to our measurement server, an Intel NUC connected to the service network of our 5G core. The measurement server acts as an iPerf3 client and starts a bidirectional measurement over TCP with no parallel streams. An associated iPerf3 server is running on the smartphones. We use the app ”UserLAnd” hosting Ubuntu for this purpose. As the iPerf3 server is running on the UE, we need to switch uplink and

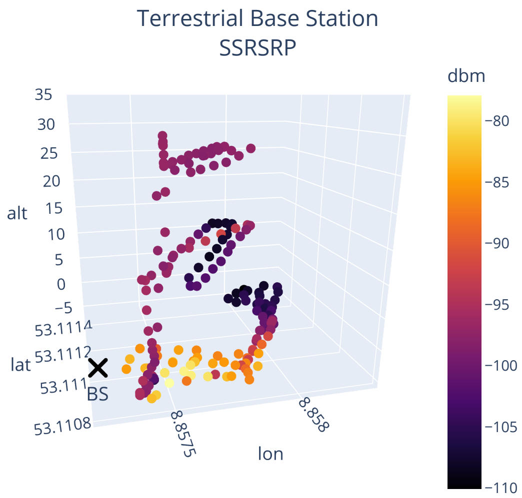

Fig. 5. 3D Measurement of SSRSRP between a Terrestrial BS and a UE on a Drone.

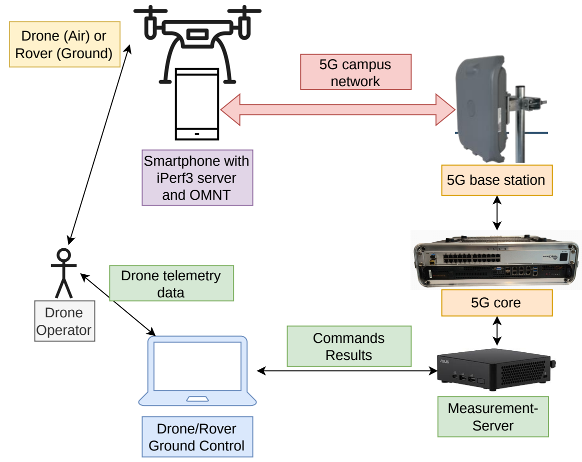

Fig. 7. Measurement Architecture. Note: As the server is running on the UE, we switch uplink and downlink after the measurement.

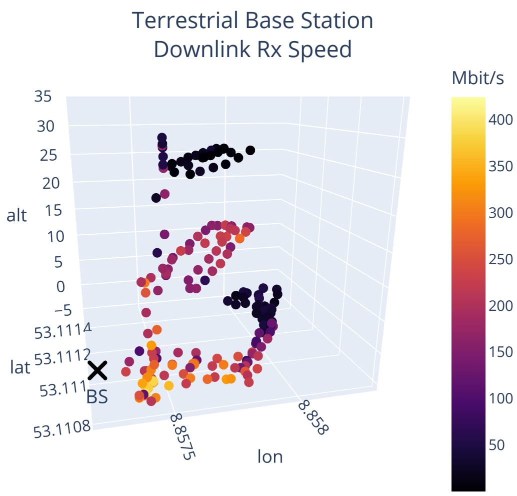

Fig. 6. 3D Measurement of Downlink Throughput between a Terrestrial BS and a UE on a Drone.

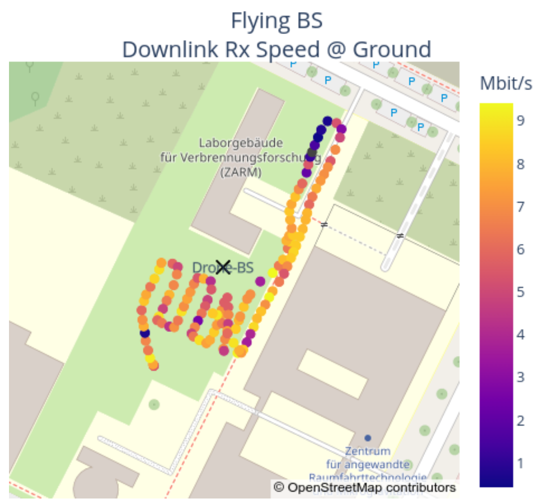

Fig. 8. 3D Measurement of Downlink Throughput from a Flying BS.

downlink afterwards to get the view of the UE. 5G Quality of Service (QoS) data (SSRSRP, SSRSRQ, . . .) as well as further information like the cell ID are continuously gathered in parallel.

When plotting the SSRSRP (see Fig. 5) and the throughput (see Fig. 6), the shading created by the building and its effect on the throughput can easily be seen. The terrestrial BS was not pointing upwards but parallel to the ground, which explains the lower signal strength and throughput at higher altitudes. The building does not have a uniform roof height, but two towers rising up on the sides. This explains higher and lower results in the "back" part of the "middle" layer, as the drone flew through the gap between the towers (line of sight) and behind one of them (shaded). Repeating this measurement with different orientations of the terrestrial base station (as well as with different positions and orientations of a flying base station) is planned for the future.

C. *Measurement: Flying, stationary BS*

With our MK-U25 drone, we can lift a base station and optionally a small core. Therefore, we can have a complete 5G cell with its own core as well as a base station of a terrestrial core flying. We can did measurements as shown in Sec.IV-B. When positioning the drone on one side of the building, we can still have shadowing effects (cf. Fig. 8). With our multiple drones, we will conduct further 3D-measurements with the flying base station. Investigations regarding a 5G link to the core network are considered in the future.

D. *Measurement: Flying, moving BS*

A subsequent investigation could focus on the behavior of a moving flying base station. As shown in Fig. 9, we executed our measurements using a stationary UE on the ground connected to a moving, flying base station attached to our drone. Repeating this measurements with different

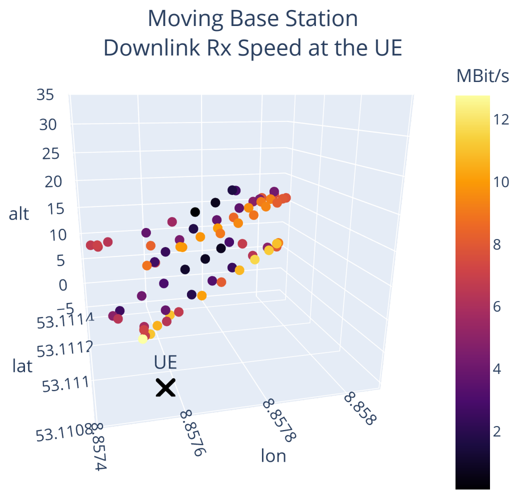

Fig. 9. Downlink Rx Speed for the UE for different position of the BS

altitudes and speeds of the flying base station is planned for the future.

V. Summary and Outlook

In this paper, we describe the structure of the OpenLab for future 3D networks that we are building at the University of Bremen and showed the results of initial measurements. Further measurements with the commercial 5G setup will be tracking handovers between terrestrial, airborne and space-borne base stations and more throughput measurements with different parameters. Furthermore, we can study the effect of buildings on the experimental field as well as altitude and velocity of a moving base station. A base station following the UEs could be of interest as well.

The implementation with the commercial hardware is completed and can be immediately used by partners and external researchers. Setting up the SDR track started in the laboratory and will be moved to the experimental field in the near future to start tests and measurement campaigns in the outdoor environment. This will include investigations of the TN-NTN handover and non-terrestrial networks with conformity to 3GPP.

With the main target of building a comprehensive and flexible testing infrastructure for 3D networks, the OpenLab fullfulls the following list of main capabilities and highlights:

1) Open testing infrastructure for all interested researchers from both, academia and industry.
2) Practical implementation of 3D networks, in which three BSs are connected to one common core network.
3) Using 5G standard-compliant commercial hardware for immediate Proof of Concept demonstrations with standard interfaces ready to be immediately used by researchers.
4) Flexible deployment with SDR-based equipment and open-source software platforms implementing the entire 5G stack and supporting NTN features for both GEO and LEO payloads on both gNB and UE sides.
5) Research-oriented infrastructure which initial tests and evaluations for newly proposed technologies/algorithms, that do not need to be standard compliant, can be easily executed.
6) Transfer from a lab environment onto physical hardware setups outside in an industrial area.

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