5G-NTN GEO-based Over-The-Air Demonstrator using OpenAirInterface

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Abstract

5G services combined with the satellites, also termed 5G Non-Terrestrial Networks (5G-NTN), have the capability of providing connectivity to the areas which were previously either unreachable or too costly to be reached by terrestrial communication networks. Proof-of-Concept (POC) demonstrators, preferably based on open-source implementation are desirable to expedite the ongoing research on 5G-NTN. In this work, we discuss the contributions made during the project 5G-GOA: 5G-Enabled Ground Segment Technologies Over-The-Air Demonstrator which aims to provide direct access to 5G services to a UE through a transparent payload Geostationary (GEO) satellite. 5G-GOA uses the open-source Software-Defined-Radio (SDR) platform OpenAirInterface (OAI) and does the necessary adaptations to achieve its objectives. Adaptations span physical layer techniques (e.g., synchronization) up to upper layer implementations (e.g., timers and random-access procedures) of the Radio Access Network (RAN). The adaptations are based on 3GPP 5G-NTN discussions and the solutions are compliant with the recently frozen 3GPP Release-17. An end-to-end SDR-based 5G-NTN demonstrator has been developed for Over-The-Satellite (OTS) testing. We present results from several experiments that were conducted for in-lab validation of the demonstrator using a satellite channel emulator before going live with OTS tests. Experimental results indicate the readiness of the demonstrator for OTS testing which is scheduled during ICSSC 2022. The source code has been submitted to OAI public repository and is available for testing.

1. Introduction

Attempts to include NTN components in cellular networks were in progress for the last few years [1][2], and finally, the specifications for 5G-NTN in 3GPP are frozen in March 2022, 3GPP Release-17. For the first time, satellites are being considered outside the transport network, and currently, the research is focused on providing direct access to 5G services at the UE. This means the NR-Uu interface does not terminate at the satellite and the user terminal on the ground directly connects to a ground-based gNB via a satellite channel. In addition, the focus is on transparent payload satellites rather than regenerative payload satellites. In the former, the satellite acts as a amplify and forward relay (with possible frequency switching between service and feeder link) while in the later satellite can do can perform on-board digital signal processing, such as modulation/demodulation and encoding/decoding. A consolidated representation of transparent and regenerative payload satellite based 5G-NTN is shown in Figure 1.

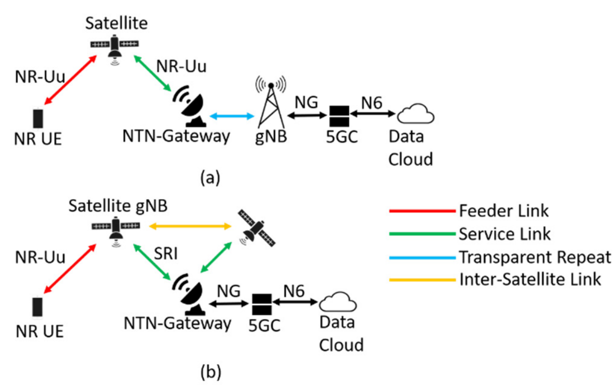

Figure 1: (a) Transparent Payload Satellite for 5G-NTN (b) Regenerative Payload Satellite for 5G-NTN

However, the integration of 5G and NTN is not straightforward due to several technical challenges; mainly the high RTD, large Doppler shift, and frequent handovers (the last two especially for Low Earth Orbit: LEO satellites). This may lead to the failure of several close-loop procedures of the terrestrial 5G protocol stack if it is used as it is. Such issues need to be investigated and addressed before the commercial deployment of 5G-NTN based services.

In this context, we discuss the developments and contributions done during the project 5G-GOA whose aim is to provide direct access to 5G services to a UE via a transparent payload GEO satellite in the Stand Alone (SA) mode of operation. The project has been funded under ESA ARTES [3] and will conclude in November 2022. Using the OpenAirInterface terrestrial 5G protocol stack as a baseline, adaptations have been done to address the challenges presented by NTN which is followed by the development of an SDR based POC demonstrator. The work has closely followed the 3GPP Release-17 work item on NTN and the solutions developed are based on 3GPP discussions and results [1][2]. In this work, we detail the demonstrator architecture and present the results obtained by conducting several in-lab experiments over the emulated GEO satellite channel. Preliminary results indicate the effectiveness and readiness of the demonstrator for the live OTS testing which is scheduled during the ICSSC 2022. To the best of our knowledge, this is the first work that focuses on both lower and higher layers of the 5G-NTN protocol stack and demonstrates end-to-end direct access to 5G services to a UE in the SA mode. The source code has been submitted for integration with OAI main develop branch and is available for testing [17].

The rest of this paper is organized as follows: In Section-2 we discuss comparable 5G-NTN projects. Section-3 focuses on the capabilities of OAI and its current status. Section-4 discusses the details of 5G-GOA, adaptations done in OAI for 5G-NTN, and the demonstrator architecture. The experimental set-up, experiments, and test results are presented in Section-5. Finally, section-6 draws concluding remarks with a future roadmap.

2. Previous Works

5G AgiLe and flexible integration of SaTellite And cellulaR (5G-ALLSTAR) [4], aimed to design, develop, and evaluate via testbeds trials, multiple access based multi-connectivity (combination of satellite and cellular access) for the support of seamless reliable, and ubiquitous broadband services. Several features in the PHY and MAC layer of OAI were adapted to cope with satellite impairments. The project demonstrated 5G-NR access through satellite as well as terrestrial networks. 5G New Radio EMUlation over SATellite (5G-EmuSat) [5] project developed a demonstrator platform implementing the PHY and MAC layer 5G-NR for direct access via a satellite channel using and extending OAI. Essential features of 5G-NR were implemented such as physical channels, timing advance, frequency offset compensation, etc. In-lab validations were done using a satellite channel emulator and the development done in OAI pertaining to both terrestrial 5G-NR and NTN were merged to the OAI repository. *5G Space Communications Lab*, from the University of Luxemburg [6] implements a POC testbed for two scenarios: Earth-orbiting satellite communications and Earth-Moon communications. However, currently, the testbed uses a 4G LTE protocol stack from OAI for RAN and adapts it to function under impairments caused by MEO and GEO satellites [6].

3. OpenAirInterface

OpenAirInterface is an open-source initiative that provides a reference implementation of gNB, UE, and 5G Core Network (5G-CN) which are standard compliant with 3GPP Release-15 (and above) [7]. OAI has software-based network functionalities which reduce the implementation cost and increases the flexibility of the deployment. OAI software stack runs on general-purpose Intel x86 architecture-based processors on top of a Linux-optimized environment. This allows OAI to exploit the Single Instruction Multiple Data (SIMD) instruction sets (SSE, SSE2, SSS3, SSE4, and AVX2) [8] for implementing highly optimized DSP routines. OAI distinguishes itself from other similar projects through its unique open-source license, the OAI public license v1.1 which was created by the OAI Software Alliance (OSA) in 2017 [9].

Currently, the OAI 5G-NR RAN supports all physical channels and signals as per the 3GPP Release-15 while limited to subcarrier spacing of 30kHz in FR1 and 120kHz in FR2. Supported bandwidths are 10; 20; 40; 80; and 100MHz Further, there is a highly efficient 3GPP compliant implementation of Low-density parity-check code (LDPC) encoder/decoder (BG1 and BG2), Polar encoder/decoder, and encoder and decoder for a short block. Furthermore, Bandwidth-Parts (BWP) a feature that is useful for power-constrained UEs is also being implemented. Apart from 5G RAN, the OAI also provides a 3GPP-compliant complete software implementation of the 5G-CN and offers support for both Non-Stand Alone (NSA) and SA operations. Further, OAI 5G-CN follows Service-Based-Architecture (SBA) which includes basic Access and Mobility Management Function (AMF), Session Management Function (SMF), and User Plane Function (UPF), and allows the deployment using docker-compose.

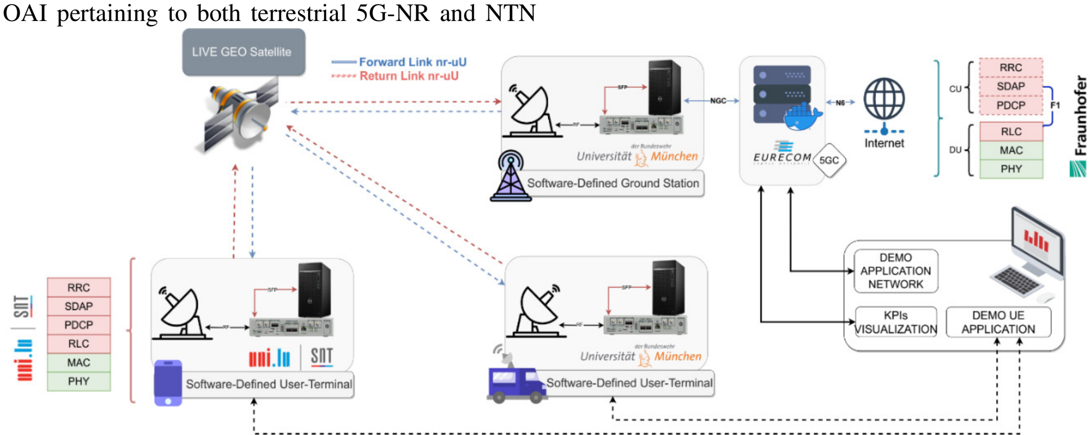

Figure 2: Architecture of 5G-GOA Proof-Of-Concept demonstrator for Over-The-Satellite testing

A comprehensive list of the capabilities of OAI 5G-NR RAN and 5G-CN can be found in [10] and [11] respectively. Currently, using Time Division Duplexing (TDD), 100 MHz bandwidth, 256 QAM, and 30 kHz of Sub-Carrier spacing, a downlink bitrate up to 330 Mbit/s with RTT up to 10ms can be achieved [12].

4. 5G-GOA

5G-Enabled Ground Segment Technologies Over-The-Air Demonstrator (5G-GOA) [13] is an ongoing ESA project, developing and implementing the necessary modifications in the 5G-NR standard to enable the direct access of terrestrial 5G services via transparent GEO satellite systems. 5G-GOA has two phases. In the first phase, challenges related to the integration of 5G and NTN were identified for all the layers of RAN. In the second phase, an SDR-based end-to-end demonstrator has been developed using OpenAirInterface. The hardware and software development in 5G-GOA relies on and uses existing technologies already available from the OAI. The solutions being developed during the project are directly based on 3GPP discussions and results (compliant with 3GPP Release-17 or later). Among the two major 5G-NTN architectures [14], transparent payload direct access and regenerative payload direct access, we have chosen the former (Scenario A1 [2]) due to implementation simplicity and OTA demo feasibility. The main impairment, in this case, is due to excessive RTD (≈ 520ms). This order of delay is greater than the maximum delay that can be covered by the Timing Advance (TA) field of Random-Access Response (RAR) which is around 2ms for 15 kHz SCS and 1ms for 30 kHz SCS [15]. As a result, PHY and MAC layer procedures of 5G will fail and several timers at the higher layers (RLC, PDCP, RRC) will expire at both the control and user plane and at both gNB and UE [16]. To address these challenges, we have implemented the necessary modifications in the existing OAI 5G protocol stack which are listed in Table 1. The source code used in 5G-GEO has been submitted to the OAI repository under OAI Public License v1.1 and is in the process to be merged with the main development branch [17].

Table 1: OAI modifications for 5G-NTN in 5G-GOA

Layer	NTN Specific Modifications in OAI
PHY	▪ Extension of OAI rf-simulator to support simulation of long propagation delays ▪ Support of 5 MHz (15 kHz SCS) bandwidth ▪ HARQ deactivation at gNB and UE
MAC	▪ Adaptations to support UL TA and RA procedures in NTN scenarios ▪ FDD scheduling
RLC	▪ Disabling HARQ-ARQ interaction ▪ Increase ARQ buffer size ▪ Increase maximum SN
PDCP	▪ Increase discardtimer ▪ Increase t-Reordering timer ▪ Increase PDU buffer size
RRC	▪ Increase selected UE timers (T300, T301, T311)
GUI	▪ Development of OAI GUI (Scope) to enable monitoring of real-time KPIs

Unlike the previous 5G-NTN projects, 5G-GOA also involves the inclusion of 5G-CN (and thus SA mode of operation). After the project conclusion, a live demo via direct satellite link is planned during ICSSC 2022.

In 5G-GoA we are targeting a demonstration of the relevant 3GPP Release-17 5G-NTN features. With the aforementioned modifications in OAI, an SDR-based demonstrator has been developed which facilitates (a) In-lab validation using a satellite channel emulator and (b) Over-The-Satellite live testing. The demonstrator consists of at least two SDR UE (one mobile UE in Munich, Germany, and another static UE in Luxembourg) and a remote gNodeB (and 5G-CN in SA mode located at UniBw teleport in Neubiberg, Germany) to verify simultaneous bi-directional end-to-end communications through GEO satellite. Both gNB and UE run on consumer grade desktops and Ettus USRP X310. A pictorial illustration of the demonstrator is shown in Figure 2.

5. Experiments and Results

In-lab validation of the demonstrator is crucial before live OTS testing. An SDR UE was connected to a single SDR gNB in 5G SA mode. Separate satellite channel emulators were used for uplink and downlink paths for introducing an RTD of 520ms (260ms for UL and 260ms for DL). The channel emulators behave simply as an analog repeater and relay the NR-Uu interface between SDR UE and SDR gNB. Detailed experimental parameters are shown in Table-2 and the block diagram of the in-lab demonstrator is shown in Figure-3.

Table 2: Experimental parameters and equipment specifications for In-lab validations

SDR gNB/UE	USRP X310 and Intel-i9 CPU
Ettus UHD	v4.2.0.1
Frequency	UL (1650 MHz), DL (1550 MHz)
SCS	15KHz
Bandwidth	5 MHz
FFT Size	512
Sampling Rate	7680ksps
PRB	25
RTD	260ms
Channel Gain	0 dB
SNR	>15 dB
Doppler	0 Hz
Duplexing	Frequency Division Duplexing
5G Mode	Stand Alone

A VPN based framework was established between UE and gNB. This was done since in the SA mode of operation, the UE is not directly accessible from the CN. Besides, VPN allows running the applications over the 5G link in a hassle-free manner. Some of the planned experiments include:

- Maximum UE throughput measurement via transport protocol (UDP, TCP, and QUICK).

- Performance of typical applications such as VoIP (based on SIP and RTP protocols).
- Performance (in terms of packet loss and jitter) of web applications such as VPN tunneling, adaptive video streaming, etc.

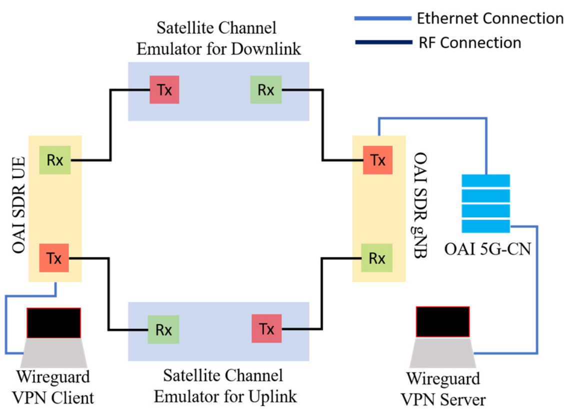

Figure 2: Experimental set-up for in-lab validations

It is important to mention here that the demonstrator is still a prototype implementation and therefore packet losses can frequently occur if tests are running for a longer period (e.g., several minutes). In addition, currently, the downlink is not as stable as the uplink, hence the majority of our tests included uplink traffic. Moreover, evaluation of the applications with typical KPIs is not appropriate now at this stage of development, however, continuous improvements are in progress.

Before testing the demonstrator for common applications, initial tests were conducted to verify the basic functionalities such as improvements in TA and RAR procedures. Ping command was used between UE and gNB (Figure-4) which confirms the successful connection between UE and gNB. Ping tests also show the emulated RTD of approximately 520ms (Figure 4).

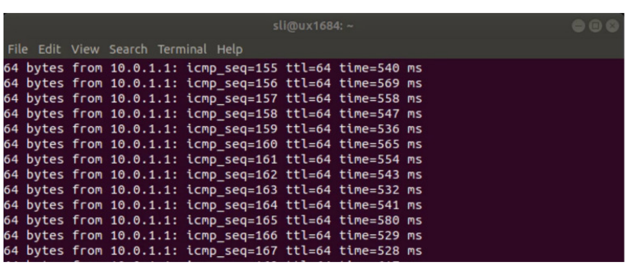

Figure 4: Ping test between UE and gNB (through VPN) confirms the successful connection and shows the RTD delay of approximately 520ms

Next, we used the iperf tool to measure the uplink UDP bandwidth. Results are shown in Table-3. As mentioned before, currently the uplink is more stable than the downlink, hence, the uplink UDP throughput is better than the downlink UDP throughput. For the same reason, currently TCP traffic does not last for more than a few seconds.

Table 3: Result of throughput tests over GEO satellite channel emulator

Carrier bandwidth	**5 MHz**	**10 MHz**
Uplink UDP Throughput	3.9 Mbps	7.4 Mbps
Downlink UDP Throughput	0.1 Mbps	0.2 Mbps

Further, three tests were performed to verify typical user applications in the 5G Uplink:

1. Web browsing
2. Video Streaming
3. VoIP Call

To verify the web browsing application, an Apache web server [18] was run on the Linux computer (Ubuntu 22.04), which has been connected to the UE, and two web page templates were hosted [19] on this machine. In the Firefox browser (104.0.2) on the Linux computer (Ubuntu 20.04), connected to the gNB/5G-CN computer, both web pages were successfully loaded over the NTN test network. Further, the video streaming application was realized and successfully verified by means of a YouTube SD stream (480p) using a VLC media player [20]. Next, to verify the VoIP application, SIP based VoIP call was initiated using the open-source tool SIPp [21] For this purpose an audio file was transmitted [22] via RTP from the UE to the 5G-CN where the RTP traffic was captured with Wireshark (Figure 5).

Figure 5: Verification of SIP based VoIP

In the SIP based VoIP experiment, a 15sec VoIP WAV file was successfully transmitted with some Jitter Drops at the beginning where the quality is only medium, however, later on, no quality reduction can be observed (Figure 6).

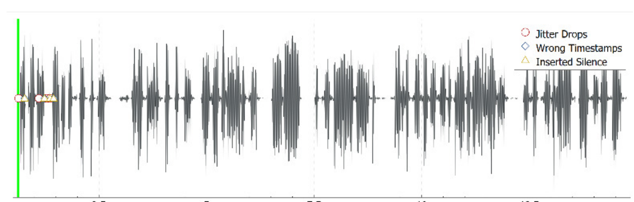

Figure 6: VoIP traffic validation where Jitter Drops are observed at beginning followed by smooth operation later on.

6. Summary and Future Roadmap

5G-NTN technology has still to undergo much long-term evolution. Early demonstrations and validation are essential to support the standardization of 5G-NTN at 3GPP. In this work, we have detailed the developments done during the project 5G-GOA which aims to provide direct access to a UE through a transparent payload GEO satellite link. 3GPP Release-17 compliant solutions have been implemented using open-source

SDR platform OpenAirInterface. In-lab validations indicate the readiness of the demonstrator for live OTS testing which is scheduled during ICSSC 2022 Stressa, Italy.

While writing this article, 5G-GOA has already completed the extensions in OAI to achieve its objectives. The source code is released for testing [17] and it is currently in the process to be merged with the main develop branch of OAI. A follow-up project OpenAirInterface Extension for 5G Satellite Links (5G-LEO) [23] is ongoing which is an extension of 5G-GOA for LEO satellites where additional challenges include compensation for Doppler and minimizing the effects of frequent handovers. The code extensions made in 5G-LEO are planned to be released in March 2023. Interested readers can refer to [24] for a detailed list of modifications made in OpenAirInterface5g

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Disclaimer

The views expressed herein can in no way be taken to reflect the official opinion of the European Space Agency.

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