5G-NTN Prototyping and Experimentation Results

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***Abstract*—The integration of 5G with a Non-Terrestrial Network (NTN) promises to achieve ubiquitous connectivity. Although the coverage of satellites is significantly larger, unfortunately, protocol development under the regimes of terrestrial and satellite communication has been done under exclusivity, hence, preventing experiencing the best of both worlds. In the recently frozen 3GPP Release 17, a significant leap has been taken by including satellites in the 5G-NR ecosystem. In this regard, Proof-of-Concept (POC) demonstrators, especially which are based on open-source implementation can play a key role in expediting the ongoing 5G-NTN research. In this paper, we discuss the goals, key achievements, and ongoing activities related to two 5G-NTN projects (a) 5G-GOA: 5G-Enabled Ground Segment Technologies Over-The-Air Demonstrator and (b) 5G-LEO: OpenAirInterface Extension for 5G Satellite Links. In both projects, the aim is to provide direct access of 5G to a ground UE via a transparent payload satellite (GEO for 5G-GOA and LEO for 5G-LEO). An open-source implementation of terrestrial 5G-NR RAN protocol stack from OpenAirInterface has been taken as the baseline and adaptations have been done in all the layers to address the challenges such as large Round-Trip-Time (RTT), high and variable Doppler, frequent handover, re-transmissions, etc. The adaptations closely comply with the 3GPP Release-17 5G-NTN specifications. An end-to-end software simulator and hardware demonstrator have been developed and in-lab validation and over-the-satellite testing have shown promising results confirming the feasibility of direct access to 5G services via satellites.**

***Index Terms*—5G, Software Defined Radio, Non-Terrestrial Networks, OpenAirInterface**

I. Introduction

For the past few years, there have been remarkable developments to include NTN components in the cellular network, especially from Release 15 onward. Finally, the first standardization of 5G-NTN can be seen in 3GPP Release 17 [1], which focuses on direct access to 5G services. This means, the 5G NR-Uu interface directly connects a UE to a ground-based gNB via the satellite channel. Besides, transparent payload satellites have been prioritized during standardization up to Release 18. This provides the opportunity to utilize the existing fleet of satellites since regenerative payloads will require to design and launch of specialized satellites capable of handling the complex signal processing of the 5G gNB protocol stack. Nonetheless, regenerative payloads might be considered in the upcoming Release 19 due to their additional advantage of the reduced round trip delay and enhanced capabilities to support inter-satellite links. Figure 1 shows a consolidated representation of transparent and regenerative payload satellite-based 5G-NTN.

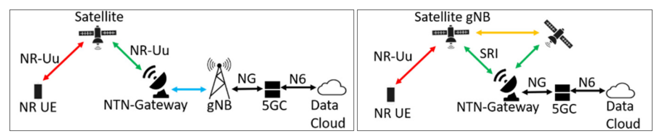


Fig. 1: Transparent (left) and Regenerative Payload (right)

Though the benefits of integrating NTN in the 5G ecosystem are enormous, the adaptation of the 5G protocol stack for TN in order to work under the challenges posed by NTN; such as high round trip delay, variable Doppler, re-transmissions, and frequent handover to name a few; has not been straightforward. These issues were investigated and solutions were proposed in 3GPP study items during the development of Releases 15 and 16 ([2], [3]). However, such solutions need to be implemented and validated before any commercial deployment of 5G NTN services. This necessitates the development of a proof of concept demonstrator, especially Software Defined Radio (SDR) based.

In this paper, we discuss the developments and goals achieved during two projects 5G GOA [4] and 5G-LEO [5]. Both the projects aim to provide direct access to 5G services to a ground UE via a transparent satellite (GEO in 5G-GOA and LEO in 5G-LEO, respectively) and are based on open source software OpenAirInterface5G [6] for SDR platforms. Adaptations have been done in OAI during 5G GOA and 5G LEO to address the challenges posed by NTN by closely following the Release 17 work item on NTN [7]. Further, a software simulator and a proof-of-concept demonstrator have been developed, which have been used for lab validations and over-the-satellite live tests. We briefly discuss features of the simulator and demonstrator followed by the results obtained during such tests. Preliminary results indicate the effectiveness of the modifications done in OAI and the readiness of the demonstrator to achieve higher TRL. To the best of our knowledge, 5G-GOA and 5G-LEO are the pioneer projects focusing on all layers of the 5G-NTN protocol stack and demonstrate end-to-end 5G direct access in the *5G Stand-Alone* (SA) mode. Moreover, the source code of NTN adaptations in OAI is in the process of getting merged with the development branch of OAI and is freely available for testing.

II. The 5G-Enabled Ground Segment Technologies Over-The-Air Demonstrator (5G-GOA)

The 5G-GOA [4] project aims to develop and implement the necessary modifications in the 5G-NR protocol stack to enable the direct access of 5G services via transparent *GEO* satellite systems. The choice of the transparent payload is motivated by the implementation simplicity and demonstration feasibility. Besides, the transparent payload is supported in Release-17 and 18, but not yet the regenerative payloads.

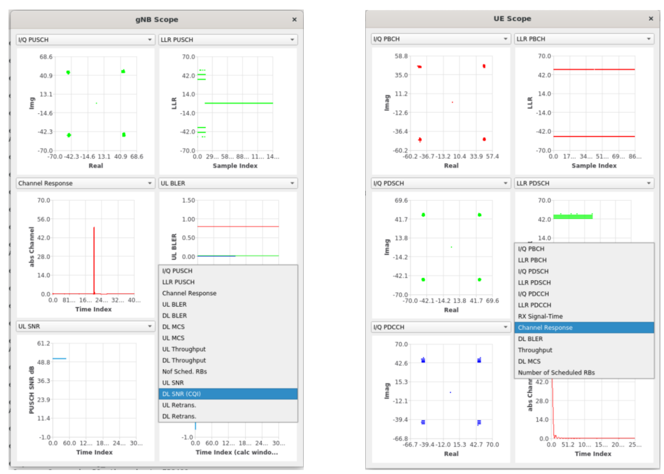
In 5G-GOA, the main channel impairment is caused by excessive RTT, $\approx$ 520ms (from gNB to UE and back) which is much greater than the maximum delay that can be handled by the Timing Advance (TA) field of Random Access Response (RAR) in terrestrial systems, which is 2 ms for 15 kHz SCS and 1 ms for 30 kHz SCS [8]. As a result, PHY and MAC layer procedures of terrestrial 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 [9]. In 5G-GOA, necessary modifications have been implemented in the existing OAI 5G protocol stack which is listed in Table I. Notice that some general 5G features, i.e., non-NTN-specific features, which are required for the 5G-GOA demonstrator, were not yet implemented in the OAI, when the 5G-GOA project started. Thus, the OAI was initially extended to have these features before implementing the NTN features. These are mainly physical layer adaptations, and they are also listed in Table I.

With all these features implemented in OAI, a Proof-Of-Concept demonstrator using Ettus USRP X310 has been developed for in-lab testing using a commercial channel emulator as well as for Over-The-Satellite (OTS) trials. Besides, the RF-Simulator in OAI has been extended to emulate the long RTT for testing the protocol stack without any SDR hardware. A high-level architecture of the 5G-GOA demonstrator is shown in Figure 2.

III. OpenAirInterface Extension for 5G Satellite Links (5G-LEO)

The 5G-LEO [5] project is an extension of 5G-GOA for low-earth orbit (LEO) satellites, where we target direct access to 5G via transparent LEO satellites. Likewise, in 5G-GOA, the choice of a transparent payload is motivated by the 3GPP specifications in Release 17.

In LEO-based systems, the main channel impairments are the time-varying RTT and time-varying Doppler due to the excessive satellite velocity of 7.5 km/s. For instance, a variable frequency offset of up to 25 ppm of the carrier frequency can be observed in such systems, which can be multiple times the SCS [10]. These challenges add on top to the challenges faced in 5G-GOA. This means that further enhancements are required in all the layers of the 5G NR protocol stack. For example (a) robust and reliable mechanisms to continuously track the time-varying frequency and timing offsets (b) a seamless handover process between multiple beams etc. In the LEO project, the OAI enhancements done during 5G-GOA have been taken as a template to further adapt the OAI to meet the requirements posed by a LEO satellite propagation channel. Please refer to Table II for the modifications implemented during the 5G-LEO project in the different layers.



(a) gNB scope (b) UE scope

Fig. 4: KPI-GUI for gNB and UE, developed during 5G-GOA

With all these augmented features implemented in OAI a Proof-Of-Concept (POC) demonstrator using Ettus USRP X310 has been developed for in-lab testing using a commercial satellite channel emulator. Besides, the RF-Simulator in OAI has been extended to emulate time-varying RTT and time-varying Doppler for testing the protocol stack without any SDR hardware. The high-level architecture of 5G-LEO is similar to 5G-GOA except for a few critical differences such as:

- Commercial channel emulator has been used to emulate the LEO satellite channel
- Single UE has been used instead of 2 UEs.

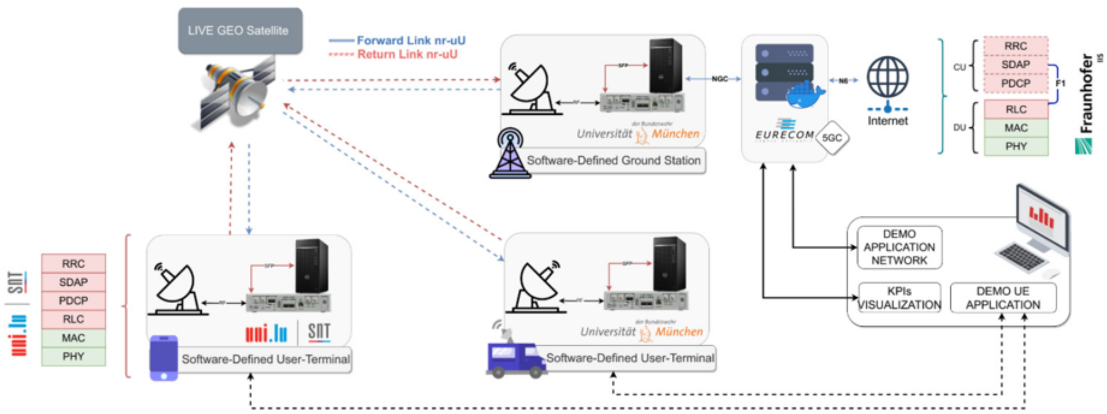


Fig. 2: High level architecture of 5G-GOA demonstrator

Layer	Modifications
PHY	• Extension of OAI rf-simulator to support simulation of long propagation delays **Non-NTN-specific features:** • Support of 5 MHz (15 kHz SCS) bandwidth • Phase Tracking Reference Symbols (PT-RS) • Support for multiple bandwidth parts (BWP)
MAC	• HARQ deactivation at gNB and UE • 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 (see Figure 4)

TABLE I: OAI modifications for 5G-NTN in 5G-GOA

- Functional Split (FAPI [11]) based approach is used to implement the gNB: (a) Centralized Unit (CU) and (b) Distributed Unit (DU).
- Two satellites are emulated where the on-ground CU remains the same while the two transparent payload satellite act as DU-0 and DU-1.
- Handover has been implemented where the UE is handed over between DU-0 and DU-1 based on a timer. This entire process of timer-based handover has been illustrated in Figure-3.

Interested readers can refer to [12] for a detailed discussion of OAI capabilities towards implementing 5G-NTN and insights on future road-map for further developing OAI as a preferred tool for research related to 5G-NTN.

IV. Preliminary Tests and Results

In this section, we briefly list the results which were obtained during the testing of 5G-GOA and 5G-LEO PoC demonstrators.

A. 5G-GOA

The 5G-GOA POC has been tested both in-lab using a commercial channel emulator [13] and OTS during several conferences, demonstrations, and workshops [14], [15]. For both types of testing, two configurations using an SCS of 15 kHz and 30 kHz have been tested for a bandwidth of 5 MHz and 10 MHz respectively. A single gNB on the ground (located at Munich) has been connected to two UEs (on the ground) located at two different sites (Munich and Luxembourg) via a satellite with a transparent payload during the tests. Link establishment and data connection have been verified with the successful full completion of the following steps.

(i) Broadcast channel PBCH is decoded by the UE.
(ii) Initial synchronization completes and RRC-Connection between gNB and UE is established.
(iii) Two UEs located on the ground are simultaneously connected to the gNB.
(iv) Higher layers (RLC, PDCP) do not state any warning

Layer	Modifications
PHY	• Extension of OAI rf-simulator to support simulation of time-variant propagation delays and frequency offset • Continuous frequency offset estimation and compensation • Continuous timing drift estimation and compensation • Uplink Power Control (Open-loop & Closed loop)
MAC	• Support for up to 32 HARQ Processes (following 3GPP Release 17) • Channel State Information (CSI) Reporting • DL/UL Adaptive Modulation and Coding (AMC) • Timer-based Handover between multiple beams
RLC	• Disabling HARQ-ARQ interaction in Acknowledged Mode transmissions • Increase ARQ buffer size • Increase t-Reassembly Timer
RRC	• Increase selected UE timers (T300, T301, T311)
GUI	• Extension of OAI GUI (Scope) to enable monitoring of real-time KPIs (see Figure 4)

TABLE II: OAI modifications for 5G-NTN in the 5G-LEO

related to timer expiry and buffer overflow. Please note that Unacknowledged Mode (UM) RLC has been used here since no re-transmission is feasible due to excessive RTT in GEO.

(v) Ping test between the application server and the UE to confirm data packet exchange within the expected time.

(vi) Data delivery between the application server and UE is verified using the following applications:
   (a) TCP and UDP bandwidth tests using iperf
   (b) Web browsing
   (c) VoIP calls

B. 5G-LEO

Likewise, 5G-GOA, the 5G-LEO POC is also being tested for 15 kHz and 30 kHz SCS, however with a commercial channel emulator to emulate a LEO satellite propagation channel instead of live satellites. This has been done due to demonstration feasibility and the requirements from European Space Agency (ESA). Since 5G-LEO is still ongoing and hence the end-to-end test results are not available at the time of writing this paper. Nonetheless, unit tests of individual components have already been done such as:

(i) Resilience to time-varying Doppler.
(ii) Resilience to time-varying RTT and timing drift.
(iii) Increased number of HARQ processes (32).
(iv) Re-transmisisons from RLC layer. Please note that Acknowledgement Mode (AM) RLC has been used in 5G-LEO since re-transmissions are possible due to the lower RTT in LEO compared to GEO.
(v) Timer-based handover which is a peculiar feature developed for 5G-LEO where the gNB initiates an intra-DU handover a certain time after the first connection is established. A detailed illustration is shown in Figure 3.

V. Conclusions and Ongoing works

5G-GOA and 5G-LEO are the pioneer projects for the latest 3GPP specifications in Release 17 to support NTN as an integral part of 5G. Therefore, it is now possible to evaluate this technology for the expectations on 5G NTN both on the lab and over existing GEO and LEO satellites, after finalization of the 5G-LEO project. Due to the available spectrum and the challenging link budgets in satellite communications, 5G NTN will not be able to provide the same data rates as terrestrial 5G networks. Nevertheless, 5G NTN is a complementary service to fulfill 5G requirements on ubiquitous coverage and seamless services. The developed OAI code from the two projects will be merged in the public OAI repository soon and made available for companies and research organizations. Upcoming works are implementations of the ongoing 3GPP Release 18 with NTN enhancements like mobility enhancements [16].

VI. Acknowledgment

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VII. Disclaimer

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

References

[1] 3GPP, 2023. [Online]. Available: https://www.3gpp.org/news-events/3gpp-news/nr-ntn
[2] "3GPP TR 38.811, "3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Study on New Radio (NR) to support non terrestrial networks (Release 15)"," 2019.
[3] "3GPP TR 38.821, "3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Solutions for NR to support non-terrestrial networks (NTN) (Release 16)"," 2021.
[4] "5G enabled ground segment technologies over the air demonstrator, online," 2023. [Online]. Available: https://artes.esa.int/projects/5ggoa

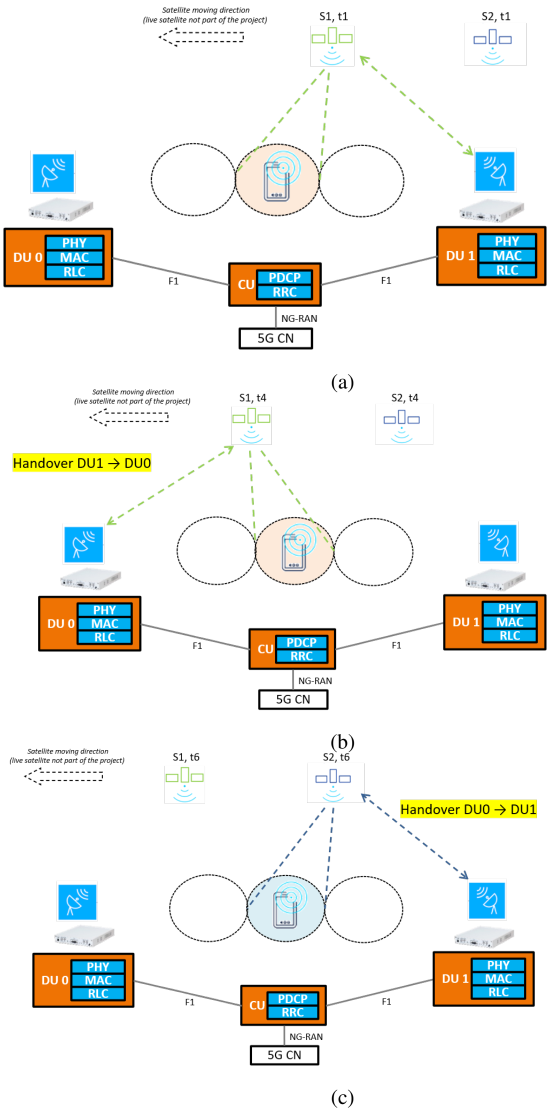

Fig. 3: Timer based Intra-DU handover proceedure in 5G-LEO. (a) UE is connected to DU-1 while the satellite moves from right to left(b) UE disconnects from DU-1 and connects to DU-0 meanwhile the CU remains the same (c) UE disconnects from DU-0 and connects to DU-1 meanwhile the CU remains the same

[5] "5G low earth orbit demonstrator, online," 2023. [Online]. Available: https://artes.esa.int/projects/5gleo

[6] "OpenAirInterface project, online," 2021. [Online]. Available: https://gitlab.eurecom.fr/oai/openairinterface5g/wikis/home

[7] 3GPP, "Rp-221819: Solutions for nr to support non-terrestrial networks (ntn)," 2022.

[8] T.-K. Le, U. Salim, and F. Kaltenberger, "An overview of physical layer design for ultra-reliable low-latency communications in 3GPP releases 15, 16, and 17," *IEEE access*, vol. 9, pp. 433–444, 2020.

[9] K. Liolis, A. Geurtz, R. Sperber, D. Schulz, S. Watts, G. Poziopoulou, B. Evans, N. Wang, O. Vidal, B. Tiomela Jou *et al.*, "Use cases and scenarios of 5g integrated satellite-terrestrial networks for enhanced mobile broadband: The sat5g approach," *International Journal of Satellite Communications and Networking*, vol. 37, no. 2, pp. 91–112, 2019.

[10] S. Cioni, X. Lin, B. Chamaillard, M. El Jaafari, G. Charbit, and L. Raschkowski, "Physical layer enhancements in 5g-nr for direct access via satellite systems," *International Journal of Satellite Communications and Networking*, 2022.

[11] L. M. Larsen, A. Checko, and H. L. Christiansen, "A survey of the functional splits proposed for 5g mobile crosshaul networks," *IEEE Communications Surveys & Tutorials*, vol. 21, no. 1, pp. 146–172, 2018.

[12] S. Kumar, A. K. Meshram, A. Astro, J. Querol, T. Schlichter, G. Casati, T. Heyn, F. Völk, R. T. Schwarz, A. Knopp *et al.*, "Openairinterface as a platform for 5G-NTN research and experimentation," in *2022 IEEE Future Networks World Forum (FNWF)*. IEEE, 2022, pp. 500–506.

[13] "Keysight technologies, online," 2021. [Online]. Available: https://www.keysight.com

[14] S. Kumar, O. Kodheli, A. Abdalla, J. Querol, S. Chatzinotas, G. Casati, T. Schlichter, T. Heyn, H. Cheporniuk, F. Volk *et al.*, "5g-ntn geo-based over-the-air demonstrator using openairinterface," *5G-NTN GEO-based Over-The-Air Demonstrator using OpenAirInterface*, 2022.

[15] S. Kumar, A. Astro, O. Kodheli, J. Querol, S. Chatzinotas, T. Schlichter, G. Casati, T. Heyn, F. Völk, S. Kaya *et al.*, "5g-ntn geo-based in-lab demonstrator using openairinterface5g," in *11th Advanced Satellite Multimedia Conference*, 2022.

[16] "3gpp rp-230809, "nr-ntn enhancements"," 2023-03.