5G Space Communications Lab: Reaching New Heights

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***Abstract*—The new era of space exploration demands a significant increase in the number of human and robotic missions, thus resulting in novel communication and service requirements. To satisfy such requirements, the fifth generation of mobile communication systems (5G), despite providing connectivity on Earth, has the potential to serve as a communication standard for space resource missions, particularly the ones targeting the Moon. In fact, 5G non-terrestrial networks (NTNs) are already in the standardization process and new techniques are being proposed in order to counteract the peculiarities of the non-terrestrial channel. However, going one step ahead and deploying constellations of satellites around the Earth or the Moon, requires first a detailed analysis and testing the validity of the proposed techniques. Therefore, in this paper we introduce the 5G Space Communications Lab, that has been developed with the purpose of simulating space-based 5G communications. The designed testbed proposed here, increases the technology readiness level (TRL) of NTN-based 5G systems, demonstrating over a laboratory environment successful 5G communication via space links.**

***Index Terms*—5G, NTN, Satellite, Moon, Testbed**

I. Introduction

The 5G communication systems are provisioning innovative services with high quality of service (QoS) and quality of experience (QoE) levels, unprecedented capacity, and very low latency [1]. However, terrestrial networks (TNs) are mainly focusing on delivering 5G services to areas already being served by existing cellular networks, and the current 5G terrestrial infrastructure cannot provide Internet access to passengers on airplanes or high-speed trains, highways, and remote areas. Thus, the 5G and beyond 5G (B5G) NTN systems, including satellites, unmanned aerial vehicles (UAVs), and high altitude platforms (HAPs), integrated with the TNs can provide best solutions to connect the unconnected, unserved and underserved regions worldwide [2].

In addition to reaching worldwide connectivity, 5G systems can also play a crucial role in the future space missions, particularly for communication over the Moon. More specifically, if we have a look at the current typical communications in space, they normally take place among two parties, thus only point-to-point. However, in the upcoming lunar exploration scenarios, multiple crewed and uncrewed missions, including a large number of robots and rovers, will need to communicate with each other. While relying on current protocols for this kind of communication would be limiting and impractical at best, developing new ones would be unnecessary. Relying on the existing terrestrial protocols (such as 4G or 5G) for future space communications is a straightforward and quick solution to accommodate these new communication requirements. In fact, Nokia has been selected by NASA to build the first ever cellular network on the Moon [3]. Moreover, 3GPP technologies (i.e. 4G/5G) are already included to be studied in the Consultative Committee for Space Data Systems (CCSDS) to provide high data rate connectivity for space missions [4].

Despite its attractiveness, having 5G communications via NTN or in space, comes with novel challenges to be considered. These challenges, have been analysed for several years now, and novel techniques that counteract them have already been proposed, not only in academia [5]–[7], but also in the standardization efforts [8], [9]. In this context, 5G NTN is not a futuristic concept anymore, but slowly becoming a reality. Nevertheless, before moving on into the stage of massive deployment for such systems (requiring a constellation of satellites orbiting Earth or Moon) there is a need for testing and validating the various existing techniques over virtual environments, able to emulate realistic space communication links.

Therefore, in this paper we introduce the 5G Space Communications Lab (5G-SpaceLab), an interdisciplinary experimental platform at the Interdisciplinary Centre for Security, Reliability and Trust (SnT), that has been developed in order to simulate 5G-based communications in space and on the Moon [10]. More specifically, the project simulates two kinds of scenarios: one to test Earth-orbiting satellite communications in view of the upcoming 5G NTN standard for satellite communications, and the other to test Earth-Moon 5G-based communications in support of future Lunar missions. Further details regarding the use cases that can take advantage of space-based 5G systems on Earth and on the Moon are provided in Section II. Section III gives light to the overall description of the 5G-SpaceLab, providing information regarding the several laboratories involved, together with the hardware and software elements included. In Section IV, two

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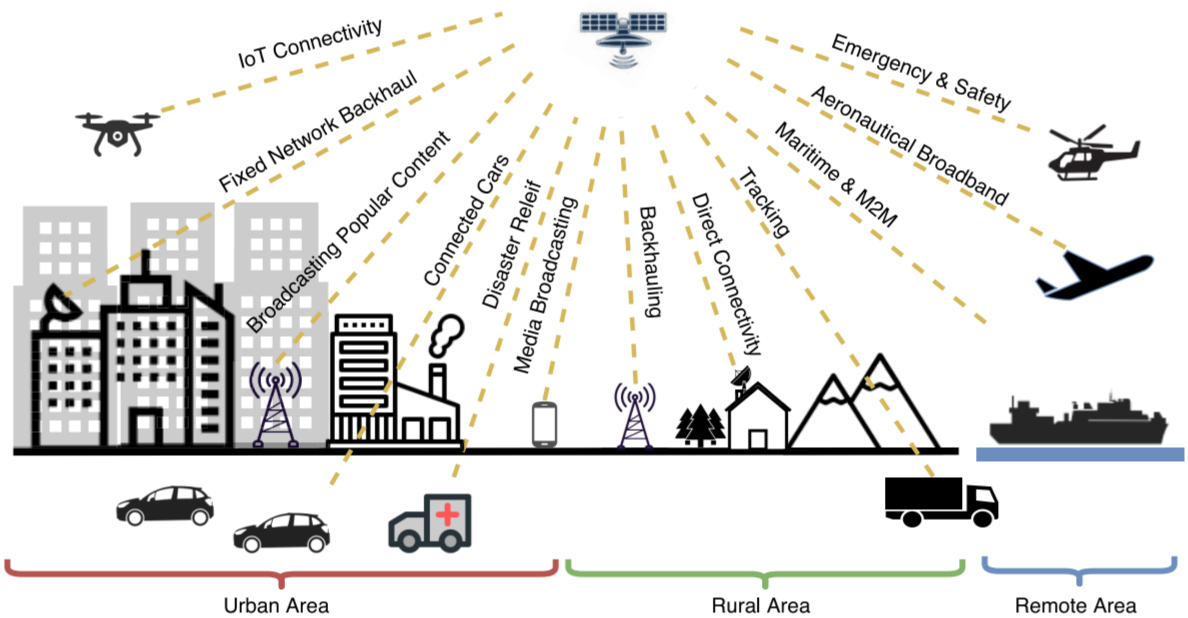


Fig. 1. 5G NTN use cases.

Demo use cases are shown where we demonstrate successful 5G communications for the Earth-orbiting scenario, as well as for the Moon-orbiting scenario. Last but not least, Section V highlights the conclusions of this work and the future technologies that are planed to be emulated in our Lab infrastructure.

II. Relevant use cases for Earth and Lunar communications.

In this section, we describe the main use cases and space mission that can profit from a space-based 5G system regarding communications on Earth and on the Moon.

A. Communication on Earth

Three major groups of 5G NTN use cases can be identified [11]. First, an NTN system can contribute to enhance the **5G network continuity** by providing connectivity in areas where a terrestrial-only network cannot reach. This is particularly true for services towards moving platforms such as aircraft, vessels, and trains. Secondly, NTN can ensure the **5G service ubiquity** in underserved or un-served areas, where there is no economical advantage in building a terrestrial infrastructure (e.g. desert, forest, urban areas). Last but not least, due to the unique capability of NTN, especially satellites places at geostationary (GEO) orbits, in offering a very wide area connectivity on Earth, it contributes towards improving the **5G network scalability**. This is particularly useful for offloading part of the terrestrial traffic, which is expected to be overload due to the massive number of devices that is expected to be connected in the future. Figure 1 provides a more complete list of use cases and the role that an NTN (satellite in this case) can play in different service areas.

B. Communication on the Moon

On the moon, there are different types of mission scenarios [12]. Each scenario has specific communication requirements, typically requiring high data rates. For further understanding, a representative list of moon mission scenarios is shown below:

- **Science and Robotic Mission Scenarios:** Lunar rovers have been an essential element of space exploration due to the hostile conditions on the moon. Among the different types of exploration missions [13], the rovers explore the lunar surface while measuring surface properties and transmitting that data via the lunar/martian relay satellite (RS). The robots can act as surface relays for stationary scientific instruments that they or others have placed there. Additionally, two robots could be used to transmit data, one of which would enter a deep crater (possibly a dark crater) for exploration, and the other would remain outside the crater. This concept would minimize the power needed by the crater rover and allow it to use its limited power for scientific or exploration needs.
- **Sortie Mission Scenarios:** Lunar exit missions have a short duration, performing scientific research and resource utilization tasks. From various landing sites, the soft landers allow the return of the crew and the collected samples to Earth. During the mission, landers and rovers will relay the data between the astronauts to the RS or directly to Earth in the case of Moon near-side missions.
- **Human Mobile Exploratory Missions:** Humans land and explore the surface for up to six months as the lander and habitat move from one location to the next. The crew and the rovers will be dependent on the lander for relaying the communication. This scenario is illustrated in Figure 2.

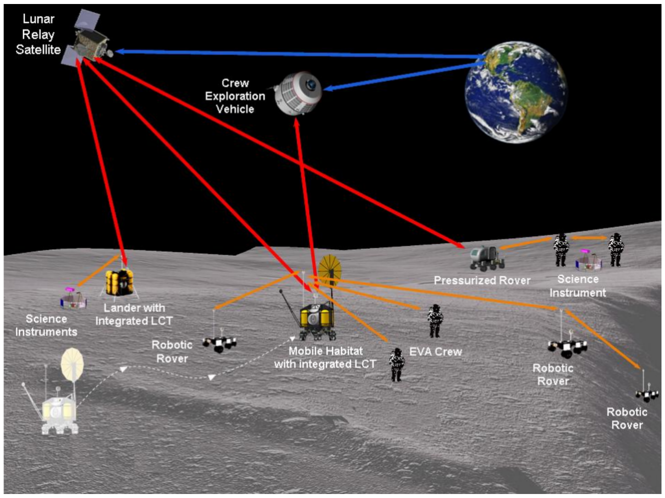


Fig. 2. Mobile Habitat Concept. [12]

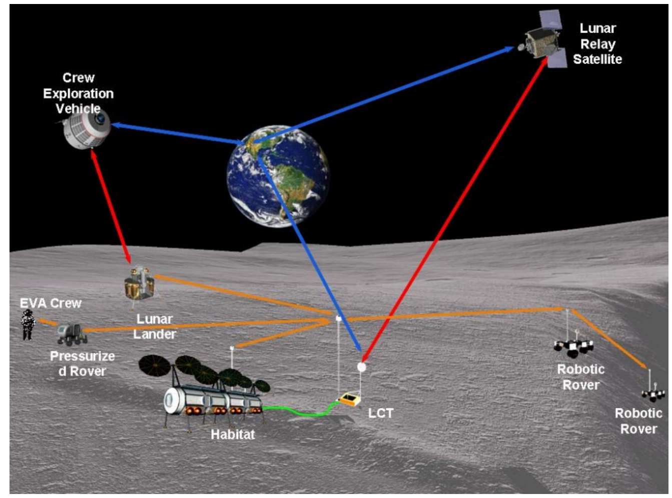


Fig. 3. Human Outpost Mission Example [12]

- **Human Outpost Mission Scenarios:** Lunar outpost will build slowly over the years. It will house a permanent or semi-permanent presence of humans on the Moon, a moonbase. Communication concepts will use several communications terminals (CTs) acting as access points, clustering communications nodes, and relaying the data to the RS for Moon/Mars-Earth and Surface-to-Surface communications. It also represents the scenario with the highest demand in terms of the required data rate, and it is illustrated in Figure 3.

III. 5G-SpaceLab Testbed

In this section, we firstly provide a general description of the 5G-SpaceLab. Then, we move on in describing the Laboratories involved in developing the testbed, as well as hardware (HW) and software (SW) elements. Please note that the HW and SW elements listed here represent only a limited list, so as to keep the focus only on the capabilities of the testbed from the 5G communication perspective. Lastly, we present the block diagram of the testbed where all the HW and SW elements are integrated towards achieving 5G communications via emulated space links.

A. General Description

The 5G Space Communications Lab (5G-SpaceLab) is an interdisciplinary experimental testbed combining the expertise, facilities and infrastructure of multiple laboratories located at the Interdisciplinary Center for Security, Reliability and Trust (SnT) of the University of Luxembourg (UniLu). The 5G-SpaceLab is a unique integrated and interdisciplinary space communications and control emulation platform that allows testing, validating and demonstrating the next-generation of space applications. The capabilities of the 5G-SpaceLab in addition to 5G NTN communications include: non-geostationary (NGSO) satellite and channel emulation, small satellite payload design and implementation, space-based edge computing, lunar rover control and teleoperation, artificial intelligence (AI)-enhanced control & communications and space-based Internet of Things (IoT) applications.

B. Laboratories

Four laboratorios from the SnT are applied in the Project. Further information regarding each of them are provided below.

- **Satellite Communications Laboratory (SatComLab)**: the SatComLab is a facility ready to teach, experiment and perform research in the fields of satellite and wireless communications. It contains an end-to-end satellite communications emulation platform, ready to investigate and validate novel communications protocols, architectures and transceivers such as 5G NTN, AI-accelerated transceivers, Cubesat communications payloads or channel & payload emulation.
- **Concurrent Design Facility (CDF-LU)**: The Concurrent Design Facility (CDF-LU) is a space system design research laboratory. The CDF-LU is equipped with 10 workstations and a multimedia ecosystem comprising of a suite of cameras, microphones, speakers, and large screens to enable collaborative and concurrent design sessions. The lab is used in space system design research along with teaching activities. In the 5G-Spacelab project, CDF-LU is being applied as a mission operations and experiment controls center. The experiment demonstrations are controlled and monitored from the CDF-LU where the research team remotely controls and monitors the experiment that is setup in the SatCom Lab. The integrated ecosystem allows multiple disciplinary specialists to collaborate and work concurrently on different segments of the experiment.
- **CubeSat Laboratory (CSL)**: The CubeSat Lab is a research facility focussed on developing small satellite systems and missions. The CSL is applied in teaching and research activities at SNT focussing on cubesats and miniaturized spacecrafts. In the current Project, the cube-

Fig. 4. 5G gound node USRPn310.

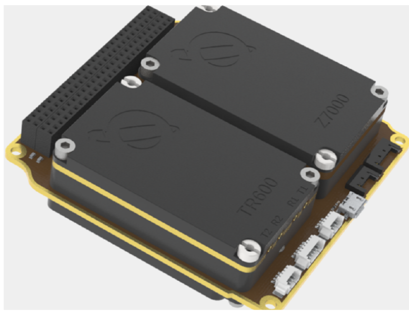


Fig. 5. Cubesat GomSpace SDR.

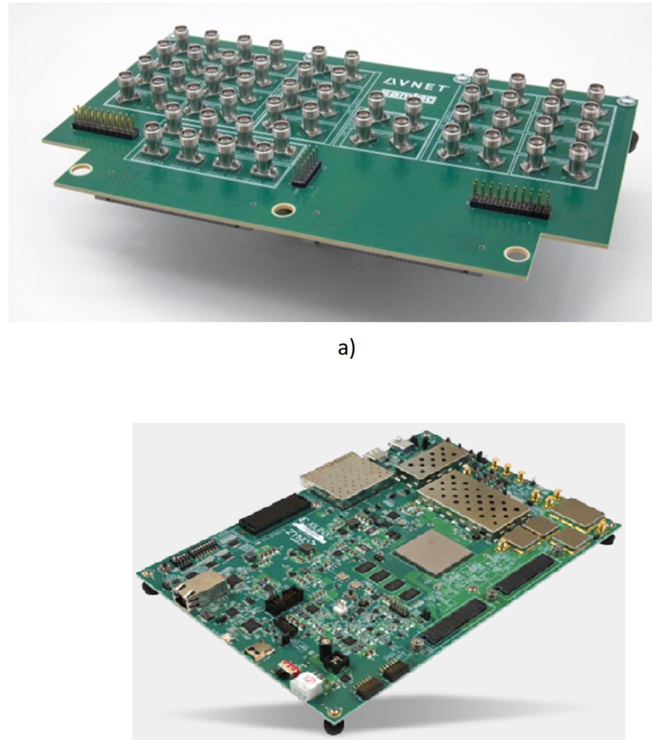
sat lab is used to develop the Cubesat Satellite that will host the communication payload for the LEO Mission. CSL is also involved in developing the formation flight algorithms which will be applied in the later phases of the project.

- **LunaLab**: the LunaLab is a facility that simulates lunar conditions for testing space applications such as autonomous navigation of lunar robots, multi-robot interaction, manipulation and transportation, additive manufacturing and regolith analysis, among others. This lab is equipped with sensor systems that allow students and researchers to monitor the success of their automated programs and the robot's actual movements. Additionally, the LunaLab has a Ground Station outside. This area is composed of computers and devices to control the equipment that is inside of the LunaLab.

C. HW elements

Major hardware components applied in the laboratory experiments are described next.

- **5G USRP Ground Nodes (eNB/gNB & UE)**: The USRP N310 is a networked software defined radio (SDR) that transmit and receive communication signals. These are the communication nodes that act as ground stations (eNB/gNB) with which we transmit the signal and the user (UE) that receives the signal in 4G and 5G waveforms.
- **CubeSat SDR (gSDR)**: Space qualified NanoCom SDR platform developed by Gomspace is used as the payload for 5G-SNT mission. This SDR platform is utilized for high-speed ground-link and inter-satellite links utilizing S- or K-band in a highly miniaturized radio system for long distance communication. It can program different topologies and configurations. A single SDR is used in the first laboratory demo experiment.
- **Channel Emulator (CE)**: there are two different hardware for the CE
  - The Zynq® UltraScale+™ RFSoC ZCU111 evaluation kit, This kit features a Zynq UltraScale+ RFSoC supporting 8 12-bit 4.096GSPS ADCs, 8 14-bit 6.554GSPS DACs, 4 GB DDR4 on PL. used as the Channel Emulator which connects 5G USRP Ground Nodes and the Cubesat SDR while emulating real-



a)

b)

Fig. 6. Channel Emulator Zynq@ Ultrascale+ a) RF Interface, and b) Motherboard.

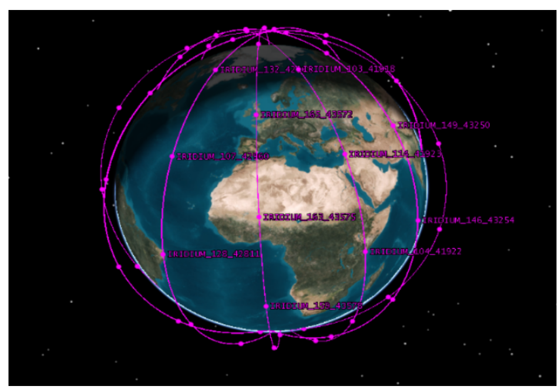


Fig. 7. STK Software.

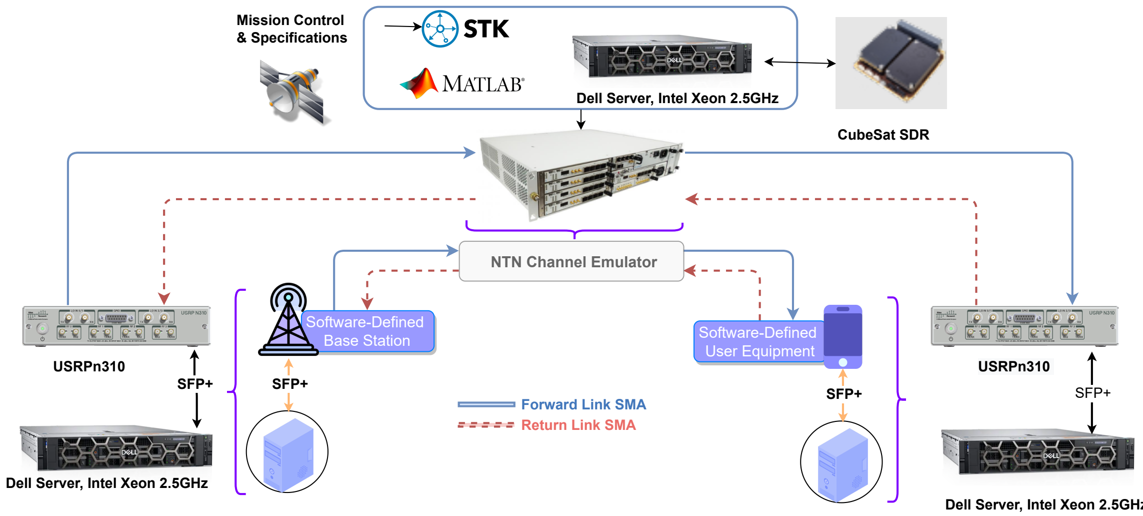


Fig. 8. 5G-SpaceLab Communication Testbed

istic conditions of the Low-Earth orbit. It integrates the communication architecture and centralizes the experiment setup emulating the delay and doppler effects.
  - The AMC574 FPGA board is a costumed industrial board based on RFSoC XCZU29DR Xilinx FPGA that support 16 channels of ADCs and DACs.
- **CubeSat prototype – CubeSat SDR interface**: A cable-interface between the CubeSat in the CubeSatLab and the CubeSat SDR in the SatComLab has been established. Both ends use the CAN bus and the CSP protocole enabling compatibility of the systems. The link between the two systems has been verified.

D. Software elements

Similar to hardware, here we provide a general description of the software tools that are applied in the laboratory experiments.

- **System Tool Kit (STK)**: The primary functionality of using STK is to have a visual representation of the satellite trajectories. This allows us to study the behavior of various satellites under different orbits and select the most appropriate (convenient) one for our project. STK tool provides (among several features):
  - A simulation framework with an accurate Earth representation in time and space.
  - High-fidelity orbit integrators.
  - Satellite lifetime and long-term orbit predictors.
  - Satellite constellation modeling.
  - Link budget calculation.
  - Scenario visualization in any way imaginable in a 3D environment.
- **Matlab**: We integrated Matlab with STK environment to calculate the link budget for each orbital scenario. Through some post-processing, relevant parameters for the channel emulator are generated, such as Doppler shift, communication delay, channel coefficients, etc.
- **Labview:** The software receives the channel parameters based on the different scenario from Matlab-STK Link Budget software through UDP connection and transfer them with some initial parameters to the FPGA.
- **Ground Node OAI GUI**: The Software is a 5G MODEM open source 3GPP compliant. It transmits the 5G waveform which broadcast network and cell information that is strictly important for establishing a connection among many user terminals (namely the forward link).
- **gSDR GUI**: GNURadio framework provides flow-based signal processing blocks for software-defined radios. GNURadio in our system is used for monitoring the spectrum in real-time and control the waveform by triggering control commands to set the reception and transmission knobs of GomSpace SDR on the fly such as frequency, rf-bandwidth, sampling-rate, gain. etc.

E. Testbed block diagram

As it can be noted in Figure 8, where the block diagram of the communication testbed is shown, the mission control and specification are designed in STK. Then, depending on the specific mission we want to emulate, Matlab is utilized in integration with STK to perform some post processing and derive the specific channel impairments for the mission of interest. These channel impairments (e.g. Doppler effects, signal attenuation, propagation delay, etc.) are then reproduced by the channel emulator. To run the 5G software-defined base station and user equipment, a server is utilized which contains the OAI 5G open source code [14] and is able to generate/receive the digital 5G waveform. The USRPs perform the digital-to-analog (DAC) in case the 5G node is

Fig. 9. 5G-SpaceLab Conceptual Demo: a) 5G communication via satellites on Earth; and b) 5G communication reaching the Moon from L2 orbit.

transmitting, and analog-to-digital (ADC) conversion in case the 5G node is receiving. The CubeSat SDR will receive the RF 5G signal in the communication chain and the spectrum of the signal can be monitored.

IV. Demo Description & Results

The aim of this section is to show our experimental results of 5G communication via space links for two main scenarios: a) 5G communication via satellites on Earth; and b) 5G communication on the Moon from the L2 orbit. For the Earth-orbiting scenario we emulate satellite at various altitudes, such as LEO which can have an altitude range of 500 - 2000 km, and MEO from 5000 - 20000 km, with the option of having also inter-satellite links (ISLs). On the other hand, for the second scenario the goal is to demonstrate 5G communication only from the L2 orbit to a potential 5G user on the Moon, while the link from the Earth to the Moon is abstracted. Please note that the L2 is one of the five Earth-Moon Lagrangian points at a distance of 61347 km from the Moon. The unique feature of Lagrangian points is that the Earth and Moon gravitational forces upon a spacecraft cancel out. This orbit is suitable for Lunar exploration because it is easily reachable and accessible from Earth and Moon at the same time [15]. Figure 9 yields a conceptual representation of the Demo, which we will detail hereafter.

A. Mission design in STK

As we mentioned in Section III, we rely on STK to design and emulate the mission since it gives us precise outputs regarding the signal-to-noise ratio (SNR) at the receiver, as well as the channel characteristics. Notably, the SNR levels will depend on the antenna parameters in the ground and space segment, as well as the overall loses in the communication medium. For the ground segment antennas (both base station and user equipment) we utilize the 3GPP specifications [9], whereas for the satellite antenna we use realistic parameters for typical cubesat missions at S-band [16]. This frequency of communication drives also the signal propagation loses, and for our demo we rely on a 2 GHz carrier frequency, as proposed in the standard [9].

B. RTT emulation

One of the most important channel characteristics emulated by our channel emulator is the the round trip time (RTT) of communication from the base station to the end user, and vice-versa. More specifically, the RTT is implemented by using a deep first in first out (FIFO) buffer that uses an external Double Data Rate (DDR) Synchronous Dynamic Random-Access Memory (SDRAM) chipset. The implemented RTT is mainly based on the frequency rate at which the data writes and reads to/from the Deep FIFO, and the depth of the FIFO buffer. By fixing the sampling frequency and changing the depth of Deep FIFO, various RTT values can be emulated, reaching implementation values of up to 1.4 seconds. This is enough to cover the RTT experienced over LEO/MEO/GEO links for 5G NTN on Earth, and the RTT from the L2 orbit to potential 5G users on the surface of the Moon.

C. Doppler emulation

In addition to the RTT, Doppler effects are a crucial impairment to be emulated, mainly caused by the movement of the NGSO platform (i.e. LEO & MEO satellites). To implement these effects, a dynamic "resampler" approach is utilized, employing a FIFO memory in combination with a finite impulse response (FIR) filter. By dynamically modifying the resampling rate of the FIFO and FIR filter coefficients, various Doppler effects are emulated depending on the satellite orbit altitude and trajectory. For 2 GHz carrier frequency the Doppler shift can reach values of up to 48 kHz in the worst case scenario of communication over LEO satellites.

D. OAI modifications to support space link characteristics

Obviously, without any modification in the standard, the 5G base station is unable to communicate with the user equipment due to the novel channel characteristics mentioned earlier. Therefore, we adapt the existing protocol by applying our modification directly in the OAI open source code. For

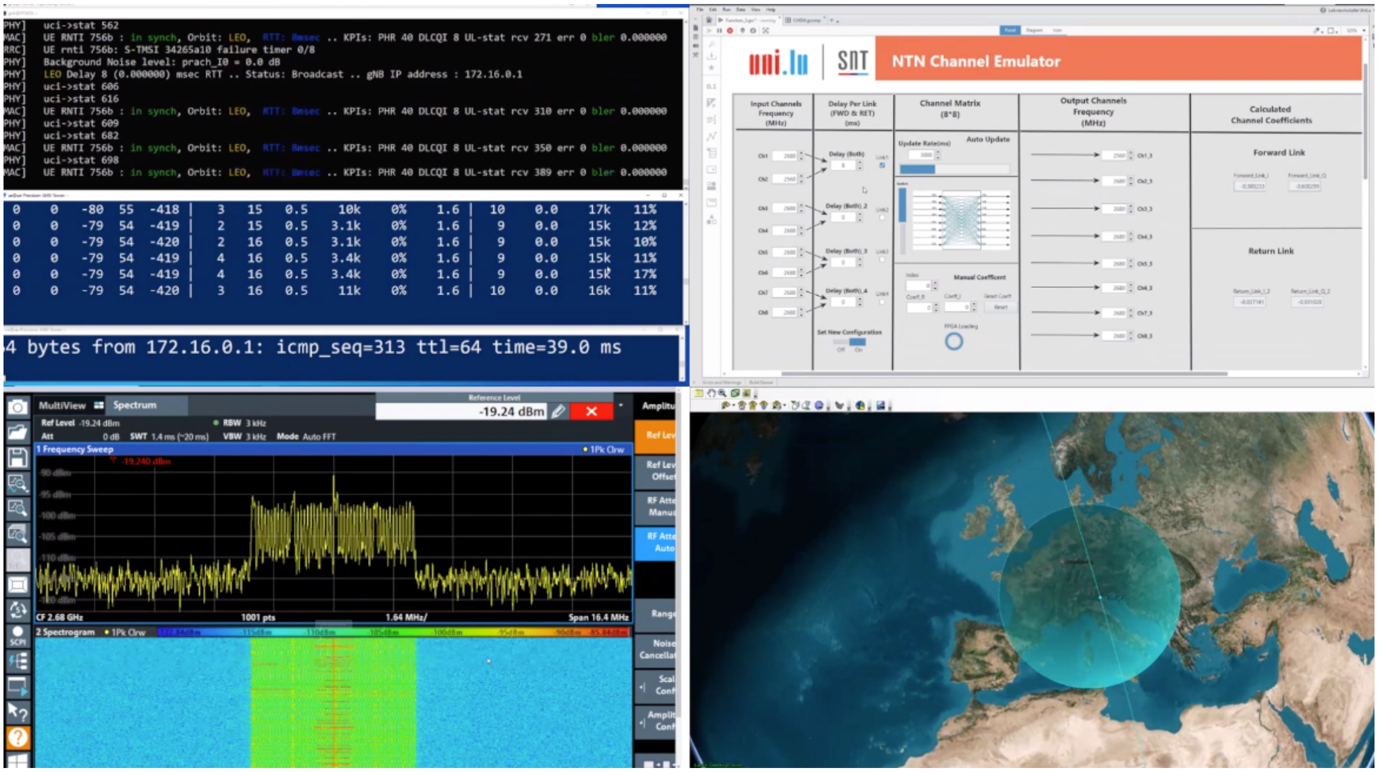


Fig. 10. A snapshot of the Demo

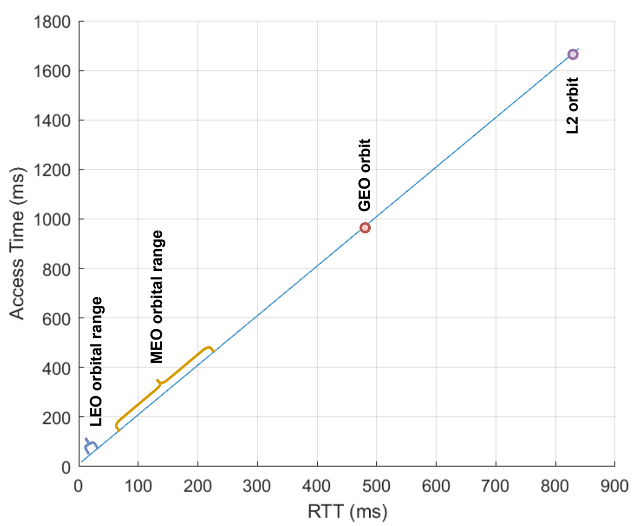


Fig. 11. Quantitative Demo Results

example, the increased RTT in the communication link would cause a failure in the access phase of the 5G when the user connects to the network and achieve uplink synchronization with the base station. A failure in this phase would prohibit the user from sending data in the uplink. More detail on our OAI implementations can be found in [17].

E. Demo Results

Figure 10 yields only a snapshot of the Demo which we run in real-time. Please note that the bottom-right shows the mission we are emulating, which in this case is a LEO one. In the top-right corner we can monitor the parameters of the channel emulator, such as delay, Doppler and channel coeficients (which dynamically change with the movement of the satellite). In the bottom-left the spectrum of the signal can be monitored, while the top-right gives us the SNR levels at the user equipment together with the access time a certain user required to have a successful access phase and be able to transmit data. To show some quantitative results in support of our Demo, in addition to having successful data transmission, we plot in Figure 11 the measured access time for various missions. As it can be seen, the access time increases linearly with the altitude, and we are able to successfully demonstrate 5G communications for LEO/MEO/GEO orbits on Earth, and L2 orbit on the Moon.

V. Conclusions & Future Work

In this work, we introduced the 5G Space Communications Lab and the developed testbed with the purpose of simulating space-based 5G communications. Two kind of scenarios have been shown, one to test Earth-orbiting satellite communications in view of the upcoming 5G NTN standard for satellite communications, and the other to test Earth-Moon 5G-based communications in support of future Lunar missions. The designed testbed proposed here, increases the technology readiness level (TRL) of NTN-based 5G systems, demonstrating over a laboratory environment successful 5G communication via space links.

In the future work, edge computing will be considered and the developed algorithms will be implemented in the tesbed. This is a crucial technology because it brings the computation and data storage closer to the source, avoiding the bottleneck created by the long space links, such as the one from Earth to the Moon. In addition, despite 3GPP technologies, the utilization of WiFi will also be considered for proximity communication on the Moon. This represents a futuristic scenario where many assets placed in a close vicinity with each-other have to communicate in order to satisfy a particular Lunar mission.

References

[1] I. Ahmed, H. Khammari, A. Shahid, A. Musa, K. S. Kim, E. De Poorter, and I. Moerman, "A survey on hybrid beamforming techniques in 5g: Architecture and system model perspectives," *IEEE Communications Surveys Tutorials*, vol. 20, no. 4, pp. 3060–3097, 2018.

[2] F. Rinaldi, H.-L. Maattanen, J. Torsner, S. Pizzi, S. Andreev, A. Iera, Y. Koucheryavy, and G. Araniti, "Non-terrestrial networks in 5g amp; beyond: A survey," *IEEE Access*, vol. 8, pp. 165 178–165 200, 2020.

[3] NOKIA. (2020, Oct.) Nokia selected by nasa to build first ever cellular network on the moon. [Online]. Available: https://www.nokia.com/about-us/news/releases/2020/10/19/nokia-selected-by-nasa-to-build-first-ever-cellular-network-on-the-moon/

[4] CCSDS. (2022, Feb.) Spacecraft onboard interface services— high data rate 3gpp and wi-fi local area communications. [Online]. Available: https://public.ccsds.org/Pubs/883x0b1.pdf

[5] A. Guidotti, A. Vanelli-Coralli, M. Conti, S. Andrenacci, S. Chatzinotas, N. Maturo, B. Evans, A. Awoseyila, A. Ugolini, T. Foggi, L. Gaudio, N. Alagha, and S. Cioni, "Architectures and key technical challenges for 5g systems incorporating satellites," *IEEE Transactions on Vehicular Technology*, vol. 68, no. 3, pp. 2624–2639, 2019.

[6] X. Lin, S. Rommer, S. Euler, E. A. Yavuz, and R. S. Karlsson, "5g from space: An overview of 3gpp non-terrestrial networks," *IEEE Communications Standards Magazine*, vol. 5, no. 4, pp. 147–153, 2021.

[7] O. Kodheli, A. Guidotti, and A. Vanelli-Coralli, "Integration of satellites in 5g through leo constellations," in *GLOBECOM 2017 - 2017 IEEE Global Communications Conference*, 2017, pp. 1–6.

[8] 3GPP 38.811, "Study on new radio (nr) to support non-terrestrial networks," Tech. Rep., Oct. 2020.

[9] 3GPP 38.821, "Solutions for nr to support non-terrestrial networks (ntn)," Tech. Rep., Jun. 2021.

[10] SnT. 5g space communications lab. [Online]. Available: https://wwwfr.uni.lu/snt/research/sigcom/5g_space_communications_lab

[11] O. Kodheli, E. Lagunas, N. Maturo, S. K. Sharma, B. Shankar, J. F. M. Montoya, J. C. M. Duncan, D. Spano, S. Chatzinotas, S. Kisseleff, J. Querol, L. Lei, T. X. Vu, and G. Goussetis, "Satellite communications in the new space era: A survey and future challenges," *IEEE Communications Surveys Tutorials*, vol. 23, no. 1, pp. 70–109, 2021.

[12] K. B. Bhasin, J. D. Warner, and L. M. Anderson, "Lunar communication terminals for nasa exploration missions: Needs, operations concepts and architectures," in *AIAA ICSSC Conference*, 2013.

[13] E. R. Jawin, S. N. Valencia, R. N. Watkins, J. M. Crowell, C. R. Neal, and G. Schmidt, "Lunar science for landed missions workshop findings report," *Earth and Space Science*, vol. 6, no. 1, pp. 2–40, 2019.

[14] OpeanAirInterface. 5g software alliance for democratising wireless innovation. [Online]. Available: https://openairinterface.org/

[15] NASA, "Earth-moon l1 / l2 infrastructure – what role does it play?" in *Human Exploration Community Workshop on the Global Exploration Roadmap*, 2011.

[16] GomSpace. S-band patch antenna for high speed communication. [Online]. Available: https://gomspace.com/shop/subsystems/communication-systems/nanocom-ant2000.aspx

[17] O. Kodheli, A. Astro, J. Querol, M. Gholamian, S. Kumar, N. Maturo, and S. Chatzinotas, "Random access procedure over non-terrestrial networks: From theory to practice," *IEEE Access*, vol. 9, pp. 109 130–109 143, 2021.