Experimentation of 5G NR-NTN waveform in Ku-band on a laboratory satellite

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***Abstract*—This paper is the result of a cooperative work between Airbus Defense and Space, Eutelsat Group, ITRI and Mediatek, with the support of Airbus Constellations Satellites and Rohde & Schwarz. It presents the tests performed using a 5G NTN (Non-Terrestrial Network) waveform, in Ku-Band, with a laboratory satellite representative of a Eutelsat Oneweb satellite, called "Flatsat". The laboratory tests included a full two-way chain in "conducted" mode, with a 5G core, an NTN-enabled gNB, a 5G-NTN modem, channel emulators and additional equipment described in this paper. The tests were successful, allowing e.g. live video streaming on a PC connected to the 5G-NTN modem.**

Keywords — 5G NTN (Non Terrestrial Network), Ku-Band, demonstration, low Earth orbit (LEO)

I. Introduction

5G NTN standards [1] specify the integration of satellite components in a 5G system. It has been adopted in the context of 3GPP Release 17 for S-band and L-Band (FR1-NTN) and Release 18 for Ka-band (FR2-NTN). Support for Ku-band is an ongoing work item within Release 19. A standardized 5G NTN in Ku-band could become of main interest and is motivated by the possible use of 5G-NTN in coming LEO constellation, as for example with the next flagship space program of the European Union (IRIS^2) [2] or with future generations of Eutelsat Oneweb LEO constellation, and more generally, opening a global market for broadband connectivity over satellites in Ku-Band to address various applications (including aero, maritime, terrestrial vehicles).

5G NTN adoption has specific challenges to overcome. Concerning link budget, 5G NR waveform is based on OFDM (orthogonal frequency-division multiplexing) transmission, which is characterized by a high PAPR (Peak to Average Power Ratio) [3], which has an impact on amplifier backoff settings to be studied. It is also interesting to characterize SNR (Signal over Noise Ratio) thresholds for SSB (Synchronization Signal Blocks) and PDSCH (Physical Downlink Shared CHannel), compensation of the Doppler effect, frequency stability and synchronization, time advance and synchronization, and tolerance to phase noise.

Airbus Defense and Space, Mediatek and Eutelsat Group are active in the field of 5G NTN, especially in the 3GPP standardization groups, to prepare its future use on LEO and GEO Satellites. The activity described in this paper aimed at testing operation and performance of a 5G UE (User Equipment) communicating with a gNB and 5GC (5G Core Network) via a real satellite in a laboratory, simulating the low-Earth orbit. In September 2024 the laboratory tests were performed with a Eutelsat OneWeb lab satellite (named "Flatsat"), operated by Airbus Constellations Satellite. An overview of the tests was presented at a 3GPP RAN meeting [6].

The interest of these tests is to validate the developments done by partners in the development of NTN-specific features within their products. It is noted that the satellite is identical to in-orbit satellites of the OneWeb constellation, and the chipset and gNB used are very close to commercial models [4].

The paper is organized as follows. Section II provides an overview of the "Flatsat" laboratory test architecture. Section III briefly summarizes the tests execution. Finally, Section IV draws some concluding remarks on the results and the next steps.

II. Flatsat laboratory test architecture

A. *Eutelsat One Web Constellation*

Eutelsat OneWeb satellite system consists of a constellation of 600+ LEO satellites, plus in-orbit spares, on 12 orbital planes, in near-polar circular orbits of altitude 1,200 km. Eutelsat OneWeb satellite payload provides a transparent RF-link (Radio Frequency link) between users and gateways. The satellites have "transparent" transponders, mapping 16 frequency slots of the Ka-band uplink into 16 different beams in the Ku-band downlink, and vice-versa. The mapping from

Ka-band slots to beams is fixed, while the Ku-band frequency slot used in each beam is configurable.

Figure 1: Eutelsat OneWeb satellite

The user equipment transmits and receives in Ku-band to/from 16 contiguous beams that move along with the satellite. Because the beams are not fixed from the user equipment perspective, they are called "Earth moving beams". Each beam illumination lasts around 11 seconds, and after about 3 minutes the satellite coverage ends. Each beam has a dedicated amplifier (this is important for PAPR/Backoff considerations).

On the feeder link, the satellites transmit/receive in Ka-band to/from two steerable antennas, allowing to maintain continuous connection to one gateway by steering continuously one satellite antenna on the gateway location. It also prepares the connection to the next gateway location with the second antenna, enabling a seamless handover.

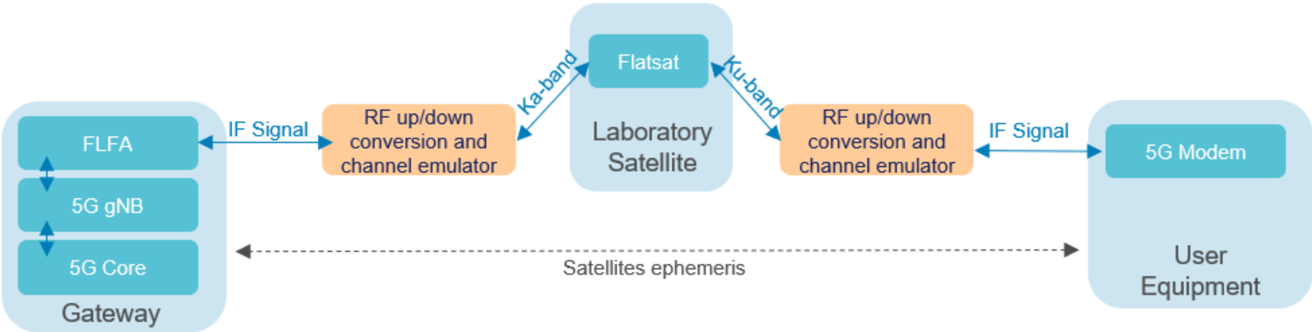

Figure 2: High level architecture of the test set up

B. *Test setup Architecture*

Fig. 2 shows the architecture of the setup implemented to demonstrate the use of a 5G NR-NTN waveform adapted in Ku-band, with a OneWeb lab satellite. The setup presents a full two-way chain, with a forward link from the gateway to the user equipment via the "Flatsat", and a return link from the user equipment to the gateway via the "Flatsat".

On the forward link, the gateway is emitting the feeder link in Ka-band, between 27,5 GHz and 30 GHz. The tests are performed in "conducted" mode, so no antenna is used. For our tests, the conversion from IF signal to Ka-band is realized by the R&S channel emulator. The frequency plan is divided into channels. Each channel corresponds to a specific user beam, and so the "Flatsat" is down-converting the signal received from each feeder-link channel to one of the eight channels of the corresponding user beam in Ku-band (between 10.7 GHz and 12,7 GHz). The transponders of the forward link are operating in automatic level control (ALC) mode. So, the output power is maintained constant by dynamic adjustment of an attenuator. We note that ALC may have unwanted consequences if the transmitted signal has variations in power.

On the return link, the user equipment transmits in Ku-Band. For our tests, the user equipment (a 5G-NTN modem) is used without its antenna and operates in L-Band (n7-band). The channel emulator up-converts this signal into Ku-band and transmits to the "Flatsat" using the antenna connector of a specific beam. Each beam can receive from one Ku channel, between 14 GHz and 14,5 GHz. The "Flatsat" up-converts the signal from Ku-band to Ka-band into the appropriate slot for feeder-link downlink to gateway.

As the tests are performed in "conducted" mode, a channel emulator between the gateway and the "Flatsat" (feeder link), and a channel emulator between the "Flatsat" and the user equipment (user link) are replacing the "real-world" radio channel by adding Doppler drifts and time delays to the signal. Only one beam was used for this test.

In the next sections, this paper will describe the main components of this test setup.

C. *The gateway*

The gateway consists of three main equipment, plus inherent connections:

- An equipment dubbed "FLFA" (Feeder Link Frequency Adjuster). Specifically developed by ITRI for the demonstration, the FLFA, implemented on a FPGA has 3 main missions:

    1. To compensate the Doppler drift on the feeder link [1]. On the uplink, the FLFA pre-compensates Doppler shift, to counterbalance the Doppler drift added by the channel emulator. So, the "Flatsat" can receive the 5G signal at the nominal frequency. On the downlink, the FLFA post-compensates the Doppler shift on the return feeder link and transmits the signal to the gNB at the nominal frequency.

    2. To handle the beam management via the feeder link frequency plan. Each frequency channel is mapped to a fixed corresponding beam. The FLFA transmits/receive in the appropriate frequency channel according to the illuminated beam.

3. To adapt the gNB interface to the channel emulator for the present test, or to the gateway RF BUC (Block Up Converter) and LNA (Low Noise Amplifier) in view of future OTA (Over The Air) tests campaign.

Figure 3: FLFA implemented on a FPGA

- A commercial 5G gNB, adapted by ITRI to implement 5G-NTN Rel17 specifications. It includes both the CU (Centralized Unit), the DU (Distributed Unit) and the RU (Radio Unit).
  1. This gNB supports 15kHz SCS (subcarrier spacing).
  2. The gNB is responsible for generating SIB19 signaling information. SIB19 is defined in 3GPP Realease 17 and provides to the UE parameters needed to access NR via NTN access such as ephemeris data or timing advance parameters.
  3. The gNB is operating in 3GPP "n7" band (2.6 GHz).
- A 5G core provided by Mediatek for the purpose of the demonstration. The 5G Core is connected to internet enabling the test of live video streaming.

Figure 4: gNB with 5G DU + CU

D. Flatsat

The “Flatsat” is a replica of the payload part of a Eutelsat OneWeb satellite. It is hosted and operated by Airbus Constellations Satellites. The “Flatsat” is not equipped with Ku antennas, so all the tests are performed in “conducted” mode. The “Flatsat” payload contains all the element to support 8 beams on the user side and transmission/reception to one gateway on the feeder link. The measurements can be realized by connecting the “Flatsat” with appropriate sources or receivers.

The tests in laboratory are limited only by the fact that the signal does not propagate in free air, but it is “conducted” by waveguides. Therefore, the effects due to antennas (gain, pointing error, etc.) and to channel (propagation losses, time delay, Doppler shift, impairments), need to be simulated by appropriate channel emulators.

E. The user Equipment

As our tests are performed in “conducted” mode, the user equipment is limited to the 5G-NTN modem without any RF antenna. The 5G-NTN modem is a prototype developed by Mediatek, based on a commercial FR1 chipset [4]. This modem is working in FDD (Frequency Division Duplexing). Its maximum bandwidth is presently of 50MHz. It has been demonstrated at MWC24 conference, integrated with an 8x8 elements antenna, and “pointing” to a robotic arm emulating the satellite movement [5].

The 5G-NTN modem supports 15kHz and 30kHz SCS (numerology #0 and #1 in 5G standard). For the purpose of the present tests, 15 kHz SCS has been used.

The user equipment compensates the Doppler effects on the user link. The 5G-NTN modem receives the ephemeris that allow to calculate and compensate the expected Doppler shift during satellite acquisition phase. Once the satellite signal is acquired, the SIB19 information shall be used instead.

The return link is pre-compensated by the 5G-NTN modem, according to real-time SIB19 information (containing precise ephemeris). The residual error should stay within the gNB tolerance margin.

F. The channel emulator

As showed in Fig. 2, two channel emulators are needed for the test set up: one operating in Ka-band, the other in Ku-band. For this demonstration, all equipment of the channel emulators was provided by Rohde & Schwarz.

Both channel emulators are composed of three equipment units: a two-way signal generator, operating simultaneously downlink and uplink, and two spectrum analyzers. The signal must be down converted to baseband to be processed by the signal generator. So, one spectrum analyzer down converts the signal from the “Flatsat” and the other spectrum analyzer, respectively from the user equipment for the user link, and from the gateway for the feeder link. The signal generator adds the time delay to the signal based on satellite position and adds the Doppler drift, based on satellite and user velocities, and realizes the up conversion.

The channel emulators have some limitations:

- The bandwidth is limited to 5 MHz. This is because beyond this limit, the Doppler spread is not correctly applied. For the purpose of the demonstration, the chosen bandwidth of the 5G-NTN OFDM carrier in forward link is 5 MHz. 50MHz was also tested, but without the full channel emulation and without Doppler effects implemented. In return link, 5 MHz is chosen for the 5G NTN channel as the standard configuration for “Flatsat” test.
- The second issue is the synchronization. Indeed, the channel emulator is simulating the Doppler shift, and the FLFA is compensating it, so they need perfect synchronization. However, the satellite ephemeris parameters are sent to the channel emulator using IP protocols, whose variable delay causes random mismatch in the ephemeris parameters transmission. As a result, if the equipment is not perfectly synchronized, the Doppler effect is not correctly compensated. So, the full chain requires a calibration, which was realized using a single tone carrier.

These limitations come from the channel emulator and will not be present when the tests will be performed over the air with an orbiting satellite.

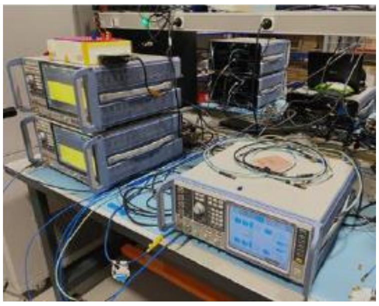

Figure 5: Ka-band channel emulator

III. TESTS EXECUTION AND RESULTS

A. Back off

On the forward link, the 5G NTN signal is an OFDM waveform. It is a known fact that, because the overall signal is formed of a sum of "random" data symbols, the large variations in the instantaneous power of the OFDM signal cause a high PAPR (Peak to Average Power Radio), significantly higher than e.g. single-carrier modulation techniques. This high PAPR requires the power amplifier in the satellite to back off its operating level below saturation point, so that the amplifier will operate in the linear region, avoiding compression and adjacent channel interferences [3].

Tests have been performed on the "Flatsat" to measure the Power Amplifier (PA) operating point, allowing to maximize the EIRP (Effective Isotropic Radiated Power) while minimizing the signal distortion, expressed as EVM (Error Vector Magnitude). Measures on PDSCH show that at least:

- 6 dB back off is needed to use 64QAM (theoretical EVM limit of 9%)
- 3dB back off is needed to use 16QAM (theoretical EVM limit of 13.5%)
- 1 dB back off is needed to use QPSK (theoretical EVM limit of 18.5%).

B. Test Plan and results

The final objective of the tests campaign is to demonstrate the use of a 5G NTN waveform with the full two-way chain described in the previous chapter. To achieve this objective, 6 intermediate tests were executed. These tests aimed to validate the behavior of the different equipment and gain confidence in the full chain prior the realization of the final test. The main configurations applied are described in table 1.

TABLE I. TEST PLAN

Item	***FLFA + Ka channel emulator***	***Flatsat***	***Ku channel emulator***	***Band (MHz)***	***PDU session***
TC#1				5 & 50	Yes
TC#2			Yes	5	Yes
TC#3	Yes			5	Yes
TC#4		Yes		5 & 50	Yes
TC#5		Yes	Yes	5	Yes
TC#6	Yes	Yes		5	Yes
TC#7	**Yes**	**Yes**	**Yes**	**5**	**Yes**

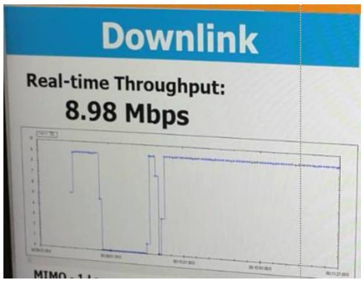

Figure 6: Forward-link: 8.98 Mbps in a 5 MHz channel

All intermediate and final test configuration enabled to establish PDU session. During the tests, different applications have been successfully tested:

- IP video streaming (YouTube), Web browsing
- Forward-link efficiency close to 2 bps/Hz (8.98 Mbps in a 5 MHz channel)

The results show that FR1 numerology is applicable to Ku-band: UE successfully attached to the network and exchanged sustained traffic. In particular, the results have been achieved with Phase Noise levels representative of real commercial equipment.

IV. CONCLUSION

In this paper, we described the test setup and first results obtained using a 5G NR-NTN waveform, in Ku-Band, with the "Flatsat" representative of a real satellite, and a UE derived from commercial product. PDU sessions have been established with the full two-way chain in "conducted" mode, and final test allowed live video streaming on a PC connected to the 5G-NTN modem.

ACKNOWLEDGMENTS

The authors would like to thank Airbus Constellations Satellites and Rohde&Schwarz for providing the required support for the successful execution of the tests, and all the members of the team that contributed to the trials.

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