MOBILE NETWORKS EXPANDING TO SPACE: OVERVIEW OF THE SERANIS BEYOND 5G TESTBED

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Abstract – In recent years, Non-Terrestrial Networks (NTNs) have gained increased attention from the 3rd Generation Partnership Project (3GPP) due to their potential to enhance cellular networks by improving coverage, resiliency, and reliability, especially in rural areas and disaster scenarios. The upcoming Sixth-Generation (6G) cellular networks aim to establish layers of cells at different altitudes with Base Stations (BSs) on Earth and in space, providing a seamless user experience. Testing and experimentation are crucial for realizing this ambitious vision. University of the Bundeswehr Munich (UniBw M) is deploying a Beyond 5G (B5G) and 6G testbed comprising both space and ground segments. The space segment of the testbed is composed of the ATHENE-1 satellite that is going to be launched in 2025. The ground segment includes the satellite ground station with several full motion antennas for the radiofrequency links and an optical ground station for the free-space optical link based on laser technology, while the Terrestrial Network (TN) component is deployed using a Fifth-Generation (5G) Non-Public Network (NPN) with multiple gNodeBs (gNBs) and multiple 5G core solutions. In its current state, the testbed includes various measurement equipment and emulators in the 5G Lab, a gNB with two active cells, a core network, a satellite ground station, and a mobile 5G on-the-move solution. This testbed allows various experiments including interference management between existing networks, positioning and localization, Public Protection and Disaster Recovery (PPDR) using Multi-Access Edge Computing (MEC) and NTN. This paper describes the components of the Seamless Radio Access Networks for Internet of Space (SeRANIS) B5G testbed, the current status, future deployment plan, preliminary test results, and planned tests.

Keywords – 5G, 6G, LEO, MEC, NPN, NTN, SatCom, testbed

1. INTRODUCTION

Non-Terrestrial Networks (NTNs) based on Fifth-Generation (5G) New Radio (NR) have been an important focus of the 3rd Generation Partnership Project (3GPP) [1]. NTN refers to any network involving flying objects, such as air-to-ground networks, High-Altitude Platform Stations (HAPSs), and satellite communication networks [2]. Satellites have the potential to complement and enhance the 5G Terrestrial Networks (TNs) by improving network coverage, resiliency, reliability, and by addressing complex use cases (e.g. natural and man-made disasters). The 3GPP standardization process resulted in the specifications for 5G-NTN in the Release-17, which was frozen in March 2022 [3].

3GPP Release-17 has been a first step in the convergence of satellite and terrestrial networks. In the next generation of cellular networks, as part of the 6G vision, cellular networks will be unified with platforms in the air and space [4, 5]. Alongside the standardization work done by 3GPP with regard to NTNs, satellite communications is going through a paradigm shift. In the past, satellite communications have been mostly based on the use of a single satellite in Geostationary Orbit (GEO). However, over the past few years the world has witnessed a surging interest in broadband services provisioned by large Low-Earth Orbit (LEO) satellite constellations (e.g., Starlink, Kuiper, and OneWeb). By incorporating Multi-Access Edge Computing (MEC) functionalities on low-orbit satellites and deploying Base Stations (BSs) on non-terrestrial nodes, Sixth-Generation (6G) networks can provide a seamless experience to users. However, such an ambitious vision requires extensive testing and experimentation.

The University of the Bundeswehr Munich (UniBw M) has an ongoing project for technology demonstration called Seamless Radio Access Networks for Internet of Space (SeRANIS). It is a small satellite mission that aims to provide a publicly accessible multifunctional experimental laboratory in orbit serving as a platform for different experiments. The mission includes several scientific areas in the field of space communication including radio science, Global Navigation Satellite System (GNSS), high-level Artificial Intelligence, (AI)-based autonomy, Earth observation in visual and Infrared (IR) wavelength, object detection algorithms, payload operation concepts, modern structures, innovative system-health-monitoring techniques, and electrical-propulsion [6]. Moreover, an important part of the mission is related to broadband, wideband, Internet of Things (IoT) satellite communication, and TN/NTN integration. One of the purposes of SeRANIS is developing a Beyond 5G (B5G) and 6G testbed with space and ground segment, to support our own research and establish an open research environment for the community.

The space segment of the SeRANIS testbed is composed of the ATHENE-1 satellite. The satellite platform has a mass of around 250 kg, including the 90 kg of experimental payload developed at the UniBw M. The payload communication capabilities include several radiofrequency links in UHF, L, S, X, Ka bands and a laser terminal for a free-space optical link. ATHENE-1 will be launched in 2025 to an orbit below 600 km ensuring six passes per day, which can be used to establish contact with the ground segment at the UniBw M in Neubiberg (Germany). The ground segment includes a ground station and the TN component of the testbed. The ground station considers several full motion antennas for the radiofrequency links and an optical ground station for the free-space optical link based on laser technology, while the TN component is deployed using a 5G Non-Public Network (NPN) with multiple gNodeBs (gNBs) and multiple 5G core solutions. 5G NPNs, also referred to as private networks, are networks that are intended for non-public (or private) use but with the same technology as public mobile networks. Since NPNs are exclusive networks, they can be designed to fit the specific needs of the network owner. This flexibility makes NPNs very desirable for industry as well as for research institutes, as it allows them to create their testbed that can be modified to investigate specific research questions [7]. The SeRANIS B5G testbed also includes a laboratory with Software Defined Radios (SDRs) and channel emulators and a complete on-the-move solution that can create an entire 5G network in a van.

While the design of the ATHENE-1 payload and the deployment of the ground segment is ongoing, our research is focusing on various aspects related to the success of the SeRANIS testbed. Current research includes use cases regarding the integration of TN and NTN, use cases for the coexistence between 5G TNs and satellite ground stations, and peculiar problems for the coexistence of 5G public and non-public networks.

The ATHENE-1 satellite will enable testing of two important use cases of integrated terrestrial and non-terrestrial networks. The first use case is satellite-to-device communication; in other words, direct connectivity between a satellite gNB and a terrestrial User Equipment (UE). The other important use case is LEO satellite backhauling. The success of these two demonstrations will lay the foundation for the development and testing of other 5G and B5G use cases.

Our testbed will enable the use of MEC for disaster relief scenarios. 5G service demand goes beyond improved mobile broadband or reduced latency and massive Machine-Type Communications (mMTC). The need for a 5G network in certain areas plagued with natural disasters or war has become eminent in recent times. 5G NTNs provide the solution thanks to their coverage and high bandwidth. However, NTN poses challenges for users requiring higher Quality of Service (QoS), high data rates, low communication latency, and low energy costs for data communication and processing [8] due to the large propagation delay of the satellite link. MEC was proposed in late 2014 by the European Telecommunications Standards Institute (ETSI) Mobile Edge Computing Industry Specification Group (MEC ISG) [9] to transfer the computation and storage capacity from remote servers to local servers, and this can greatly improve the QoS, latency, and energy consumption of user devices. Consequently, disaster relief provision via satellite backhaul emerges as a practical implementation of MEC in NTN 5G networks. Thanks to the LEO satellite capabilities of our testbed we will be able to test MEC applications via satellite.

Another research question we focus on is the positioning aspect of 5G. Accurate positioning is a fundamental element of 5G for location-based services, and is a requirement from the regulatory bodies for emergency and disaster relief services [10, 11]. Standard GNSS has limitations in indoor environments, making it essential to investigate alternative approaches for positioning. The 5G and 6G communication systems will require high-precision location services [12] that will complement GNSS, particularly in indoor and urban settings. Several positioning techniques have been proposed for terrestrial positioning, including Angle of Arrival (AoA)/ Angle of Departure (AoD), Time of Flight (ToF), and Time Difference of Arrival (TDoA) [13]. TDoA, which is supported by 3GPP specifications, offers some distinct advantages, such as providing high positioning accuracy with synchronization between base stations, but without synchronization requirements between base stations and the target. Moreover, TDoA does not require a multi-antenna system as for the AoA or AoD techniques. In addition, the ATHENE-1 satellite, together with the terrestrial infrastructure, can be exploited for new hybrid positioning and localization approaches using ephemeris data and broadcast signals transmitted by the satellite.

Another important aspect of 5G networks is the seamless connectivity regardless of whether the users are in motion or still. Handover, the process of transferring an ongoing communication session between cells, plays a critical role in maintaining uninterrupted connections and has been under restricted requirements in the 3GPP Technical Specification (TS) for 5G [14]. In [15], a formal analysis of handover in 5G is done. The automotive test track in our testbed provides us the opportunity to evaluate handover Key Performance Indicators (KPIs) in 5G and B5G networks considering the cells of terrestrial gNBs and the gNB on board the ATHENE-1 satellite.

In the path of unification of TN and NTN, coexistence between the two infrastructures is also important. The allocation of the 3.3 - 4.2 GHz band, which is commonly used for satellite communications, to 5G NR [16] has raised concerns about interference at Satellite Ground Stations (SGSs). A study [17] determined that the deployment of a nearby 5G network operating in the C-band would greatly impact the satellite station in Burum. Further research [18], [19] indicated that to avoid significant interference, a separation of over 15 km between the BSs and the SGSs is necessary. Authors in [20] and [21] demonstrated that even interference from adjacent band 5G signals can disrupt satellite services. Deploying a 5G NPN around our existing SGS will allow us to investigate the impact of the 5G to SGS interference and vice versa. Thanks to the flexibility of the testbed, we can generate different signals with a varying number of streams, power, and bandwidth to analyze the resulting interference and experiment with different mitigation techniques.

The 5G terrestrial network component of the SeRANIS testbed relies on an NPN. NPN, in Germany as well as other countries, operates in a dedicated frequency range adjacent to the spectrum reserved for public networks. Although operating in different frequency ranges, NPNs could affect the performance of 5G public networks especially in the uplink. The impact of this problem and solutions to mitigate it have to be assessed to ensure the coexistence between the two types of 5G networks.

To the best of the authors' knowledge, the SeRANIS B5G testbed will be the first one to complement a multi-gNB 5G NPN deployment with a LEO satellite and a large ground segment, including an optical ground station for free-space optical communication. These unique capabilities will enable us to conduct novel research on several topics. The scope of the paper is to present the SeRANIS B5G testbed, the components, the current status, future deployment plan, preliminary test results, and planned tests. The rest of the paper is structured as follows. Section 2 gives an overview of other 5G NPN testbeds, Section 3 describes the network and its components, Section 4 presents the capabilities and initial test results, Section 5 explains the planned experiments and Section 6 concludes the paper.

2. RELATED WORK

This section provides an overview of existing 5G NPNs testbeds in the literature.

The 5G-VINNI [22] is a testbed deployed to demonstrate the practical implementation of infrastructure to support and allow vertical industries to test and validate specific 5G applications. 5G-VINNI has seven sites with different capabilities. It includes 5G Non-Standalone (5G NSA) and 5G Standalone (5G SA), mmWave, low power wide area networks for IoT, a space segment with GEO and Medium Earth Orbit (MEO) gateways, a nomadic 5G node for Public Protection and Disaster Recovery (PPDR) use cases.

5G Playground is a versatile 5G SA testbed operated by Fraunhofer FOKUS, Fraunhofer HHI, and innovation cluster 5G Berlin [23]. The 5G Playground offers test facilities for various radio access technologies for indoor and outdoor measurements, ultra-reliable low latency communication for factory shop floors, an automotive testbed environment, coverage of dense urban areas, and a portable 5G edge node.

The 5G-Industry Campus Europe is a 5G campus network with a focus on industrial applications [24] based on the campus of RWTH Aachen. It relies on 5G NSA and can use cellular test networks in various outdoor and indoor locations with an outdoor network of around 1 km^2 and a shop floor of 8000 m^2. The network is implemented with a Fourth-Generation (4G) anchor band at 2.3 GHz and a 5G network in the n78 band.

Recently, researchers from TU Kaiserslautern published the results of the performance analysis of the private campus network deployed on their campus [25]. The campus represents a flat and dense urban development. The network is a 5G SA network operating in the n78 band with three outdoor BS masts covering two cells each. In addition, there are also indoor networks for the demonstration of industry-related applications. The testbed setup at TU Dresden has a similar setup also including a 5G NSA network [26].

The Ericsson testbed [27] consists of a terminal mounted in a van with an external omnidirectional antenna. It also includes a massive Multiple-Input-Multiple-Output (MIMO) solution that supports up to 16-layers spatial multiplexing. The testbed is deployed in two different environments: a dense urban area with micro-cells and an open line-of-sight area. Furthermore, they have similar testbeds using different frequency bands in [28] and [29].

5G Test Network Finland (5GTNF) [30] is a testbed with multiple sites in Finland with different capabilities. The sites include an outdoor test network covering an autonomous vehicle testing area, a wideband mmWave 5G test network with indoor and outdoor coverage, LoRa test networks, and Long-Term Evolution (LTE) networks.

POWDER [31] is a flexible testbed deployed at the University of Utah campus with the main site covering an area of about 6 km^2. The main site has numerous office, lab, and classroom buildings ranging from one to twelve stories. Many of the BSs are co-located with commercial cell towers, providing a similar Radio Frequency (RF) coverage as that observed in operational networks. POWDER offers a range of functional experiment environments with popular network stacks such as OpenAirInterface and srsLTE for 4G and 5G networks and Open RAN for virtualization and programmability.

COSMOS [32] is deployed in a densely populated urban environment in West Harlem, New York City, with an emphasis on mmWave wireless, converged optical-wireless networking, edge cloud, and full programmability. The radio hardware is based on SDRs, small SDR nodes are used as end clients while larger nodes are used as BSs. The testbed can operate between 400 MHz and 6 GHz. Moreover, it has 28 GHz mmWave capability. The network is interconnected via fiber optic connections, free-space optical and microwave backhaul.

Eurecom has deployed a Cloud Radio Access Network (CRAN) using OpenAirInterface (OAI) that consists of three main parts: i) the Remote Radio Unit (RRU) which functions as a radio transceiver, ii) the radio aggregation unit which connects multiple RRUs to a Baseband Unit (BBU) and serves as a data processing unit, iii) the radio cloud center which is responsible for centralized baseband processing and controls the radio aggregation unit. A total of 20 RRUs are deployed on the ceilings of corridors across two floors of the Eurecom building. Additionally, a high-power commercial Remote Radio Head (RRH) is connected to the C-Radio Access Network (RAN) server through a common public radio interface gateway [33].

5GENESIS is a testbed distributed across five sites [34]. It offers various capabilities such as an edge-computing-enabled shared radio infrastructure, satellite communications infrastructure with a GEO satellite, ultra-dense areas covered by various network deployments, indoor nodes and nomadic outdoor clusters, and mMTC including 5G Narrowband Internet of Things (NB-IoT). The scope of the use cases includes secure content delivery and low latency applications in large public events, service continuity and ubiquitous access, and mission-critical services in the lab and outdoor deployments.

The University of Luxembourg developed its 5G space lab testbed in [35]. The testbed consists of SDRs for terrestrial and satellite communications, channel emulators for non-geostationary satellites, various software tools as the simulation framework, and an 80 m^2 laboratory space that simulates the surface of the Moon. The capabilities of the 5G-SpaceLab include 5G NTN communications, non-geostationary satellite emulation, small satellite payload design and implementation, space-based edge computing, lunar rover control, and space-based IoT applications.

A test network focusing on disaster relief based on WiFi instead of 5G is described in [36]. The testbed consists of four entities: i) the UE, equipped with a 2.4 GHz WiFi interface; ii) the communication entity responsible for bridging UE data with the data backend; iii) the flight management unit, which runs an auto-pilot, maintains a control link, and provides telemetry data for the control plane decisions; iv) the ground control station which is responsible for processing the information received from the Unmanned Aerial Vehicles (UAVs) and bridging inter-UAV and controller messages. In the paper, the authors demonstrate an infrastructure for disaster areas.

The 5G/6G Hub based at European Space Agency (ESA)'s European Centre for Space Applications and Telecommunications (ECSAT) at Harwell in the UK is composed of a 5G NPN with SatCom connectivity in a business-driven facility designed to engage the wider community [37]. The agency has also planned to launch the STERLING satellite, an in-orbit 6G laboratory to allow experimentation, optimization, and validation of key 6G technologies and techniques [38]. ESA has signed a memorandum of intent with SeRANIS to collaborate and experiment with 5G and 6G NTN communications [39].

Compared with existing testbeds, to the best of the authors' knowledge, the SeRANIS B5G testbed will be the first one to complement a multi-gNB 5G NPN deployment with a LEO satellite and a large ground segment, including an optical ground station for free-space optical communication. This allows for testing and evaluation of emerging 5G and 6G use cases and applications.

3. SERANIS B5G TESTBED

The B5G testbed at the UniBw M campus in Neubiberg (Germany) described in this paper is part of the research activities of the SeRANIS mission. SeRANIS is a small satellite mission that aims to provide a publicly accessible multifunctional experimental laboratory in orbit and it will serve as a platform for different experiments. An important part of the mission is related to broadband, wideband, IoT satellite communication, and TN/NTN integration. One of the purposes of SeRANIS is developing a B5G and 6G testbed with space and ground segment [40]. The space segment is composed of the ATHENE-1 satellite which is going to be launched in 2025, while the ground segment includes a ground station and the TN component of the testbed.

The ground segment is located on the UniBw M campus, which covers a large area of about $1.3\,\text{km}^2$ south of the city of Munich. The campus is surrounded mainly by small suburbs and fields, while inside the campus it provides different facilities, densely developed areas with buildings and roads, and low-density developed areas with warehouses and fields. The campus has an automotive test track and a restricted zone for UAVs. The campus is populated by about three thousand students and workers who move within it by various means, such as by car, bicycle, and on foot. These unique factors turn the UniBw M campus into a perfect testbed for the use of mobile networks, replicating a modern city environment on a smaller scale. The UniBw M campus is already home to the Munich Mobility Research Campus (MORE) project that aims to transform the university into a model mobility city of the future [41]. In early 2023, the MORE project launched a mobility-sharing technology supported by different types of electric vehicles, enabling all members of the UniBw M to experience the latest mobility-sharing technology [42]. Collaboration with the MORE project could provide the testbed with a large number of users

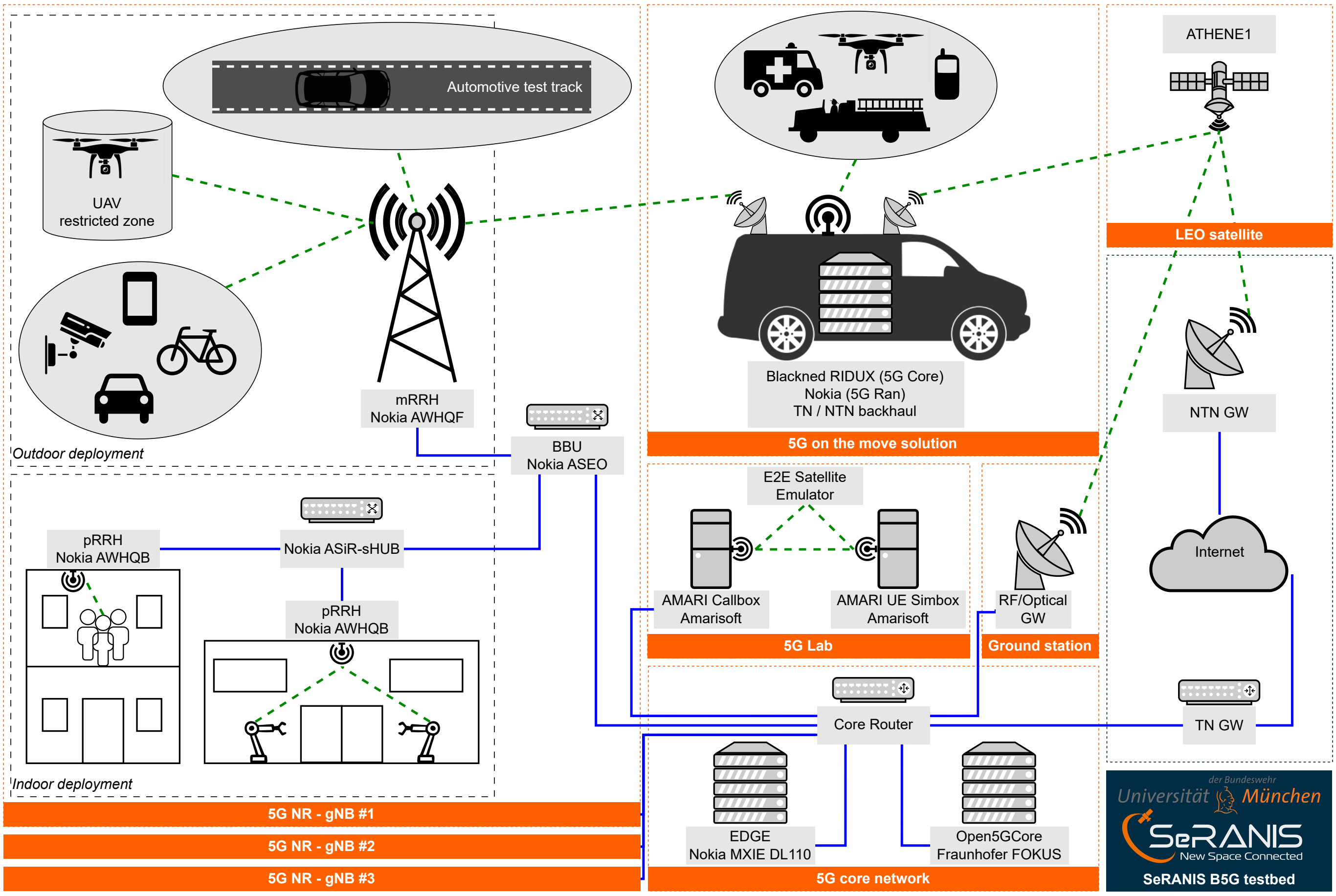

Fig. 1 – SeRANIS B5G testbed network diagram.

and/or possible measurement devices across the campus.

The SeRANIS B5G testbed presented in this paper is a complex entity with several components as shown in Fig. 1. The main components can be summarized as follows:

- 5G NTN Lab with SDRs and satellite channel emulators;
- Radio access network (5G RAN) component of the NPN;
- Core network (5G core) component of the NPN;
- 5G on-the-move solution;
- LEO satellite;
- Satellite ground station.

All the components of the testbed can interact with each other, as shown in Fig. 1, creating a multitude of possible scenarios and experiments. At the time of writing, only a limited part of the overall network has been installed and full ground segment implementation is planned for the end of 2024, while the launch of the ATHENE-1 is planned for 2025.

3.1 5G NTN Lab

The 5G Lab offers vast opportunities for researchers to investigate the entire 5G protocol stack in one lab. The 5G Lab is equipped with three complete 5G SA solutions from Amarisoft (including 5G RAN, core network, and UE simulator) [43], several SDRs, measurement equipment, open-source software, and commercial 5G terminals of different vendors. This solution enables the testing of 5G and LTE mobile networks. It can create a network with several 3GPP compliant BSs, eNodeBs (eNBs) or gNBs, and core components (Evolved Packet Core (EPC)/5GC) allowing functional and performance testing. The 5G Lab is also equipped with satellite channel emulators, modulators, and demodulators to simulate different TN and NTN integration scenarios. The end-to-end satellite communication system for 5G backhauling can also be emulated via software using OpenSAND [44].

In addition, the 5G Lab hosts several x64 computers and SDRs with an adapted OpenAirInterface protocol stack considering 3GPP Release-17 enhancements for NTN. The adaptations that were implemented take into account all layers of the OAI 5G protocol stack. This enables the setup of an in-lab NTN for direct access, complete with two user terminals and a BS. An OAI-based 5G core net-

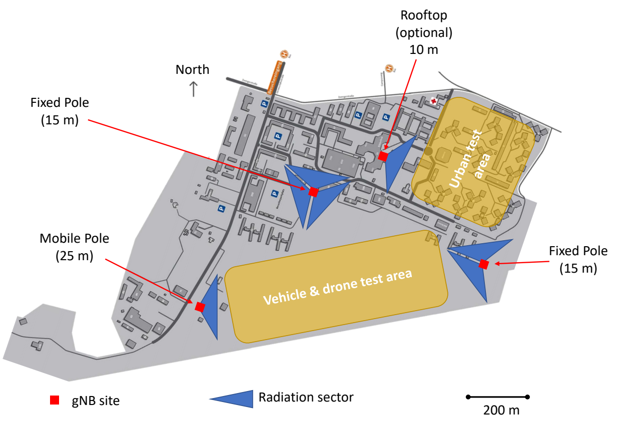

Fig. 2 – Overview of the gNB sites on the campus.

Fig. 3 – Simulation results of signal strength.

work was also included in [45, 46] to facilitate end-to-end testing.

The 5G Lab also includes an RF-capable Field-Programmable Gate Array (FPGA) board, a versatile tool that significantly augments the capacity for capturing and analyzing In-phase and Quadrature-phase (IQ) samples. This FPGA board serves as a vital resource, allowing a deeper delve into the characteristics of received signals. Furthermore, the FPGA board's capabilities extend beyond signal analysis, enabling more functionalities such as interference measurements and position estimation. Leveraging the FPGA's parallel processing capabilities, interference from neighboring signals can be accurately quantified and analyzed, leading to insights that contribute to enhanced signal quality and reliability. Moreover, interfacing with the diverse array of 5G Lab equipment, the FPGA facilitates the implementation of algorithms and techniques for fine-tuning positioning estimation. Through careful calibration and optimization, the FPGA board can support the generation of accurate location data.

3.2 5G RAN

On the campus of the UniBw M, it is planned to establish a terrestrial 5G mobile network with three gNB locations with the option to add a fourth one. The different sites of the gNBs have been chosen according to different criteria. The first and most important one is the coverage of the campus area. The second one is getting the best conditions for localization purposes. Therefore, a geometric triangle arrangement has been planned as seen in Fig. 2. Within the planned coverage area there are two planned test tracks: one for vehicle and airborne test scenarios with drones and the other one contains many buildings and trees. The latter test area simulates an urban test scenario for pedestrians and cyclists. There will be a wide spectrum of test options by the maximum range on the test track of about 1 km and a covered area of about 240 000 m^2.

The three gNB sites will be equipped with commercial Nokia components. Each site has up to three 5G micro-Remote Radio Heads (mRRHs) depending on the location. The locations and heights of the gNB sites can be seen in Fig. 2. Therefore, fixed or mobile pole installations are used to assemble the mRRHs in the locations. In the case of gNB sites located on buildings, special rooftop mountings with adjustable directions of radiation will be used. The mRRHs can transmit up to 40 Watts. All mRRHs are connected via two exclusive single-mode dark fiber optic lines to one of the three BBUs.

This will allow data rates of more than 10 Gbps which are required for the communication between the gNBs and the core network. The BBUs are connected to the core components' Core Router (CR), Edge Core (EC), and the Virtual Private Network (VPN) Router via Ethernet lines. The whole RAN can be expanded by an additional mobile RAN from Blackned described further in subsection 3.4, which can be used for very specific and flexible test scenarios, e.g. in a van to set up a nomadic 5G network.

A first coverage simulation for the planned four gNB sites has been done with Matlab and a radiation simulation tool from Nokia. The simulation had the following parameters: n78 band with 3.7 to 3.8 GHz and transmitting power of 40 Watts per RRH. The expected result of radiation coverage in both test areas can be seen in Fig. 3. The signal reception on and above the vehicle and drone test area is expected to be higher than -60 dBm. In the urban test area, the signal strength could decrease to -100 dBm because of the buildings and plants in this area. Moreover, the results will be evaluated after all sites are in operation.

3.3 5G core

We operate 5G core solutions from different vendors to test interoperability and benefit from the different capabilities of each of them. Two 5G core solutions from Nokia and Fraunhofer FOKUS are currently integrated into the network.

The Nokia 5G core architecture is based on 3GPP release 15 where there is a clear separation between the user and the control plane function, with a service-based architecture for the control plane functions. The service-based interfaces are based on HTTP/2 with JSON as an application layer serialization protocol. The complete 5G system is deployed on-premises with 5G gNBs and all 5G network functions at the edge. This keeps the data local and secure and ensures low latency for high-bandwidth applications. The edge is connected to the Nokia Digital Automation Cloud (NDAC) data center regional cloud, which provides cloud-based management functions.

Open5GCore is a software implementation of the 3GPP 5G core network created by Fraunhofer FOKUS to be used for research and development purposes. The core network is deployed as a small-scale operator testbed and 5G private network and can be accessed by prototype or off-the-shelf phones. It can be integrated with 5G SA, 5G NSA, LTE, NB-IoT LTE, WiFi, and satellite. The 5G core implements several 5G core functions such as Access and Mobility Management Function (AMF), Authentication Server Function (AUSF), Session Management Function (SMF), Unified Data Management (UDM), Network Repository Function (NRF), User Plane Function (UPF), and Network Slice Selection Function (NSSF). It supports features like network slicing, location service, local offload, edge-central split, Xn handovers, roaming, high capacity UPF, QoS and session management, benchmarking, and service-based architecture implementation using HTTP/2 OpenAPI and REST. Open5GCore supports Voice over 5G (Vo5G) by integrating with Kamailio IMS, which is an open-source implementation of 3GPP IMS containing a high-performance SIP Express Router and OpenIMSCore. The core solution's compatibility with both open source and commercial RAN presents a great opportunity for researchers to test or validate their existing networks.

3.4 5G on-the-move solution

The 5G on-the-move solution is based on Blackned's Ridux system which sits on the application layer and consists of a mobile 5G core hardware and a Nokia 5G RAN hardware. Blackned Ridux supports call management technology with which it is possible to switch telephone calls and video calls, geolocation capabilities, and integration of 3rd party applications for IoT applications [47]. Additionally, the core network supports narrowband and broadband applications, multi-service aggregation, edge computing, and security features. Blackned is a software manufacturer and specialist in mission-critical communication systems. The 5G on-the-move solution can be installed in our van to create a complete modular 5G pop-up/nomadic network.

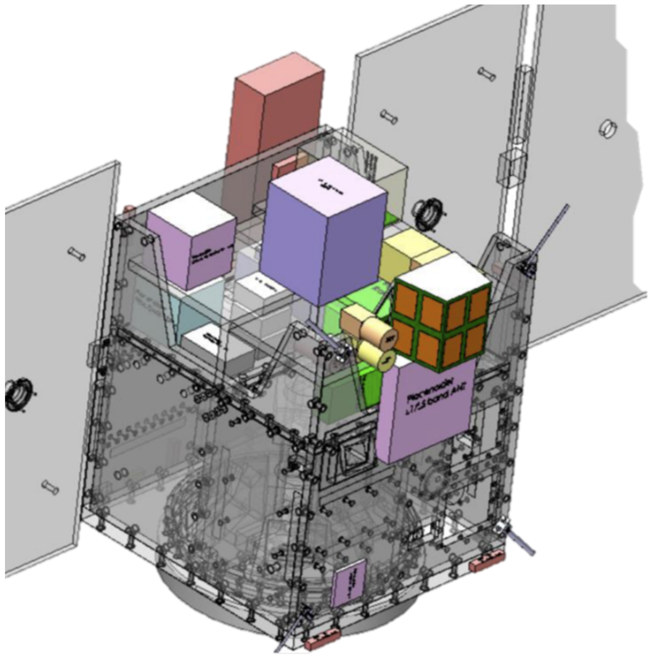

Fig. 4 – Model of the ATHENE-1 satellite.

3.5 LEO satellite

ATHENE-1 is the name of the satellite of the SeRANIS mission, the model of which is shown in Fig. 4. It is a procured satellite platform with a mass of around 250 kg including the 90 kg of experimental payload developed at the UniBw M. The mission plans to examine and test more than 15 technological developments in the field of space communication such as electric propulsion, modern satellite structures, functional materials, modern operating procedures, AI-based docking manouvres, AI-based error management, event monitoring, multispectral object recognition, laser communication, GNSS spoofing and jamming detection, novel antenna concepts, and radio science. Moreover, an important part of the mission is related to broadband, wideband, IoT satellite communication, and TN/NTN integration. The satellite payload embeds several radiofrequency links in UHF, L, S, X, Ka bands and a laser terminal for a free-space optical link. The satellite is developed with a software-defined approach that enables over-the-air reconfiguration of payload to support planned and future experiments. The launch of ATHENE-1 is expected in 2025 into an orbit below 600 km. The selected orbit will ensure six passes per day that can be used to establish contact with the ground segment at the UniBw M in Neubiberg (Germany). The mission lifetime is expected to be five years and the satellite has an active de-orbiting system to comply with space debris mitigation requirements. The integration of the ATHENE-1 into the SeRANIS B5G testbed will be an essential part of testing LEO satellite backhauling solutions, satellite-to-device direct communication, seamless connectivity between TN and NTN, and new applications such as MEC.

Fig. 5 – Ground station of the Munich Center for Space Communications.

3.6 Satellite ground station

The UniBw M hosts the Munich Center for Space Communications (MCSC) [48], a versatile research facility for satellite and space communication. The MCSC offers a powerful satellite ground station with multiple antennas covering a large spectrum of frequencies enabling the connection with satellite networks including the radiofrequency links of the ATHENE-1. The current capabilities of the ground station shown in Fig. 5 include:

- Full-motion antenna with an aperture diameter of 4.6 m operating in C, X, and Ku-bands;
- Full-motion antenna with an aperture diameter of 4.9 m operating in X and Ka-bands;
- Full-motion antenna with an aperture diameter of 7.6 m operating in Ku-band;
- Smaller antennas ranging from 0.75 m to 2.4 m aperture diameter;
- S-band and Ka-band tracking antennas for LEO satellites;
- SATCOM-On-The-Move (SOTM) antenna installed on the roof of a van.

The payload of ATHENE-1 will include a Laser Communication Terminal (LCT) for high-speed data up and downlinks [49]. The main goal is to demonstrate the feasibility of optical links for routine operations and investigate the optical channel. The ground segment of SeRANIS consequently comprises an Optical Ground Station (OGS) operating at high efficiency in the visible and in near-infrared wavelength range from 1000nm to 1700nm [50].

4. INITIAL RESULTS

The SeRANIS B5G testbed in Fig. 1 represents the network diagram of the complete planned infrastructure but, at the time of writing, only some parts are fully operational. However, this section provides initial results of ongoing research using current components of the SeRANIS testbed or data/measurements generated through it. The different nature of the proposed experiments shows the wide range of applications of the testbed.

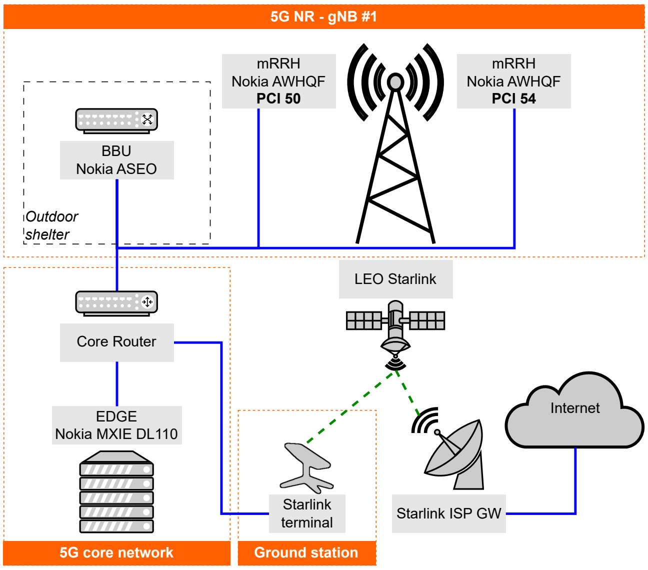

Fig. 6 – Diagram of the network under test.

4.1 First performance evaluation

This first network evaluation aims to collect passive and active measurements to determine the performance of the network. This evaluation considers a single BS with two antennas (network under test) operating with low transmission power to provide coverage over a limited area of the campus (area under test). Measurements are carried out using Rohde & Schwarz mobile network testing devices (devices under test) and the collected raw data is analyzed with customized Matlab scripts.

4.1.1 Network under test

The network under test considered for this first evaluation is a 5G SA network operating in the Frequency Range 1 (FR1), specifically in the 3GPP band n78, frequency range from 3.7 GHz to 3.8 GHz reserved for 5G private networks by the German telecommunications regulator [51]. The network operates in Time-Division Duplexing (TDD), allowing the use of the entire available spectrum in both downlink and uplink, but in separate time slots. The network is configured to transmit only one Synchronization Signal Block (SSB); therefore, it does not support beamforming, similar to an LTE network.

The 5G RAN component of the network under test consists of a single BS, the 5G gNB located in the southwestern part of the campus next to the satellite ground station. It consists of an outdoor shelter and a temporary mast pole of approximately 4 m in height. The planned final mast tower will instead have a height of 25 m. The top of the pole hosts two RRHs oriented at 110°N and 290°N respectively, with 0° mechanical and electric tilt. Each RRH embeds a 4-port cross-polarized directional antenna of approximately 10 dBi gain, a horizontal Half Power Beam Width (HPBW) of approximately 65°, and a

Table 1 – 5G gNB #1 main parameters.

Parameter	Sector 1	Sector 2
PCI	50	54
Antenna direction (°)	110	290
Antenna tilt (°)	0	0
Antenna gain (dBi)	10	10
Antenna horizontal HPBW (°)	65	65
Antenna vertical HPBW (°)	35	35
Antenna height (m)	4	4
Antenna power (dBm)	27	27
Center frequency (MHz)	3750	3750
Bandwidth (MHz)	100	100

vertical HPBW of approximately $35°$. Due to the limited height of the current pole, the RRHs are using a low power configuration, 27 dBm, to provide coverage only in the BS proximity and allow for preliminary measurements. The two RRHs are logically mapped into two different cells, identified by the Physical Cell ID (PCI)) 50 and 54. The main parameters of the 5G gNB #1 are summarized in Table 1.

The two RRHs are connected through optical fibers to the BBU installed inside the outdoor shelter. The BBU is connected to the core router that provides access to the 5G core component of the network and the Internet. Internet access is provided through a Starlink terminal including LEO satellites even before the launch of ATHENE-1. Fig. 6 shows a simplified network diagram of the network under test for this first evaluation.

4.1.2 *Area under test*

The area under test considered for this first evaluation is a 450 m footpath around the BS (Fig. 7 and Fig. 8b). Due to the limited height of the temporary pole, the east and south-east directions of the path have several obstructions that prevent the line-of-sight propagation, such as other shelters and the large parabolic dishes of the NTN teleport. The west and north-west directions of the path have obstructions due to the presence of trees. The measurement path starts from the BS traveling in an easterly direction. The estimated measurement time for a complete lap of the measurement path is approximately 6 min considering an average walking speed of 4.5 km/h.

4.1.3 *Devices under test*

The measurement devices utilized during this first evaluation are a complete Mobile Network Testing (MNT) solution from Rohde & Schwarz including a TSMA6 scanner and an Android QualiPoc smartphone. The scanner is controlled by the ROMES4 software, which performs passive measurements without being registered to the network. It can measure 5G NR SSBs and decode the Physical Broadcast Channel (PBCH) and Master Information Block (MIB) of each detected SSB [52]. Nevertheless, the QualiPoc device performs passive and active measurements. It can decode the protocol layers of the supported technologies, layer 3 (L3) text messages, Transmission Control Protocol/Internet Protocol (TCP/IP), Real-time Transport Protocol (RTP), and perform a range of service tests including call testing, voice quality, data testing, video streaming, and video quality [53].

Table 2 – Mapping between SS-RSRP values and RX status. Association between status and power values from practical considerations.

RX status	Value (dBm)
Excellent	$P_{RX}^{SS-RSRP} \geq -80$
Good	$-80 < P_{RX}^{SS-RSRP} \leq -90$
Poor	$-90 < P_{RX}^{SS-RSRP} \leq -100$
Very poor	$P_{RX}^{SS-RSRP} < -100$

4.1.4 *Measurement analysis*

This first evaluation of the network focuses on two analyses:

- Received power analysis using the Synchronization Signal Reference Signal Received Power (SS-RSRP) values;
- RTT and connectivity analysis using the results of ping test results.

The first analysis focuses on the SS-RSRP values measured by the TSMA6 and QualiPoc Android. The SS-RSRP is defined as the linear average over the power contributions of the resource elements that carry the SSB. 5G UE, such as smartphones, do measurements of SS-RSRP and use it for cell selection, cell reselection, power control, mobility procedures, and beam management procedures [54]. The analysis of the SS-RSRP values along the measurement path is crucial to understand the coverage and the performance of the BS. Table 2 maps the ranges of power values into receiver status groups to facilitate the graphical representation.

Fig. 7 shows the results of the SS-RSRP analysis. Figures 7a, 7b, and 7c are based on measurements carried out with the TSMA6, while Fig. 7d is based on measurements carried out with the QualiPoc Android device. In particular, Fig. 7a shows the SS-RSRP RX status of PCI 50 (sector 1). It is worth noting that PCI 50 presents excellent and good received power only for the initial part of the path, while the east/southeast direction presents degraded received power due to obstacles in the line-of-sight. Similar considerations can be done for Fig. 7b representing the SS-RSRP RX status of PCI 54 (sector 2). In this case, the sector provides excellent and good coverage in the west direction. A degradation of the received power is present behind the trees in the north-west direction. Considering the power values of the two sectors, Fig. 7c shows the best server analysis. It shows which PCI

Fig. 7 – Received power analysis using SS-RSRP values: (a) RF status according to Table 2 of PCI 50 recorded by the TSMA6; (b) RF status according to Table 2 of PCI 54 recorded by the TSMA6; (c) Best server visualization carried out using TSMA6 data; (d) Serving cell visualization extracted from QualiPoc data.

has the highest power values for each point of the path. This representation clearly shows two handover opportunities around positions P1 and P3. The latter observation is confirmed by the result in Fig. 7d. In this case, the figure shows the SS-RSRP of the serving cell, the cell on which the UE is camped [55]. It is worth noting that the south-eastern part of the measurement path has very poor received power from both PCI 50 and 54, which explains why the handover takes place in P2 and there is no service cell between P1 and P2.

The second analysis considers the results obtained with the active test set programmed on the Android QualiPoc device:

- Ten consecutive ping attempts toward a local server hosted in the outdoor shelter;
- Ten consecutive ping attempts toward a popular DNS server on the Internet.

Fig. 8 shows the results of the ping analysis. In particular, Fig. 8a shows a boxplot representation of the RTT, wherein in each box the central mark indicates the median, while the lower and upper edges of the box indicate the 25th and 75th percentiles, respectively. Whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using the '+' marker symbol [56]. The statistical analysis of the RTT shows a median value of 17.2 ms for the local server and a median value of 56.2 ms for the external server. The outliers are around 50 ms and 250 ms for the local and external servers, respectively. The achieved local RTT performance is aligned with the 5G NR latency observed in [57], while external RTT performance is aligned with the Starlink performance obtained in [58].

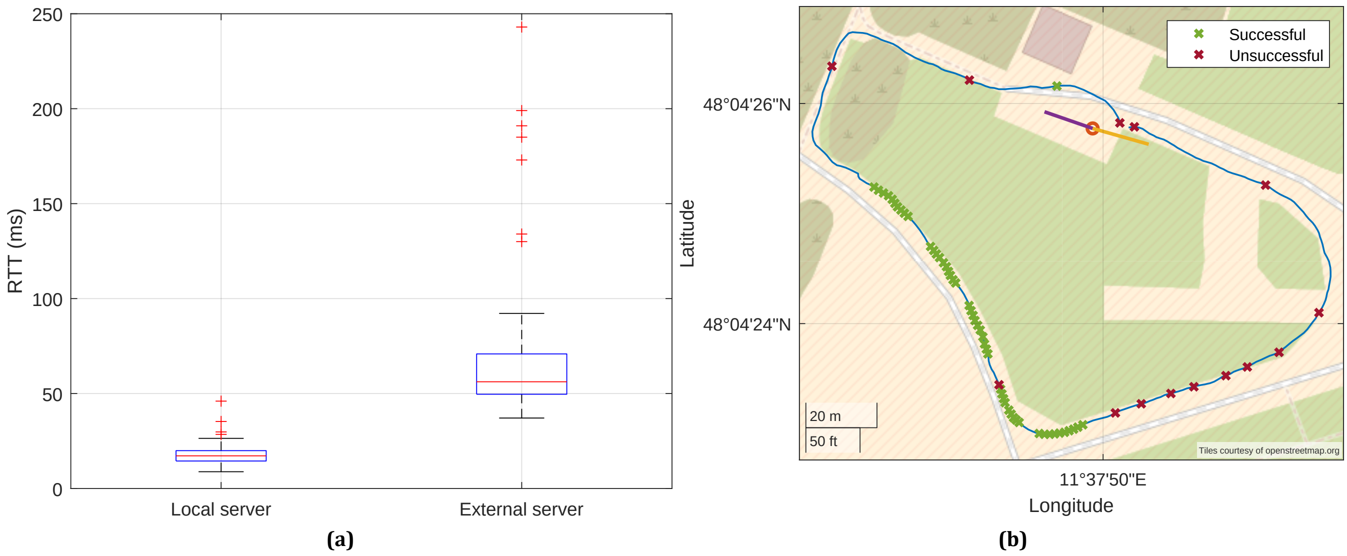

Fig. 8 – Round-Trip Time (RTT) and connectivity analysis using the ping tool: (a) Boxplot representation of the RTT measurements for the local and external server; (b) Mapping of the ping attempts on the measurement path.

Fig. 8b maps the successful and unsuccessful ping attempts on the measurement path. This graphical representation shows interesting results for the test of the network under test. Although the SS-RSRP analysis shows a good power level in the first part of the measurement path (Fig. 7a), Fig. 8b highlights the problematic behavior of the PCI 50 (sector 1). The analysis shows that there are no successful ping attempts when PCI 50 is the serving cell (Fig. 7d). Investigating the layer 3 messages exchanged between the UE and the BS, the problem lies in the establishment of the Radio Resource Control (RRC) connection. The UE successfully establishes an RRC connection but immediately starts a new connection request. While for some parts of the measurement path, especially in the east/south-east direction, this behavior could be explained by the low received power due to the current state of the network under investigation, the erratic behavior in the first and last parts of the measurement path needs to be thoroughly investigated to understand the possible reasons.

4.2 Edge test with high latency

In a previous paper [59], we presented a proof-of-concept test that investigates the potential of a localized 5G UPF installed at the gNB to reduce the latency and increase broadband of the UE to the core network in a 5G NTN. The latency and user throughput were measured using user datagram and transmission control transport protocols. The experiments were performed in our 5G lab featuring various vendor and open-source tools. Two different testbed setups were used to carry out experiments, Fig. 9a presents the testbed without satellite backhaul, while Fig. 9b presents the testbed with satellite backhaul. Three offloading scenarios were considered: local core, the gNB and 5G core are started on the same local PC; central UPF, the gNB is started on the local PC while the core functions are started on a remote PC; edge UPF, the gNB and edge UPF are started on the local PC while the other core functions are started on the remote PC.

The Transmission Control Protocol (TCP) uplink and downlink throughput for the three offload configurations with and without LEO satellite backhaul is presented in Fig. 10. For the downlink results shown in Fig. 10, we observed a significant drop in throughput for the central UPF configuration compared to the other two configurations in the presence of the LEO satellite, and this is due to the large delay and increased contention introduced in the channel by the satellite backhaul. For the uplink result, we also observed a similar trend in the results, where the central UPF performs worse than the other two offload configurations. However, the edge UPF result is comparable to the local core result. Hence, by simply moving a network function (UPF in this case), one can achieve the same throughput results as if the entire core functions were installed locally.

The results presented show the application of MEC in satellite non-terrestrial networks. However, an edge UPF alone is not enough for optimal results at the edge, especially when routing to an application installed at the central core side (see latency results in [59]). The application of an edge application close to the edge UPF can help mitigate the issue of the large transmission time between the UE to Google server. Further experiments will consider the application of MEC in remote areas, for public protection, or during a disaster e.g. for positioning applications so that users who may be displaced during a natural disaster can be easily located.

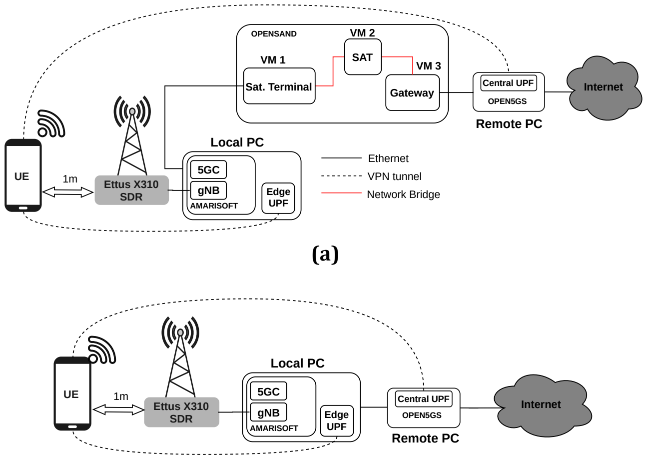

Fig. 9 – Testbed: (a) LEO satellite backhauling; (b) Terrestrial backhauling.

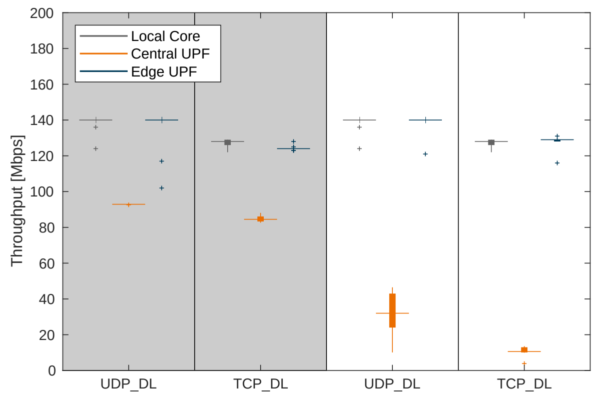

Fig. 10 – TCP downlink and uplink throughput for the different offloading scenarios. The gray area represents results without LEO satellite, while the white area represents results with LEO satellite.

4.3 C-band interference at SGSs

With the scarcity of the radio frequency spectrum, there has been an increasing focus on the coexistence of different technologies within the same frequency range. As discussed in the introduction, an example of this is the allocation of the 3.3 - 4.2 GHz band, which is commonly used for satellite communications, to 5G NR [16]. Various studies raised concerns regarding the interference at SGSs [17, 18, 19, 20, 21, 60]. In a previous work, we focused on the cancellation of the SSBs of 5G as the first step. The short burst nature of the SSB blocks poses a challenge for the adaptive cancellation algorithms. We have shown that the information carried on the SSB can be used to overcome this challenge. The pilot symbols in the SSBs can be used to improve the slow convergence speed of the Least Mean Squares (LMS) filter by initializing the filter based on the channel estimates. Moreover, the number of interfering BSs can also be estimated using the pilot symbols in the SSBs. We considered a scenario where the signals transmitted from N BS antennas cause interference at the SGSs. M reference antennas are placed around the SGS to capture the interfering signals from the BSs. We assumed that the satellite signal was only received at the SGS. The considered scenario is depicted in Fig. 11.

The interference cancellation approach was based on the LMS filter. We exploited the physical layer properties of the SSBs and the information they carry to improve the performance of the LMS filter. The steps followed to cancel the 5G SSB interference at the SGS were as follows:
Step 1, Timing & Frequency Offset Correction: The Primary Synchronization Signal (PSS) is used to synchronize the received signals in time and frequency;
Step 2, Cell ID Search: The Secondary Synchronization Signal (SSS) is used to estimate the number of interfering BSs. This can be done since the combination of PSS and SSS results yields a specific N_{ID}^{cell} for each interferer;
Step 3, Channel Estimation: The channel estimate is calculated;
Step 4, Initialization of the LMS filter: An estimate of the optimal filter weights is calculated and the LMS filter is initialized using the optimal weights;
Step 5, Filtering: Finally, the time and frequency synchronized signals are passed through the LMS filter to cancel the interference.

To test the proposed approach in practice, we used the signals we recorded at our SGS before the initial deployment of the testbed. Our results showed that there is a significant gain to be obtained by initializing the adaptive filter based on the channel estimates calculated using the pilot symbols in the SSBs, as seen in Fig. 12.

As explained above, in the case of SSB interference, the information carried in the SSBs can be exploited for interference cancellation. A considerable improvement is achieved by using the pilot symbols in the SSBs to estimate the channel and initialize the interference cancellation filter. When we expand this work to user signals, however, the pilot symbols are user-specific and unknown at the SGS. Due to this reason, the interference cancellation approach at the SGS needs to resort to blind channel estimation algorithms.

Ongoing work as part of the SeRANIS testbed is the extension of the described interference cancellation approach to user signals using blind channel estimation algorithms, specifically, the noise subspace-based method. Shin et al. [61], outlined conditions for establishing channel identifiability and introduced a blind channel estimation technique based on the noise subspace method for MIMO-Orthogonal Frequency Division Multiplexing (OFDM) systems. In their methodology, the autocorrelation matrix of the received signal is estimated by aggregating multiple blocks of received OFDM symbols. However, due to the necessity for a considerable number of samples for accurate autocorrelation matrix estimation, the algorithm

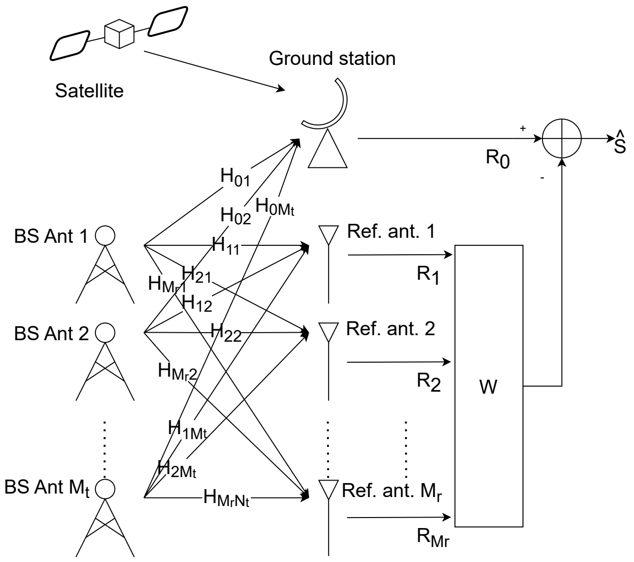

Fig. 11 – Considered scenario: Reference antennas are used to capture the interference from the BSs; Reference signals are multiplied with the appropriate weights and subtracted from the signal at SGS to cancel the interference.

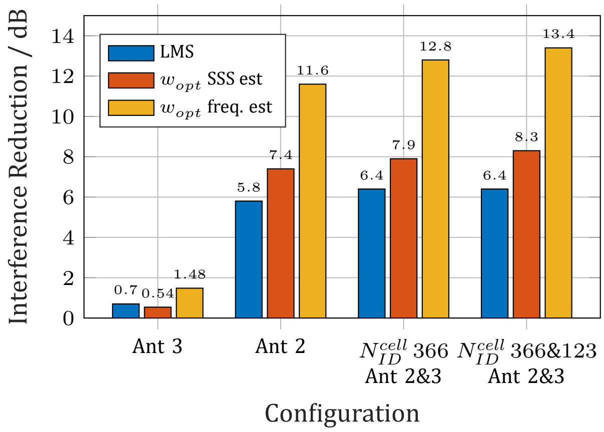

Fig. 12 – Interference reduction performance using different reference antennas and N_{ID}^{cell} configurations

converges slowly. To address this issue, [62] proposed to use a small sliding window over the received OFDM symbols to increase the number of equivalent symbols and use them to estimate the autocorrelation matrix. This increases the convergence speed at the cost of accuracy. For the interference cancellation problem, we exploit the ideas provided in [61] and [62] to come to an approach that quickly converges while preserving the accuracy of the estimation.

In Fig. 13, the simulation results are shown for the interference cancellation achieved using the modified blind channel estimation algorithm compared to [61] and [62]. The scenario consists of a single BS and two reference antennas. Here, J refers to the window size used for the calculation of the autocorrelation matrix in terms of OFDM symbols in [61] and G refers to the window size used for the calculation of autocorrelation matrix in terms of samples in [62]. γ_{xs} refers to the 5G signal-to-satellite-signal ratio. For the simulations, the 5G signal-to-noise ratio was set to 20 dB. Given enough time, [61] with $J = 2$ achieves a performance close to the scenario where the channels are known. However, it converges slowly and if the channel is not constant for long enough, its performance is limited. Setting $J = 1$ improves the convergence speed since there are twice as many OFDM blocks used for the calculation of the autocorrelation matrix compared to the $J = 2$ case. The drawback with $J = 1$ is that the interference reduction for a long coherence time is significantly degraded. The method in [62] increases the number of OFDM blocks even further by partitioning the received signal into smaller blocks. In this case, the number of OFDM blocks used for the calculation of autocorrelation matrix is increased even further compared to $J = 1$. Consequently, the convergence speed of the algorithm is even faster at the cost of accuracy. With our approach, a sweet spot between [61] and [62] can be achieved as seen from the blue curves. The convergence of our modified algorithm is quick and it offers a performance very close to the cancellation with perfect channel knowledge which is represented with the dotted flat line.

5. PLANNED EXPERIMENTS

This section provides an overview of the planned experiments involving various aspects related to the integration of TN and NTN, the coexistence of 5G TNs and satellite ground stations, and peculiar problems for the coexistence of 5G public and non-public networks. Some of the planned experiments will benefit greatly from the launch of the ATHENE-1 satellite.

5.1 Satellite-to-device communication and backhauling

The ATHENE-1 satellite will enable testing of two important use cases of integrated terrestrial and non-terrestrial networks. The first use case is satellite-to-device communication, in other words, direct connectivity between a gNB and a terrestrial UE. Satellite-to-device communication will be demonstrated using the Ka-band digital-transparent payload of the ATHENE-1 and the adapted OAI protocol stack for NTN [45]. Both UE and satellite gNB will be based on open-source software that can run on x64-based Linux computers. Such a scenario with a broadband Ka-band link is particularly relevant for the automotive sector. Moreover, satellite-to-device communication will be also demonstrated for IoT applications using the UHF and S-band payload of the satellite [6].

The other important use case is LEO satellite backhauling. In mobile communication networks backhauling generally refers to the connection between the core network and the RAN and is typically implemented with a fiber connection. Satellite backhauling is a solution to extend the coverage of mobile networks where fiber and point-to-point microwave links are difficult to implement. It

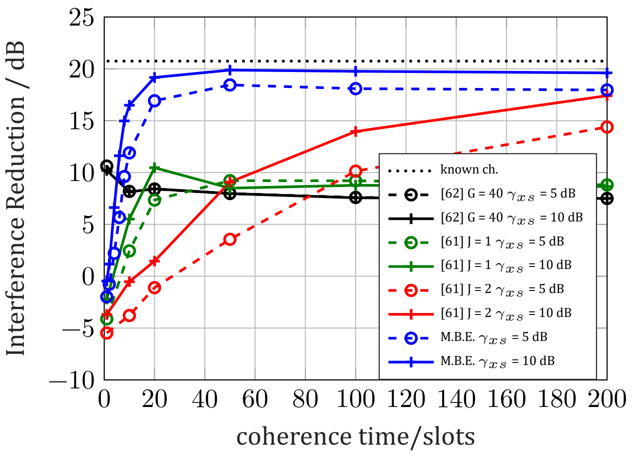

Fig. 13 – Comparison of [61], [62] and the described modification. γ_{xv} is set to 20 dB, M_r = 2 and M_t = 1.

allows the creation of mobile "pop-up" networks, which are crucial in emergency or disaster recovery scenarios. High-speed LEO backhauling solutions will be demonstrated using the ATHENE-1 satellite. Along with the Ka-band communication link, the experimental free-space optical link will be tested to achieve a target 1 Tb/s in the downlink and 100 Mb/s in the uplink [50].

The success of these two demonstrations will set the stage for development and testing of other 5G and B5G use cases.

5.2 Disaster relief using MEC and NTN

As discussed in the introduction, disaster relief provision via satellite backhaul emerges as a practical implementation of MEC in NTN 5G networks. Very limited literature exists that has addressed the use of MEC in a 5G satellite-terrestrial network for PPDR. A PPDR testbed was used in [63] to demonstrate that a 4G/5G mobile network could be effectively augmented with a satellite network using a core-edge split concept. The authors concluded that the distribution of EPC components achieves an integrated satellite-terrestrial network architecture that fulfills the needs of government agencies and emergency responders. Due to the flexibility and distribution of 5G core architecture to be deployed at the edge of the network, it is more suited for public protection and disaster control. Our previous work [59] details the advantage of an edge UPF in a satellite-terrestrial network with distributed 5G core functions. However, we observed that the edge UPF alone was not sufficient to deal with applications at the central side and hence we propose that an edge application be positioned close to the gNBs and users, and this is useful to serve in situations of public safety or during a disaster to provide first responders and relief. Our testbed leverages a location application server positioned at the edge UPF.

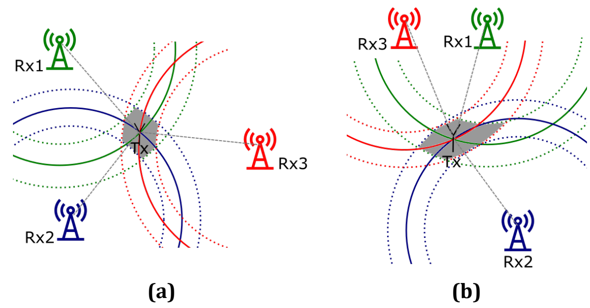

Fig. 14 – BS locations' effect on positioning accuracy.

5.3 Positioning and localization

As discussed in Section 1, TDoA emerges as the most suitable candidate for precise positioning within our network. However, it is important to acknowledge that the performance of TDoA positioning is influenced by multiple factors, which can be fine-tuned to enhance its accuracy significantly.

This study aims to shed light on two pivotal factors that impact positioning accuracy in 5G networks. The first factor is the installation positions of BSs within an indoor environment. As detailed in [64], we conducted an investigation into the effect of BS locations on TDoA accuracy in various simulated environments. The conclusion drawn from this investigation was that Geometric Dilution of Precision (GDoP) calculations can serve as a viable alternative to time and power-intensive simulations. In Fig. 14, we illustrate two distinct setups of three BSs, namely Rx1, Rx2, and Rx3, which are utilized to estimate the position of the target, Tx. The gray area depicted in the figure represents the positional ambiguity arising from noise variance, commonly referred to as GDoP. The gray area size and shape illustrate how moving only one BS, Rx3, in, otherwise, the same setup can degrade the positioning accuracy. This opens the door to investigate how different BS constellations can result in different positioning accuracy, and how the optimization process proposed in [64] can be utilized in a real-life implementation to get the optimum BS constellation to achieve higher accuracy.

After the establishment of the SeRANIS B5G testbed with both its indoor and outdoor components, a validation of the GDoP approach and the simulation outcomes from [64] can be performed through a measurement campaign conducted exclusively within the indoor segment of the network. Furthermore, the inclusion of a sufficient number of outdoor BSs enables the assessment of TDoA positioning performance, facilitating the creation of accuracy maps. These maps can then be compared with simulated GDoP accuracy maps, thereby facilitating comparative analysis of the outdoor and indoor accuracy levels. This comparative study aims to investigate the influence of various parameters, such as multipath propagation and shadowing, on positioning accuracy and verify their alignment with the GDoP model.

The second factor that would be investigated is the combined positioning estimation using GNSS and 5G. In [65], an investigation and measurement campaign was conducted for Time of Arrival (ToA) estimation in LTE. A similar experiment can be done with TDoA instead of ToA using our 5G network instead of the LTE public network where we have more control over the different training and control signals. Furthermore, an experiment combining 5G and GNSS will be implemented. A 5G positioning system can be seamlessly integrated into the Multi-Sensor Navigation Analysis Tool (MuSNAT) GNSS software receiver, thereby facilitating a holistic and high-precision positioning solution that leverages the strengths of both technologies. This integration holds promise for advancing the state-of-the-art in positioning accuracy and expanding the applications of multi-sensor navigation systems.

In addition, the ATHENE-1 satellite can be exploited for new hybrid positioning and localization approaches. The satellite could embed ephemeris data into broadcast signals. Ephemerides provide information about the satellite's position relative to the Earth, with respect to time. By decoding and measuring the signals transmitted by the satellite together with signals from terrestrial BSs, new hybrid location and positioning approaches could be tested.

5.4 Handover

Our B5G testbed encompasses multiple BSs, covering a car track on our UniBw M campus in Neubiberg that allows for high-speed mobility tests. The experimental setup includes a moving vehicle equipped with a UE and connected to the 5G network. The UE will be programmed to initiate a continuous data transmission while traversing the track and crossing two cells of the same gNB or two cells of different gNBs, simulating handover scenarios where the user is engaged in a bandwidth-intensive activity. Moreover, the satellite-to-device communication capability of the ATHENE-1 can be used in a similar scenario. While the car is traveling along the predefined path the serving cell of the terrestrial gNB is deactivated, forcing a handover to the satellite gNB. Handover could also be tested between two terrestrial cells in which one of the cells belongs to a gNB with satellite backhauling.

To evaluate the handover Key Performance Indicators (KPIs), we will focus on several performance metrics, including handover latency, packet loss, and service continuity. Handover latency will be measured as the time required to complete the handover process, including the time to detect and initiate the handover, transmit control signaling, and resume data transmission. Packet loss will be assessed by monitoring the number of lost packets during the handover process. Additionally, we will examine the impact of handover on service continuity, ensuring that the user experiences minimal disruption in

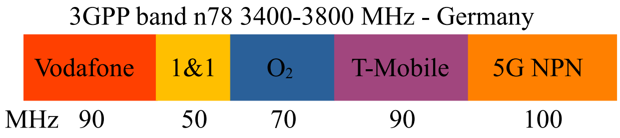

Fig. 15 – 3GPP band n78 3400-3800 MHz Germany frequency plan.

ongoing applications and services. This experiment aims to provide valuable insights into the performance of handover procedures in 5G and B5G networks. By evaluating the handover KPIs under challenging mobility scenarios, we can identify potential bottlenecks.

5.5 C-band interference at SGSs

The work in Section 4.3 will be extended in the future for the cancellation of the user signals. The main difference with the user signals will be the unavailability of the pilots in the SSB. Since the DM-RS symbols for user signals are user specific, a third party is not able to estimate the channel by using the DM-RS. Different channel estimation such as blind methods need to be utilized. The deployment of the SeRANIS B5G testbed will provide a more controlled test environment where we can transmit arbitrarily configured PDSCH signals with a different number of streams, power and bandwidth. This will enable us to test alternative approaches to cancel the user signals. Moreover, we will conduct further interference measurements and develop interference management and cancellation strategies in a real-world scenario.

5.6 Uplink degradation

The German frequency plan in the 3GPP band n78 3400 MHz to 3800 MHz is shown in Fig. 15. The first 300 MHz of the available spectrum is assigned to four public national operators, while the last 100 MHz is reserved for private local operators. To avoid potential interference situations, the deployment of multiple 5G TDD networks requires synchronization of adjacent networks. In particular, operators have to agree on a compatible frame structure. The GSM Association (GSMA) provides guidelines and recommendations for the coexistence of TDD networks in the 3.5 GHz band [66]. Regarding the frame structure, in which D, U, and S represent downlink, uplink, and special slots, respectively, two alternatives are recommended: DDDDDDDSUU for coexistence with existing LTE TDD networks, or DDDSUUDDDD for coexistence with other 5G TDD networks. Both frame structures take into account an asymmetric, downlink intense traffic pattern, an assumption typical of public networks based on the enhanced Mobile Broadband (eMBB) use cases. Unlike public networks, NPNs have different requirements. A more balanced or uplink-oriented TDD configuration should be considered [67] in use cases that require higher uplink capacity and lower latency.

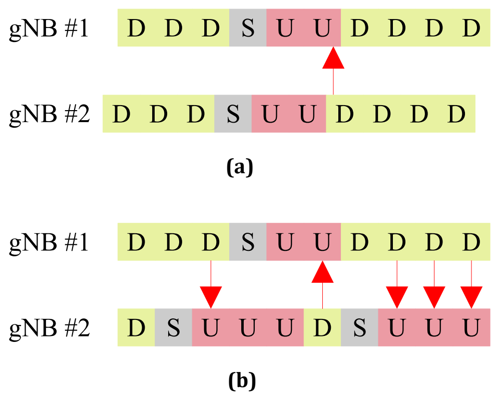

Fig. 16 – Operative examples with TDD configurations: (a) Frame misalignment due to a synchronization problem; (b) Downlink and uplink mismatch problem.

Although different networks operate in separate frequency ranges, shoulder and spurious emissions, and intermodulation products can affect uplink performance in the case of unsynchronized networks or different TDD configurations. This problem was already present in previous generations of TDD networks, but the use of Active Antenna Systems (AASs) to enable beamforming in the 5G network increases the problem [68]. AASs embed a large number of passive antennas together with active electronic components, reducing cable losses. Incorporating multiple bandpass filters for the multitude of passive elements would drastically increase the weight and cost of AASs, so it is not practical.

Due to the relevance of the problem in 5G networks, two experiments are planned in the SeRANIS B5G testbed. The experiments consider two gNBs operating in two adjacent frequency ranges within the assigned spectrum, e.g., 3730 MHz to 3750 MHz and 3750 MHz to 3770 MHz. In the first experiment, the two gNBs operate with the same TDD configuration but are not synchronized (Fig. 16a). In the second experiment, the two gNBs are synchronized but with different TDD configurations, one oriented to the downlink and the other to the uplink (Fig. 16b). The objective of these experiments is to quantify the uplink degradation, investigate and test solutions to mitigate its impact. The uplink degradation will be characterized as a function of different system parameters. The SeRANIS B5G testbed offers several alternatives for implementing these experiments. The two gNBs could be implemented with two fixed BSs of the 5G RAN, or with a fixed BS and the 5G on-the-move solution (Fig. 3), allowing uplink degradation to be characterized in a multitude of different scenarios. In addition, the use of a flying gNB with a drone in the UAV restricted zone can provide important insights into the uplink degradation problem in the coexistence scenario with HAPSs and terrestrial BSs.

6. CONCLUSION

The B5G and 6G testbed of the UniBw M is an important part of the Seamless Radio Access Networks for Internet of Space (SeRANIS), a small satellite mission that aims to provide a publicly accessible multifunctional experimental laboratory in orbit serving as a platform for different experiments. The Seamless Radio Access Networks for Internet of Space (SeRANIS) B5G and 6G testbed comprises both space and ground segments. The space segment of the testbed is composed of the ATHENE-1 satellite. It consists of a platform with a mass of around 250 kg, which carries the 90 kg of experimental payload developed at the UniBw M that is going to be launched in 2025. The ground segment includes a ground station and the TN component of the testbed. The ground station considers several full motion antennas for the radiofrequency links and an optical ground station for the free-space optical link based on laser technology, while the TN component is deployed using a 5G NPN with multiple gNBs and multiple 5G core solutions. The full ground segment deployment is expected during 2024. While the design of the ATHENE-1 payload and the deployment of the ground segment are ongoing, our research is focusing on several aspects including the integration of TN and NTN, coexistence between 5G TNs and satellite ground stations, and peculiar problems for the coexistence of 5G public and non-public networks. This paper describes the components of the testbed, the current status, future deployment plan, preliminary test results, and planned tests. The unique capabilities of the Seamless Radio Access Networks for Internet of Space (SeRANIS) B5G testbed introduced in this paper will enable testing and evaluation of emerging 5G and 6G use cases and applications. The ultimate goal of testbed is to support the UniBw M research and create an open environment for the entire research and development community.

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REFERENCES

[1] Xingqin Lin, Björn Hofström, Eric Wang, Gino Masini, Helka-Liina Maattanen, Henrik Rydén, Jonas Sedin, Magnus Stattin, Olof Liberg, Sebastian Euler, Siva Muruganathan, Stefan Eriksson G., and Talha Khan. *5G New Radio Evolution Meets Satellite Communications: Opportunities, Challenges, and Solutions*. arXiv:1903.11219. 2019. arXiv: `1903.11219 [cs.NI]`.

[2] Xingqin Lin, Stefan Rommer, Sebastian Euler, Emre A. Yavuz, and Robert S. Karlsson. "5G from Space: An Overview of 3GPP Non-Terrestrial Networks". In: *IEEE Communications Standards Magazine* 5.4 (2021), pp. 147–153. DOI: 10.1109/MCOMSTD.011.2100038.

[3] Mohamed El Jaafari, Nicolas Chuberre, Stephane Anjuere, and Laurent Combelles. "Introduction to the 3GPP-defined NTN standard: A comprehensive view on the 3GPP work on NTN". In: *International Journal of Satellite Communications and Networking* January (2023), pp. 220–238. ISSN: 15420981. DOI: 10.1002/sat.1471.

[4] Hayder Al-Hraishawi, Mario Minardi, Houcine Chougrani, Oltjon Kodheli, Jesus Fabian Mendoza Montoya, and Symeon Chatzinotas. "Multi-Layer Space Information Networks: Access Design and Softwarization". In: *IEEE Access* 9 (2021), pp. 158587–158598. ISSN: 21693536. DOI: 10 . 1109 / ACCESS . 2021 . 3131030. arXiv: 2110.08031.

[5] Mustafa Ozger, Istvan Godor, Anders Nordlow, Thomas Heyn, Sreekrishna Pandi, Ian Peterson, Alberto Viseras, Jaroslav Holis, Christian Raffelsberger, Andreas Kercek, Bengt Mölleryd, Laszlo Toka, Gergely Biczok, Robby de Candido, Felix Laimer, Udo Tarmann, Dominic Schupke, and Cicek Cavdar. "6G for Connected Sky: A Vision for Integrating Terrestrial and Non-Terrestrial Networks". In: Ml (2023). arXiv: 2305 . 04271. URL: http : / / arxiv.org/abs/2305.04271.

[6] Artur Kinzel, Johannes Bachmann, Rishi Jaiswal, Manohar Karnal, Ernesto Novo, Francesco Porcelli, Alexander Schmidt, Robert Schwarz, C.A. Hofmann, Roger Förstner, and A. Knopp. "Seamless Radio Access Network for Internet of Space (SeRANIS): New Space Mission for Research, Development, and In-Orbit Demonstration of Cutting-Edge Technologies". In: *International Astronautical Congress 2022*. Sept. 2022.

[7] 3GPP. *Non-Public Networks (NPN)*. URL: https : / / www . 3gpp . org / technologies / npn (visited on July 7, 2023).

[8] Zhenjiang Zhang, Wenyu Zhang, and Fan Hsun Tseng. "Satellite Mobile Edge Computing: Improving QoS of High-Speed Satellite-Terrestrial Networks Using Edge Computing Techniques". In: *IEEE Network* 33 (1 Jan. 2019), pp. 70–76. ISSN: 1558156X. DOI: 10.1109/MNET.2018.1800172.

[9] Milan Patel, Yunchao Hu, Patrice Hédé, Jerome Joubert, Chris Thornton, Brian Naughton, Julian, Roldan Ramos, Caroline Chan, Valerie Young, Soo Jin Tan, Daniel Lynch, Sadayuki Abeta, Lan Chen, Kenji Shimizu, Adrian Neal, Peter Cosimini, Adam Pollard, and Guenter Klas. "Mobile-Edge Computing – Introductory Technical White Paper". In: (). eprint: https://portal.etsi.org/portals/0/tbpages/mec/docs/mobile-edge_computing_-_introductory_technical_white_paper_v1%2018-09-14.pdf. URL: https://portal.etsi.org/portals/0/tbpages/mec/docs/mobile-edge_computing_-_introductory_technical_white_paper_v1%2018-09-14.pdf.

[10] FCC. *Wireless E911 Location Accuracy Requirements*. Compliance Guide 07-114. Federal Communications Commission, June 2020.

[11] EU. *European Electronic Communications Code*. Compliance Guide L321. European Union (EU), Dec. 2020.

[12] 3GPP. *5G; NG Radio Access Network (NG-RAN); Stage 2 functional specification of User Equipment (UE) positioning in NG-RAN*. Technical Specification (TS) 38.305. Version 17.5.0. 3rd Generation Partnership Project (3GPP), July 2023.

[13] Kavi Kumar Khedo Arvind Ramtohul. "Mobile Positioning Techniques and Systems: A Comprehensive Review". In: *Mobile Information Systems* 2020 (2020). DOI: 10.1155/2020/3708521. URL: https://www.hindawi.com/journals/misy/2020/3708521/.

[14] 3GPP. *5G; Management and orchestration; 5G end to end Key Performance Indicators (KPI)*. Technical Specification (TS) 38.305. Version 17.10.0. 3rd Generation Partnership Project (3GPP), July 2023.

[15] Aleksi Peltonen, Ralf Sasse, and David Basin. "A comprehensive formal analysis of 5G handover". In: *Proceedings of the 14th ACM Conference on Security and Privacy in Wireless and Mobile Networks*. 2021, pp. 1–12.

[16] 3GPP. *NR; User Equipment (UE) radio transmission and reception; Part 1: Range 1 Standalone*. Tech. rep. 38.101. 3GPP, 2022.

[17] A.H. van den Ende, H. Dekker, P.H. Trommelen, Y. Toh, K. Das, R. Djapic, B. Devecchi, V. Voogt, P.Ch. Hoefsloot, J. van den Oever, and E. Gandini. *Coexistence of 5G mobile networks with C-Band Satellite Interception in Burum*. Tech. rep. TNO 2018 R11156. TNO, 2018.

[18] Ho-Kyung Son and Young-Jun Chong. "Coexistence of 5G system with Fixed satellite service Earth station in the 3.8GHz Band". In: *International Conference on Information and Communication Technology Convergence (ICTC)*. 2018, pp. 1070–1073. DOI: 10.1109/ICTC.2018.8539462.

[19] Xinxin Miao and Mingchuan Yang. "Co-channel Interference Between Satellite and 5G System in C Band". In: *Machine Learning and Intelligent Communications*. Springer International Publishing, 2021, pp. 410–416. ISBN: 978-3-030-66785-6.

[20] Haifeng Tan, Yanjie Liu, Zhiyong Feng, and Qixun Zhang. “Coexistence analysis between 5G system and fixed-satellite service in 3400–3600 MHz”. In: *China Communications* 15.11 (2018), pp. 25–32. DOI: 10.1109/CC.2018.8543046.

[21] Abdulmajeed Al-Jumaily, Aduwati Sali, Vćtor P. Gil Jiménez, Fernando Pérez Fontán, Mandeep Jit Singh, Alyani Ismail, Qusay Al-Maatouk, Ali M. Al-Saegh, and Dhiya Al-Jumeily. “Evaluation of 5G Coexistence and Interference Signals in the C-Band Satellite Earth Station”. In: *IEEE Transactions on Vehicular Technology* 71.6 (2022), pp. 6189–6200. DOI: 10.1109/TVT.2022.3158344.

[22] Mona Ghassemian, Paul Muschamp, and Dan Warren. *Experience Building A 5G Testbed Platform*. 2020. DOI: 10.48550/ARXIV.2008.01628. URL: https://arxiv.org/abs/2008.01628.

[23] Fraunhofer FOKUS. *NGNI 5G Playground*. 2023. URL: https://www.fokus.fraunhofer.de/go/en/fokus_testbeds/5g_playground (visited on Jan. 31, 2023).

[24] Fraunhofer Institute for Production Technology IPT. *5G-Industry Campus Europe*. 2023. URL: https://5g-industry-campus.com/ (visited on Jan. 31, 2023).

[25] Sachinkumar Bavikatti Mallikarjun, Christian Schellenberger, Christopher Hobelsberger, and Hans Dieter Schotten. “Performance Analysis of a Private 5G SA Campus Network”. In: *Mobile Communication - Technologies and Applications; 26th ITG-Symposium*. 2022, pp. 1–5.

[26] Justus Rischke, Peter Sossalla, Sebastian Itting, Frank H. P. Fitzek, and Martin Reisslein. “5G Campus Networks: A First Measurement Study”. In: *IEEE Access* 9 (2021), pp. 121786–121803. DOI: 10.1109/ACCESS.2021.3108423.

[27] Bjoern Halvarsson, Arne Simonsson, Anders Elgcrona, Ranvir Chana, Paulo Machado, and Henrik Asplund. “5G NR Testbed 3.5 GHz Coverage Results”. In: *2018 IEEE 87th Vehicular Technology Conference (VTC Spring)*. 2018, pp. 1–5. DOI: 10.1109/VTCSpring.2018.8417704.

[28] Daisuke Kurita, Kiichi Tateishi, Atsushi Harada, Yoshihisa Kishiyama, Shoji Itoh, Hideshi Murai, Arne Simonsson, and Peter Okvist. “Indoor and Outdoor Experiments on 5G Radio Access Using Distributed MIMO and Beamforming in 15 GHz Frequency Band”. In: *2016 IEEE Globecom Workshops (GC Wkshps)*. 2016, pp. 1–6. DOI: 10.1109/GLOCOMW.2016.7848932.

[29] Kjell Larsson, Bjoern Halvarsson, Damanjit Singh, Ranvir Chana, Jawad Manssour, Minsoo Na, Changsoon Choi, and Sungho Jo. “High-Speed Beam Tracking Demonstrated Using a 28 GHz 5G Trial System”. In: *2017 IEEE 86th Vehicular Technology Conference (VTC-Fall)*. 2017, pp. 1–5. DOI: 10.1109/VTCFall.2017.8288043.

[30] 5G Test Network Finland (5GTNF). *Overview*. 2023. URL: https://5gtnf.fi/overview/ (visited on June 28, 2023).

[31] Joe Breen, Andrew Buffmire, Jonathon Duerig, Kevin Dutt, Eric Eide, Mike Hibler, David Johnson, Sneha Kumar Kasera, Earl Lewis, Dustin Maas, Alex Orange, Neal Patwari, Daniel Reading, Robert Ricci, David Schurig, Leigh B. Stoller, Jacobus Van der Merwe, Kirk Webb, and Gary Wong. “POWDER: Platform for Open Wireless Data-Driven Experimental Research”. In: *Proceedings of the 14th International Workshop on Wireless Network Testbeds, Experimental Evaluation & Characterization*. 2020, pp. 17–24. DOI: 10.1145/3411276.3412204. URL: https://doi.org/10.1145/3411276.3412204.

[32] Dipankar Raychaudhuri, Ivan Seskar, Gil Zussman, Thanasis Korakis, Dan Kilper, Tingjun Chen, Jakub Kolodziejski, Michael Sherman, Zoran Kostic, Xiaoxiong Gu, Harish Krishnaswamy, Sumit Maheshwari, Panagiotis Skrimponis, and Craig Gutterman. “Challenge: COSMOS: A City-Scale Programmable Testbed for Experimentation with Advanced Wireless”. In: *Proceedings of the 26th Annual International Conference on Mobile Computing and Networking*. 2020. DOI: 10.1145/3372224.3380891. URL: https://doi.org/10.1145/3372224.3380891.

[33] Theoni Magounaki, Florian Kaltenberger, and Raymond Knopp. “Real-time Performance Evaluation of Relative Calibration on the OAI 5G testbed”. In: *2019 53rd Asilomar Conference on Signals, Systems, and Computers*. 2019, pp. 564–568. DOI: 10.1109/IEEECONF44664.2019.9048761.

[34] Georgios Gardikis, Nikos Papadakis, Andreas Perentos, Marios Fotiou, Alexandros Phinikarides, Michael Georgiades, Luc Ottavj, Mamoutou Diarra, Thierry Masson, António J. Morgado, Shahid Mumtaz, Jara S. de Puga, Carlos E. Palau, Charalampos Skiadasn, Harilaos Koumaras, and Michail Alexandros Kourtis. “The 5GENESIS testing facility as an enabler for integrated satellite/terrestrial 5G experimentation”. In: *2019 IEEE Wireless Communications and Networking Conference Workshop (WCNCW)*. 2019, pp. 1–6. DOI: 10.1109/WCNCW.2019.8902802.

[35] Oltjon Kodheli, Jorge Querol, Abdelrahman Astro, Sofia Coloma, Loveneesh Rana, Zhanna Bokal, Sumit Kumar, Carol Martinez Luna, Jan Thoemel, Juan Carlos Merlano Duncan, Miguel Angel Olivares Mendez, Symeon Chatzinotas, and Bjorn Ottersten. “5G Space Communications Lab: Reaching New Height”. In: *18th International Conference on Distributed Computing in Sensor Systems (DCOSS)*.

2022, pp. 349–356. DOI: 10.1109/DCOSS54816.2022.00063.

[36] Mehmet Ariman, Mertkan Akkoç, Talip Tolga Sari, Muhammed Raşit Erol, Gökhan Seçinti, and Berk Canberk. "Energy-efficient RL-based aerial network deployment testbed for disaster areas". In: *Journal of Communications and Networks* 25.1 (2023), pp. 25–34. DOI: 10.23919/JCN.2022.000057.

[37] ESA CSC. *ESA 5G/6G Hub*. en. URL: https://connectivity.esa.int/esa-5g6g-hub (visited on Feb. 19, 2023).

[38] ESA CSC. *Opportunity: 6G satellite precursor - sterling in-orbit laboratory*. en. URL: https://connectivity.esa.int/opportunity-6g-satellite-precursor-sterling-inorbit-laboratory (visited on Feb. 19, 2023).

[39] ESA CSC. *ESA signs memorandum of intent with Seranis to collaborate and experiment with 5G and 6G NTN Communications*. en. URL: https://connectivity.esa.int/news/esa-signs-memorandum-intent-seranis-collaborate-and-experiment-5g-and-6g-ntn-communications.

[40] *6G Research Hub*. en-US. URL: https://seranis.de/en/6g-research-hub/ (visited on Apr. 5, 2023).

[41] Universität der Bundeswehr München. *Munich Mobility Research Campus*. de. URL: https://www.unibw.de/more (visited on July 28, 2023).

[42] Universität der Bundeswehr München. *MORE Sharing*. de. URL: https://www.unibw.de/ivr/imv/forschung/more-sharing (visited on July 28, 2023).

[43] *Amarisoft Tests & Measurements*. en-US. URL: https://www.amarisoft.com/products/test-measurements/ (visited on July 28, 2023).

[44] *OpenSAND*. URL: https://www.opensand.org/ (visited on July 28, 2023).

[45] Sumit Kumar, Ashish Kumar Meshram, Abdelrahman Astro, Jorge Querol, Thomas Schlichter, Guido Casati, Thomas Heyn, Florian Volk, Robert T. Schwarz, Andreas Knopp, Paulo Marques, Luis Pereira, Roberto Magueta, Adam Kapovits, and Florian Kaltenberger. "OpenAirInterface as a platform for 5G-NTN Research and Experimentation". In: *Proceedings - 2022 IEEE Future Networks World Forum, FNWF 2022* (2022), pp. 500–506. DOI: 10.1109/FNWF55208.2022.00094.

[46] Florian Völk, Thomas Schlichter, Florian Kaltenberger, Thomas Heyn, Guido Casati, Robert T. Schwarz, and Andreas Knopp. "Field Trial of a 5G Non-Terrestrial Network Using OpenAirInterface". In: *IEEE Open Journal of Vehicular Technology* 3.June (2022), pp. 243–250. DOI: 10.1109/ojvt.2022.3175308.

[47] Blackned. *Ridux*. 2023. URL: %7Bhttps://blackned.de/ridux/%7D (visited on July 3, 2023).

[48] *Space Communications*. de. URL: https://www.unibw.de/satcom/spacecom (visited on Apr. 5, 2023).

[49] Patricia Martín Pimentel, Benjamin Rödiger, Christopher Schmidt, Christian Fuchs, Christoph Rochow, T. Hiemstra, Andreas Zager, Philipp Wertz, Marcus Knopp, Marc Lehmann, and Falk Mrowka. "Cube laser communication terminal (CubeLCT) state of the art". In: *Acta Astronautica* 211 (Oct. 2023), pp. 326–332. ISSN: 0094-5765. DOI: 10.1016/j.actaastro.2023.06.026. (Visited on Feb. 18, 2024).

[50] Robert T. Schwarz, Marcus T. Knopp, Hung Le Son, Alexander Koehler, and Andreas Knopp. "Optical Ground Station for Free-Space Optical Communication Research and Experimentation". In: *Photonic Networks; 24th ITG-Symposium*. 2023.

[51] *Bundesnetzagentur - Regionale Netze*. URL: https://www.bundesnetzagentur.de/DE/Fachthemen/Telekommunikation/Frequenzen/OeffentlicheNetze/LokaleNetze/lokalenetze-node.html (visited on June 29, 2023).

[52] *R&S®ROMES4 Drive test software*. en-ca. URL: https://www.rohde-schwarz.com/ca/products/test-and-measurement/network-data-collection/rs-romes4-drive-test-software_63493-8650.html (visited on June 29, 2023).

[53] *QualiPoc Android*. en-ca. URL: https://www.rohde-schwarz.com/ca/products/test-and-measurement/network-data-collection/qualipoc-android_63493-55430.html (visited on June 29, 2023).

[54] 3GPP. *5G; NR; Physical layer measurements*. Technical Specification (TS) 38.215. Version 17.3.0 Release 17. 3rd Generation Partnership Project (3GPP), Mar. 2023.

[55] 3GPP. *5G; NR; User Equipment (UE) procedures in idle mode and in RRC Inactive state*. Technical Specification (TS) 38.304. Version 17.3.0 Release 17. 3rd Generation Partnership Project (3GPP), Jan. 2023.

[56] Mathworks. *Visualize summary statistics with box plot - MATLAB boxplot - MathWorks United Kingdom*. URL: https://uk.mathworks.com/help/stats/boxplot.html?s_tid=doc_ta (visited on June 29, 2023).

[57] Yong Zhao, Mingshuo Wei, Chunlei Hu, and Weiliang Xie. "Latency Analysis and Field Trial for 5G NR". In: *2022 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*. ISSN: 2155-5052. June 2022, pp. 1–5. DOI: 10.1109/BMSB55706.2022.9828792.

[58] Simon Heine, Florian Völk, Robert T. Schwarz, and Andreas Knopp. "Concept and evaluation of 5G backhauling via starlink". In: *39th International Communications Satellite Systems Conference (ICSSC 2022)*. Vol. 2022. 2022, pp. 69–75. DOI: 10.1049/icp.2023.1364.

[59] Pheobe Agbo and Petra Weitkemper. "Analysis of Different MEC Offloading Scenarios with LEO Satellites in 5G Networks". In: *2023 IEEE COINS: IEEE International Conference on Omni-layer Intelligent systems*. 2023.

[60] Luciano Alexandre, Lucas Veiga, Agostinho Linhares, José Moreira, Marcelo Abreu, and Arismar Sodré Junior. "Coexistence Analysis Between 5G NR and TVRO in C-Band". In: *Journal of Communication and Information Systems* 35.1 (July 2020), pp. 198–202. DOI: 10.14209/jcis.2020.21.

[61] Changyong Shin, Robert W. Heath, and Edward J. Powers. "Blind Channel Estimation for MIMO-OFDM Systems". In: *IEEE Transactions on Vehicular Technology* 56.2 (2007), pp. 670–685. DOI: 10.1109/TVT.2007.891429.

[62] Biling Zhang, Jung Lang Yu, and Wan Ru Kuo. "Fast Convergence on Blind and Semi-Blind Channel Estimation for MIMO–OFDM Systems". In: *Circuits, Systems, and Signal Processing* 34.6 (2015), pp. 1993–2013. DOI: 10.1007/s00034-014-9947-6. URL: http://dx.doi.org/10.1007/s00034-014-9947-6.

[63] Florian Völk, Robert T. Schwarz, Mario Lorenz, and Andreas Knopp. "Emergency 5G Communication on-the-Move: Concept and field trial of a mobile satellite backhaul for public protection and disaster relief". In: *International Journal of Satellite Communications and Networking* 39 (4 July 2021), pp. 417–430. ISSN: 15420981. DOI: 10.1002/SAT.1377.

[64] Ali Eltohamy, Matthias Korb, Rudolf Zetik, and Reiner S. Thomä. "Optimum Access-Point Constellation for Indoor Time Difference of Arrival Positioning". In: *2023 IEEE/ION Position, Location and Navigation Symposium (PLANS)*. 2023, pp. 1234–1240. DOI: 10.1109/PLANS53410.2023.10140137.

[65] Chun Yang, Thomas Pany, and Petra Weitkemper. "Effect of antenna ports on TOA estimation with 4G LTE signals in urban mobile environments". In: *Proceedings of the 33rd International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS+ 2020)*. 2020, pp. 2166–2181.

[66] GSMA. *5G TDD Synchronisation Guidelines and Recommendations for the Coexistence of TDD Networks in the 3.5 GHz Range*. Apr. 2020. URL: https://www.gsma.com/spectrum/wp-content/uploads/2020/04/3.5-GHz-5G-TDD-Synchronisation.pdf (visited on July 28, 2023).

[67] NGMN Alliance. *5G TDD Uplink*. Dec. 2021. URL: https://www.ngmn.org/wp-content/uploads/220117-5G-TDD-Uplink-White-Paper-v1.0.pdf (visited on July 28, 2023).

[68] Peter Busch. *Impact and mitigation of interference (internal and external)*. Presented at Mobile Network Testing (MNT) Forum 2023, Rohde & Schwarz Munich, May 2023.

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