Field Trial of a 5G Non-Terrestrial Network Using OpenAirInterface

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Satellites enable the provision of global 5G coverage utilizing a customized protocol stack for direct access of 5G devices. This paper reports the results of a field trial based on an Open Source Software (OSS) 5G protocol stack modified for Satellite Communications. 5G New Radio (NR) functions have been adapted to support 3GPP Non-Terrestrial Networks (NTN) standardization for Release 17. Some of the currently discussed enhancements for 5G NR direct access for NTNs were evaluated in this study utilizing a geosynchronous satellite system. NTN devices and base station were software-defined solutions communicating via satellite through a standardized 5G NR waveform. The results show that OSS implementations running on general purpose platforms greatly support the research and standardization process for 5G-Beyond NTNs. New functions related to NTNs can be evaluated at an early stage over channel emulators or real world satellites to highlight the capabilities of space based 5G-Beyond networks. Therefore, OSS can be a starting point to turn the vision of 6G protocols on-board the satellite into reality.

Index Terms—**Satellite communication, Satellite ground stations, 5G mobile communication, Radio access networks, Space communications**

I. INTRODUCTION

The Fifth Generation Mobile Networks (5G), is set to revolutionize the world of mobile communications. Satellites will play an essential role in the development of 5G-Beyond networks and in this field major satellite operators see future market potential. In this context, the current 3rd Generation Partnership Program (3GPP) work programme for Release 17 of the 5G New Radio (NR) standardization defines new features to support transparent (non-regenerative) satellites. In this architecture the satellite acts as a amplify-and-forward relay. This step towards standardizing satellite links in the 5G network represents only the first phase of the seamless integration of non-terrestrial systems in future 5G-Beyond architectures.

The standardization efforts on Satellite Communication (SatCom) in 3GPP is commonly known as Non-Terrestrial Networkss (NTNs). The ambition is to achieve initial integration of NTNs into 5G by evolving the protocols and functions of the 5G Core Network (5GC) and Radio Access Network (RAN), including the NR radio interface, to support NTNs. As part of the standardization process on 5G (3GPP Release 15 to 17), this is the first time that satellites are being studied in detail outside of the transport network to provide value to a direct end user. Here, the terminal no longer communicates with a base station via a terrestrial mobile radio channel, but via a satellite channel to a distant base station as part of the satellite ground components. This NTN is intended to enable the integration of Geostationary Earth Orbit (GEO) and upcoming Non-Geosynchronous Orbit (NGSO) satellites (e.g. [1], [2]) in both transport and access networks. Within the first two phases of the 5G standardization in 2017 to 2019, two fundamental studies (see [3] and [4], respectively) were conducted to investigate in which network architectures GEO satellites (Fig. 1) can play a role in the future 5G/6G infrastructure [5].

The current focus of Release 17 3GPP standardization is on satellites and High-Altitude Platform System (HAPS) with transparent (non-regenerative) payloads. Release 17 features taking care of NTN aspects and issues were frozen in March 2022. The extensions on standardization provide a specification how 5G NR can be used for direct access via satellite between Low Earth Orbit (LEO) and GEO.

Previous studies have identified two main types of service links between satellites and earth stations: First, direct connectivity with handheld devices transmitting at a maximum power of $23\,\mathrm{dBm}$ and omnidirectional antenna. Second, broadband connectivity utilizing Very Small Aperture Terminals (VSAT) with directional antennas. Furthermore, the standardization distinguish between direct and indirect access as shown in Fig. 2. The direct access allows an end user terminal to directly utilize a satellite link whereas the indirect access and backhauling is required to use a relay or base station on earth. This study considers the novel direct access architecture where the 5G NR waveform is employed for the first time on a satellite link.

However, this convergence is expected to be realized in 10 years as part of the 6G standard. Until then, a truly "intelligent" network will be set up in space that makes optimum use of the capacities of satellites in different orbits. These efforts in standardization can pave the way for an even more significant role of NTNs in the 6G standards. First definitions of the 6G network at a scientific level have been recently established initial research and development goals for the next 10 years. Recent work has already shown first efforts in terms of deriving first concepts and exploration of new technologies [6], [7], [8]. It is expected that NTNs will be

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a main service provider in the overall 6G ecosystem. Early prototypes of the NTN technology are important for the 6G community and the Release 18 standardization process.

Open Source Software (OSS) can make an important contribution to new NTN innovations, since New Space companies, can rely on a basic framework for their future software development. Porting the 5G/6G protocol stack on-board will be an unprecedented innovation. The integration becomes even more important, in the light of satellites connecting with each other via inter-satellite links. Implementing base station functions on-board the satellite is therefore only logical in future 6G networks.

In addition to the commercial implementations of the 3GPP based standards by the major network equipment suppliers, there is a small group of OSS projects implementing 3GPP RAN components. Several projects have been implemented the Fourth Generation Mobile Networks (4G) Long Term Evolution (LTE) standard. GNU‘s Not Unix (GNU) Radio provides an LTE User Equipment (UE), Evolved Node B (eNB) and Evolved Packet Core (EPC) implementation [9]. There are currently no activities with respect to 5G NR, and even the development on the LTE components have not been continued. Software Radio Systems (SRS) provides an OSS implementation of several LTE features for UE, eNB and EPC [10]. In April 2021, SRS renamed the OSS project from srsLTE to srsRAN, as 5G Non-Standalone Access (NSA) support was released for the srsUE. In Mai 2022, srsRAN brought 5G Standalone Access (SA) support to both Next Generation Node B (gNB) and UE. At the moment, the OpenAirInterface™ (OAI) project [11] seems to provide the most advanced implementation of 5G NR gNB and 5G NR UE. On the contrary to the other OSS projects, the OAI gNB is already reaching a downlink throughput higher than $250\,\mathrm{Mbps}$ with a single layer $80\,\mathrm{MHz}$ configuration utilizing a Commercial Off-The-Shelf (COTS) device.

The contribution of this article is to demonstrate the feasibility of the 5G NR protocol stack via a NTN. We developed a prototype based on the OAI OSS and off-the-shelf radio hardware which has partly been published in [12]. The results from an Over-The-Air (OTA) field trial over a transparent GEO satellite are reported in detail in this article.

The paper is organized as follows: In Section II, the current status of the 5G OSS protocol stack OAI is described. Section III presents the NTN adaptions of the 5G protocol stack, which were the baseline for our study. The field trial is reported in Section IV. An outlook on future work is given in Section V. Conclusions are drawn in Section VI.

II. OpenAirInterface 5G Development Status

To bring the 5G/6G protocol stack on-board the satellite, an inter-operable, modular and open network architecture including a strong OSS ecosystem is necessary. OAI implements 4G and 5G RAN and Core Network (CN) as specified by the 3GPP on general purpose x86 computing hardware and COTS Software Defined Radio (SDR) cards such as the Universal Software Radio Peripheral (USRP). Real-time operation requires specific hardware and operating system constraints for different hardware targets. An SDR system performs most of the signal processing using a general purpose computer, combined with dedicated hardware such as signal processors and/or Field Programmable Gate Arrays (FPGAs). Receiver bandwidths of a few $10\,\mathrm{MHz}$ can be realized with general purpose computers. This allows the deployment of 4G LTE as well as 5G NR networks at a very low cost [11].

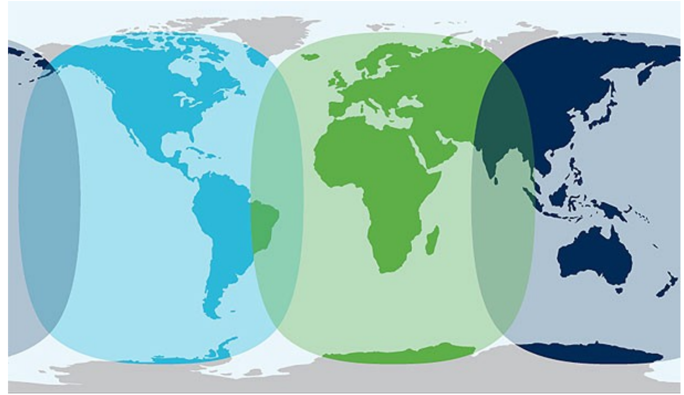

Fig. 1. Three GEO satellites can almost cover the whole globe [13].

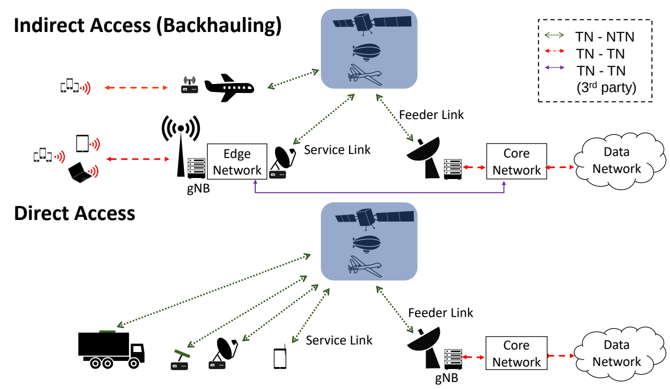

Fig. 2. High level 5G NTN architectures for the indirect access (backhauling) and the direct access. The direct access architecture utilizes the NR waveform on both, feeder link and service link. A direct access UE is sending data over the SatCom link without relay in between.

Most terrestrial 5G NR deployments today use the NSA mode, which requires an existing 4G LTE network. In the NSA option all the control plane traffic is exchanged with the UE through the 4G eNB. Once the UE is attached to the EPC and connected to the cell, the end-to-end user-plane traffic between the UE and the 5GC is delivered through the gNB.

For any new network deployment the SA mode is much more interesting compared to NSA mode. The 5G SA mode requires a new 5GC and does not use legacy LTE radio access. For future NTNs the 5G SA mode seems to be the most attractive architecture as well. Fig. 3 shows the OAI 5G RAN architectures discussed in the following subsections.

A. 5G Non-Standalone Access

Initial terrestrial deployments of 5G NR will use the NSA option. In the NSA mode all Control Plane (CP) traffic is exchanged between the UE and the 4G eNB. The eNB communicates with the gNB over X2-C interface. This allows

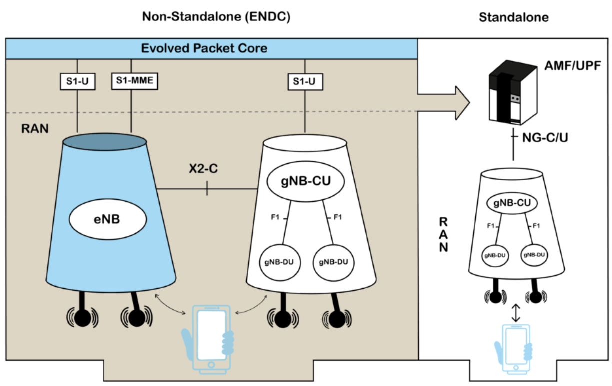

Fig. 3. OAI 5G RAN project showing the architecture for 5G NSA and SA.

the exchange of all required NR configuration to and from the UE. The S1-C interface is required for the communication between the eNB and the EPC to successfully attach the UE. Once the UE is attached to the EPC and connected to the 5G cell, the end-to-end user-plane traffic between the UE and the CN (S1-U interface to the SGW) is delivered exclusively through the gNB.

B. 5G Standalone Access

For 5G NTN, as well as other applications of 5G (in, e.g., Industry 4.0), the 5G network will need to operate in SA mode which does not depend on legacy 4G LTE, but requires a new 5GC. The 5GC Service-Based Architecture (SBA) is fully cloud-aligned and supports control plane function interaction, re-usability, flexible connections and service discovery [14]. A high level representation of the 5G SA system is illustrated in Fig. 4. The main 5GC functions have all been implemented in the OAI 5GC and can easily be deployed using docker-compose:

- Access and Mobility Management Function (AMF)
- Session Management Function (SMF)
- Network Repository Function (NRF)
- User Plane Function (UPF)
- SPGW-U-tiny

Compared to NSA, in SA the gNB needs to also implement the complete Radio Resource Control (RRC) layer and handling of all the associated messages as well as the NG Application Protocol (NGAP) to interface with AMF (N2 interface) and UPF (N3 interface). A support of multiple Bandwidth Parts (BWP) at the gNB is needed for the SA mode. The BWP feature has been included into 5G NR to support various UE categories in terms of bandwidth. In addition, a more advanced UE can use a small bandwidth if less data is transmitted and open the full cell bandwidth when a large amount of data is needed. The initial access of a UE happens only on the initial BWP. Support for contention based access is needed as well. In addition, support for common and dedicated control channels is required. Only after the initial connection and authentication with the AMF, the full BWP is configured and used for user-plane traffic.

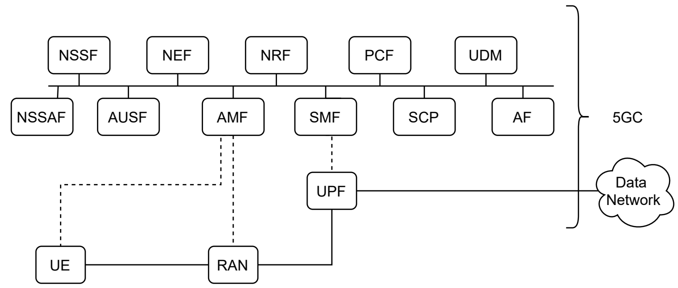

Fig. 4. High level 5G SA architecture.

C. noS1 mode

With the *noS1* mode no eNB or CN is needed to establish a connection between an OAI UE to an OAI gNB. This mode is a mixture of the NSA and SA mode. The *noS1* mode only supports user-plane traffic. Control-plane traffic is injected and received via Ethernet. One exception is the Random Access (RA) procedure that is also happening in *noS1 mode*. The UE knows the parameter configuration in advance by means of a configuration file. We chose the *noS1* mode because the OAI 5GC development had not been completed. All user traffic terminates at the OAI gNB and is not forwarded to another data network.

III. Non-terrestrial networks adaptations

The basic framework for the NTN standardization is the terrestrial 5G NR standard. An overview and summary of the 5G NR RAN system is given in [15]. The current 3GPP focus is on transparent communication payload satellite systems, meaning all the enhancements are added to the UE and the gNB on earth. UEs and gNBs are required to handle a very large propagation delay compared to terrestrial systems. The 3GPP studies assume a Frequency Division Duplex (FDD) system, earth fixed tracking area, and UEs with Global Navigation Satellite System (GNSS) capability. Typical SatCom effects and their impact on the NR standard are shown in Table I. The following enhancements are included into the 3GPP Rel. 17 specification [4]:

- Timing-relationship
- Uplink (UL) time and synchronization
- Hybrid Automatic Repeat Request (HARQ) operation (adaption of the number of HARQ processes and disabling of HARQ feedback)
- RA procedure
- Value range extension of Radio Link Control (RLC) and Packet Data Convergence Protocol (PDCP) parameters
- Cell selection/reselection
- UL scheduling
- Handover
- Service continuity to move between terrestrial and non-terrestrial service

A. 5G OAI Extensions to support NTN

The basic configuration for terrestrial networks implemented in OAI supports 30 kHz Sub-Carrier Spacing (SCS) and a

TABLE I
KEY EFFECTS ON THE 5G NR STANDARD TO SUPPORT NTN DIRECT ACCESS.

Effect	Impact on NR
Long latency	HARQ
Long latency	PHY procedures (ACM, power control)
Long latency	MAC/RLC Procedures
Differential delay	RACH
Differential delay	TA in RA response message
SatCom channel impairments	Demodulation Reference Signal (DMRS) frequency density
SatCom channel impairments	Cyclic prefix
SatCom regulatory constraints	FDD access
Doppler effect	Initial synchronization DL
Doppler effect	DMRS time density
Delay variation due to large cell size	TA adjustment
Moving cell pattern for NGSO	Hand-over/paging
Phase noise impairment	PTRS
High-power amplifier back-off	Peak to Average Power Ratio (PAPR) reduction techniques

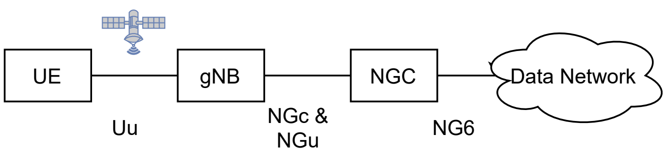

Fig. 5. 5G NTN architecture for direct access including UEs, a transparent satellite link, a gNB and the 5GC.

bandwidth of $40\,\mathrm{MHz}$. Within a $10\,\mathrm{ms}$ frame, 20 slots (each $0.5\,\mathrm{ms}$) are transmitted. A Time Division Duplex (TDD) period of 10 slots includes 7 Downlink (DL) slots, 1 mixed slot and 2 UL slots. However, since most of the NTN scenarios operate in FDD mode, the implementation of OAI 5G features to support FDD operation with configurable intermediate frequencies at Physical Layer (PHY) was required. Our FDD implementation was limited to the PHY and was still relying on the TDD scheduling procedures at the Medium Access Control (MAC) layer, i.e. the scheduler was allocating resources according to a TDD DL and UL time domain allocation pattern. Our implementation provides UL and DL transmissions which is separated in frequency and time. This half-duplex mode does not use the spectrum efficiently compared to a true TDD and FDD mode. This mode will be replaced in our future implementations by a true FDD mode.

To enable this field trial, $10\,\mathrm{MHz}$ bandwidth with $30\,\mathrm{kHz}$ SCS, including the necessary changes for Physical Random Access Channel (PRACH) have been implemented as well. In addition, Phase-Tracking Reference Symbols (PTRS) in Physical Downlink Shared Channel (PDSCH) and Physical Uplink Shared Channel (PUSCH) were added to our OAI repository.

B. 5G OAI pre-standard extensions for NTN Rel-17

The main degradation of the 5G signal over the satellite channel is due to the large propagation delay, which can be hundreds of times the average terrestrial delay. For geostationary spacecrafts at $35\,786\,\mathrm{km}$ altitude, the delay in one direction is approximately $250\,\mathrm{ms}$, with a Round Trip Time (RTT) of around $0.5\,\mathrm{s}$.

In order to account for the large GEO satellite propagation delay, the features listed in Table II were implemented in our OAI repository, thus, enabling the final NTN field trial.

TABLE II
FEATURES INTRODUCED IN OAI TO SUPPORT THE 5G PROTOCOLS OVER NTNS.

Feature	Description
Initial timing advance at UE side based on the target channel propagation delay	The computation of the initial timing advance for the reception of the initial DL synchronization signals and the transmission of the RA preamble shall take into account the characteristic propagation delay of the satellite channel.
Extension of time domain allocation (k_2) for PUSCH scheduled by Random Access Response (RAR) UL grant (clause 6.2.1.1 of [4])	In case of PUSCH transmission initiated by the RA procedure, the UE receives an UL grant via RAR. The UL scheduling is given by $n+k_2+\Delta$ (clause 8.3 of [16]), where n is the slot in which the RAR was received. To take into account the longer propagation delay the k_2 is extended with by means of k_{offset} .
Extension of time domain allocation (k_2) for PUSCH scheduled by DCI (clause 6.2.1.1 of [4])	In case of PUSCH transmission initiated by Physical Downlink Control Channel (PDCCH), the UE receives an UL grant via Downlink Control Information (DCI). The UL scheduling is given by $n \cdot \frac{2^{\mu_{\mathrm{PUSCH}}}}{2^{\mu_{\mathrm{PDCCH}}}} + k_2$ (clause 6.1.2.1 of [17]), where n is the slot in which the DCI was received and μ is the numerology. To take into account the longer propagation delay the k_2 is extended with by means of k_{offset}.
Extension of RAR window (clause 7.2.1.1.1.2 of [4]).	The RAR window, during which the UE monitors the PDCCH for a RAR message, is designed for terrestrial communications and covers only up to a few milliseconds after the transmission of the preamble. Therefore, size is extended by means of a slot offset UE_{k_2} to delay the start of the RAR window.
Disabling of HARQ (clause 7.2.1.4 of [4]).	UL HARQ retransmission and feedback for DL transmission are disabled by means of changes to the OAI gNB scheduler. The number of the HARQ processes is also increased.

IV. 5G-NTN TRIALS OVER GEO SATELLITE

A. Test Setup

The reference architecture for the demo is depicted in Fig. 6 and consists of a 5G NR link between OAI UE and OAI gNB, both located on ground at the Earth station in Neubiberg, Germany. This research facility enabled a real OTA test of our NTN platform over a GEO satellite located at 13.2° East and casting a single NTN cell for our European service zone. Table III shows the most relevant configuration parameters of the demo platform. The GEO satellite itself operated as an analog repeater in space that frequency-converts, amplifies, and forwards the received NR signals, thus relaying the Uu air interface between the OAI UE and OAI gNB. Our satellite link budget calculation is shown in Table IV. The setup allows a guaranteed C/N of at least $9.3\,\mathrm{dB}$ for the 5G NR UL and DL. This leads to a maximum throughput of approximately $20\,\mathrm{Mbps}$ with COTS satellite modems.

Both gNB and UE as shown in Fig. 8 were running on consumer computers with ETTUS X310 USRP operating in L-band below $2\,\mathrm{GHz}$. We used a Block Upconverter (BUC)

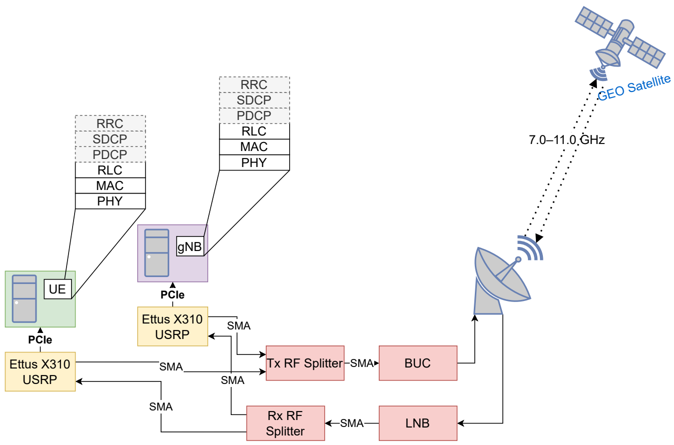

Fig. 6. 5G NTN architecture (*noS1* mode) for the field trial. Our demonstrator includes adapted PHY, MAC, and RLC layer for OAI.

TABLE III
CONFIGURATION PARAMETERS OF THE NTN DEMO.

Parameter	Description
Bandwidth	10 MHz (DL and UL)
Frequency band	7.0 GHz to 11.0 GHz (X-band)
Satellite position	13.2° East
Antenna	4.9 m parabolic (50 dBi receive gain, Fig. 7)
Modulation	QPSK and 16-QAM modulation scheme

Fig. 8. Two Ettus X310 URSPs functioning as both the gNB and the UE in the NTN demonstration.

TABLE IV
LINK BUDGET CALCULATION.

Link Information	Unit	DL	UL
Occupied Bandwidth	kHz	10000.0	10000.0
Effective EIRP per Carrier	dBW	53.4	53.4
Total Path Loss	dB	202.6	202.7
Effective G/T Satellite	dB/K	6.5	6.6
Effective G/T Earth station	dB/K	24.2	24.2
C/N Total	dB	12.7	12.6
C/(N+I+XPD+IM)	dB	11.4	11.3
C/N required	dB	9.3	9.3
Link Margin	dB	2.1	2.1

Fig. 7. GEO transmissions with a 4.9 m satellite antenna and co-located gNB and UE in the laboratory building.

in our UL transmission to convert a frequency band from the lower USRP frequency to the higher satellite transmission frequencies. Our Low-Noise Block Downconverter (LNB) converted the received satellite signals to the lower USRP frequencies. During our field test, all traffic was terminated at our OAI base station (*noS1* mode), so no transport and CN was needed to send Internet Protocol (IP) user traffic between the UE and gNB.

B. Results

The OTA test consisted of the following steps: (i) verify the proper functionality of the RA adaptations by performing a successful initial connection setup between UE and gNB; (ii) verify the proper functionality of the time-domain adaptations by successfully decoding the 5G DL transmission signal; (iii) verify the proper functionality of the implemented 5G Timing Advance (TA) procedure by successfully decoding the 5G UL transmission signal, thus, achieving UL synchronization.

After receiving the initial synchronization sequences we observed a successful four-step RA procedure with our NTN network prototype: The UE transmitted the RA preamble which was received by the gNB. A RA response sent by the gNB indicated the preamble reception and provided a timing-alignment command to adjust the transmission timing of the UE. Afterwards UE and gNB exchanged *Message 3* in the UL and *Message 4* in the DL to resolve collisions with potential other UEs. In addition, the RA procedure was also used to re-

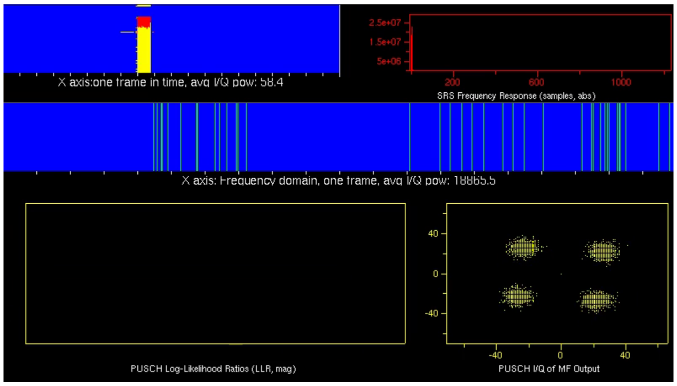

Fig. 9. OAI GUI: QPSK constellation diagram of the PUSCH at the NTN gNB (bottom right).

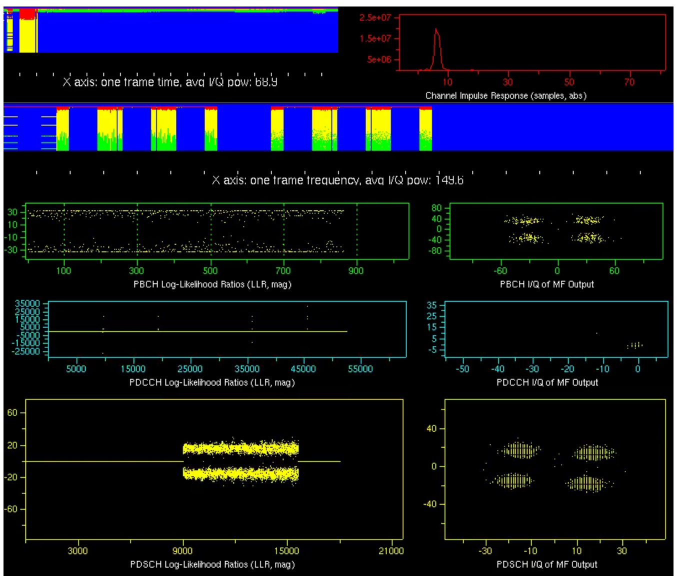

Fig. 10. OAI GUI: QPSK constellation diagram of PBCH (top right) and the PDSCH (bottom right) at the NTN UE.

establish UL synchronization if the UE lost synchronization due to a too long period without any UL transmission.

Over the course of the tests, the satellite drift of the GEO spacecraft in its orbital station-keeping box was also compensated by the NTN TA procedure. By means of a Linux ping command, we measured a RTT between gNB (IP address: 10.1.10.1) and UE (IP address: 10.1.10.2) ranging between 530 and 570 milliseconds. The RTT measurements with our prototype, shown in Fig. 11, are comparable with COTS satellite modems. The Quadrature Phase Shift Keying (QPSK) constellation diagrams in the IQ domain, of the Physical Broadcast Channel (PBCH), PDSCH and PUSCH shown in Fig. 10 and 9 visually confirm the successful reception of the PHY signals with negligible phase rotation of the constellation points. No 5G PTRS was utilized due to the high Signal-to-Noise Ratio (SNR). Please note that all the control information was transmitted via Ethernet between UE and gNB.

Fig. 12 shows the spectrum of the received signals from the

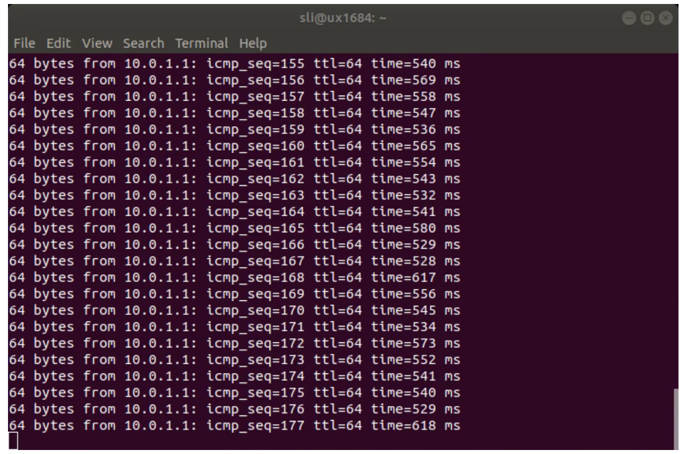

Fig. 11. Measurement of the RTT between UE and gNB with ICMP messages.

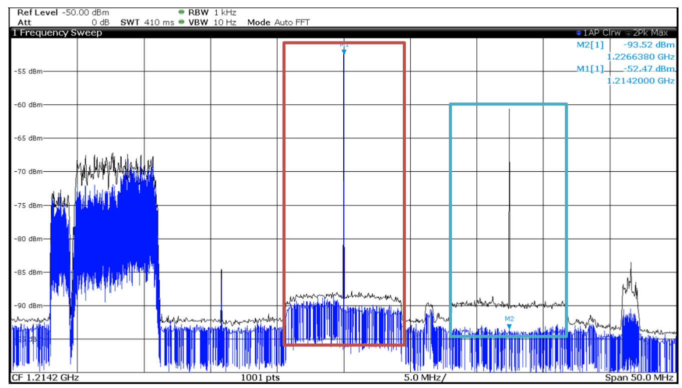

Fig. 12. Transmitting and receiving satellite spectrum from gNB (left; red) and UE (right; blue).

GEO satellite at the $4.9\,\mathrm{m}$ satellite antenna. The two carriers[1] in the red box and the blue box belong to the gNB and the UE, respectively. The maximum received power is highlighted with a spectral mask (black line). Furthermore, the satellite transponder was also used by other satellite modems during our field trial. Fig. 12 (left) shows spectrum occupied by COTS modems. However, utilizing large guard bands between the modem carriers and the 5G NR carriers we tried to avoid in-band interference.

V. Future Work

The evolution of this NTN platform is being continued in the European Space Agency (ESA) funded 5G-GOA project [18]. Aim of the project is to produce a standard compliant 5G NTN network, consisting of an adapted UE and gNB. The intention is to verify a bidirectional end-to-end communication between two user terminals and the 5GC. Therefore, additional changes in the protocol stack are needed. The OAI PHY will be adapted to support: (i) $5\,\mathrm{MHz}$ bandwidth with $15\,\mathrm{kHz}$ SCS; (ii) multiple BWPs; (iii) full FDD scheduling at the MAC layer, by enabling continous DL and UL transmission/reception; (iv)

[1] The Local Oscillator (LO) for both gNB and UE was clearly visible. There seems to be a problem or driver issue with the daughter boards for ETTUS X310 USRPs. Calibration did not resolve it. We will apply filtering to mitigate the LO for future tests.

multi-UE support with the necessary enhancements of the simultaneous RA; (v) enhancement of the feature *disable HARQ* for a better collaboration with the upper layers (especially RLC and PDCP), as we observed issues in the data transmission with our implementation during this field trial.

Furthermore, the OAI Graphical User Interface (GUI) will be extended within the project to show Key Performance Indicators (KPIs) of the 5G communication link such as the Block Error Rate (BLER) of the transmissions, achievable throughput per UE and experienced delay of the link, including effects of retransmissions on IP layer. 5G-GOA will merge the developed extensions and improvements into the main development branch of OAI in September 2022. The ultimate goal of the OAI protocol stack for NTNs is to support in orbit 5G NR NTN experimentation and validation on-board the satellite.

In addition to customizing the protocol stack for GEO satellites, the next step is to conduct initial tests of 5G NR over NGSO channel emulators. Many issues regarding the realization of a 5G satellite system for NGSO constellations are still unresolved and raise a variety of technical and scientific problems. An example of a known difficulty is that low-flying satellites move around the Earth at high speeds. In such a scenario, a 5G end user will be within the footprint of the satellite for a few minutes only. Therefore, the connection from one satellite to a subsequent one, has to be handed over without any interruption of the 5G NTN link. This issue is even more challenging with high UE mobility like in high-speed train and airplane use cases which have been analyzed in [19], [20], [21].

VI. Conclusion

In this paper, we reported the results of our 5G non-terrestrial field trial. A dynamic investigation and prototyping of the 5G protocol stack via GEO satellite, as currently discussed in the 3GPP NTN RAN meetings, was performed. We showed that the OSS OAI, compliant with 5G Release 15, can be adapted in such a way that the protocol stack is able to achieve bidirectional IP traffic transmission via a GEO satellite. Our test results illustrate the importance of OSS for the 5G-Beyond research & development phase and satellite integration into 6G networks. OSS could be a starting point to bring the 5G/6G protocol stack on-board the satellite. The development of an OSS 5G/6G ecosystem will be an innovation driver for SatCom in the next few years.

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References

[1] N. Pachler, I. del Portillo, E. F. Crawley, and B. G. Cameron, “An Updated Comparison of Four Low Earth Orbit Satellite Constellation Systems to Provide Global Broadband (pending publication),” *IEEE International Workshop*, 2021. [Online]. Available: http://systemarchitect.mit.edu/docs/pachler21a.pdf

[2] SES Satellites, “O3b mpower,” Oct. 2021. [Online]. Available: https://o3bmpower.ses.com

[3] 3GPP, “Study on new radio (NR) to support non-terrestrial networks (release 15) v15.3.0,” 3GPP, techreport 38.811, Jul. 2020.

[4] ——, “Solutions for NR to support non-terrestrial networks (NTN) (release 16) v16.0.0,” 3GPP, techreport 38.821, Dec. 2019.

[5] P. D. Arapoglou, S. Cioni, E. Re, and A. Ginesi, “Direct Access to 5G New Radio User Equipment from NGSO Satellites in Millimeter Waves,” *2020 10th Advanced Satellite Multimedia Systems Conference and the 16th Signal Processing for Space Communications Workshop, ASMS/SPSC 2020*, 2020.

[6] S. Kota and G. Giambene, “6G Integrated Non-Terrestrial Networks : Emerging Technologies and Challenges,” *IEEE International Workshop*, 2021.

[7] X. Lin, S. Cioni, G. Charbit, N. Chuberre, S. Hellsten, and J.-f. Boutillon, “On the Path to 6G : Embracing the Next Wave of Low Earth Orbit Satellite Access,” *IEEE Communications Magazine*, no. December, pp. 36–42, 2021.

[8] G. Araniti, A. Iera, S. Pizzi, and F. Rinaldi, “Toward 6G Non-Terrestrial Networks,” *IEEE Network*, pp. 1–8, 2021.

[9] openLTE, “Openlte is an open source implementation of the 3gpp lte specifications,” Oct. 2021. [Online]. Available: http://openlte.sourceforge.net/

[10] srsRAN, “srsran your own mobile network,” Oct. 2021. [Online]. Available: https://www.srslte.com/

[11] F. Kaltenberger, A. P. Silva, A. Gosain, L. Wang, and T.-T. Nguyen, “OpenAirInterface: Democratizing innovation in the 5G era,” *Computer Networks*, vol. 176, no. 107284, Jul. 2020. [Online]. Available: http://www.eurecom.fr/publication/6243

[12] F. Kaltenberger, T. Schlichter, T. Heyn, G. Casati, F. Völk, R. T. Schwarz, and A. Knopp, “Building a 5g non-terrestrial network using openairinterface open-source software,” in *EuCNC/6G Summit 2021, 2021 Joint EuCNC & 6G Summit, 8-11 June 2021, Porto, Portugal (Virtual Conference)*, IEEE, Ed., Porto, 2021.

[13] Marine Satellite Systems, “Inmarsat fleet broadband,” Oct. 2021. [Online]. Available: http://www.marinesatellitesystems.com/

[14] Nokia Networks, “5G core,” Jan. 2019. [Online]. Available: https://networks.nokia.com/5g/5g-core

[15] F. Rinaldi, A. Raschellà, and S. Pizzi, “5G NR system design: a concise survey of key features and capabilities,” *Wireless Networks*, vol. 27, no. 8, pp. 5173–5188, 2021.

[16] 3GPP, “Nr; physical layer procedures for control (release 16) v16.8.0,” 3GPP, techreport 38.213, Dec. 2021.

[17] ——, “Nr; physical layer procedures for data (release 16) v16.8.0,” 3GPP, techreport 38.214, Dec. 2021.

[18] 5G GOA Consortium, “5g-goa - 5g enabled ground segment technologies over the air demonstrator,” May 2021. [Online]. Available: https://artes.esa.int/projects/5ggoa

[19] E. Juan, M. Lauridsen, J. Wigard, and P. E. Mogensen, “5G New Radio Mobility Performance in LEO-based Non-Terrestrial Networks,” *2020 IEEE Globecom Workshops, GC Wkshps 2020 - Proceedings*, pp. 1–6, 2020.

[20] T. Darwish, G. K. Kurt, H. Yanikomeroglu, M. Bellemare, and G. Lamontagne, “LEO Satellites in 5G and Beyond Networks: A Review from a Standardization Perspective,” pp. 1–17, 2021. [Online]. Available: http://arxiv.org/abs/2110.08654

[21] A. Baltaci, E. Dinc, M. Ozger, A. Alabbasi, C. Cavdar, and D. Schupke, “A Survey of Wireless Networks for Future Aerial Communications (FACOM),” *IEEE Communications Surveys and Tutorials*, vol. 23, no. 4, pp. 1–1, 2021.

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