Functional Split on Regenerative Satellite Payload for 5G Non-Terrestrial Networks

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Abstract— **With Release 17 satellites were incorporated in the 3GPP 5G New Radio standard. Current approaches in the geostationary orbit impose intolerable delay for mobile communication, while lower earth orbits require constellations of thousands of satellites to ensure global user connectivity. More flexible architectures are required to serve the multitude of applications foreseen in 6G. The talk will examine the performance of our proof-of-concept implementation for a minimal regenerative payload for 5G Non-Terrestrial Networks. It is implemented mostly in the ground segment to reduce computational demands on the satellite platform. The flexible System-on-Chip used for the space segment is representative of a state-of-the-art regenerative payload. It provides improved signal quality compared to a transparent satellite while keeping power consumption and processing requirements low. We assess a high technological readiness level for the design since it is validated against a realistic scenario. Our implementation can therefore be used as basis for further experimentation with non-terrestrial network architectures and to evaluate candidates for standardisation.**

Keywords—NTN, Non-terrestrial networks, Functional Split, 5G, Regenerative Payload

I. Introduction

The global adoption of 5G has brought unprecedented connectivity, driven by the benefits of open standardisation and widespread deployment. As the industry is looking towards 6G, the inclusion of satellite systems is emerging as a key feature. Several proposed designs point toward the need for regenerative payloads and onboard processing to support next-generation capabilities and fulfil the vision of ubiquitous connectivity using 3D networks.

Functional splits enable the distribution of 5G base station (gNB) processing tasks either between ground and space segment or among dedicated hardware components in orbit [7]. By using standardized interfaces between those entities, it is envisaged that the radio access network (RAN) becomes more open and modular, thus allowing interoperability of different equipment vendors.

To explore these concepts, this work presents a laboratory demonstration of a functional split, implemented for a geostationary (GEO) regenerative satellite. The proof-of-concept setup includes a satellite radio interface (SRI) connecting the split components of the gNB, with processing emulated on an UltraScale+ RFSoC platform. This demonstration aims to provide insights into the feasibility and performance of such architectures, paving the way for their potential adoption in future satellite-terrestrial networks.

The paper is structured as follows: Section II sums up recent notable advancements in the field. Section III describes our architecture, detailing hardware and software components as well as the scenario parameters used in the implementation. Section IV displays the expected results and Section V concludes this manuscript.

II. State of the Art

Satellite payloads are steadily evolving to accommodate modern applications. In addition to the growing popularity of larger constellations, individual satellites incorporate more complex technology. Due to this, computational intense signal processing tasks can be carried out on-board the satellite.

A. Regenerative Payloads

The requirements posed by enhanced communication standards, such as 5G NR, demand for higher processing power in space. Currently, 3GPP discusses the role of regenerative payloads and results are expected to be included in Release 19 [3].

To allow for short development cycles and adaptive functionality, Field Programmable Gate Array (FPGA) based payloads have been deployed, that can be reconfigured after launch. An example of such a payload is the Fraunhofer On-Board Processor (FOBP), which is part of the Heinrich Hertz satellite [2]. The Heinrich Hertz Mission by Germany's space agency aims to test and validate new satellite communication technologies under space conditions, thus enhancing satellite resilience and versatility. The parameters of the Heinrich Hertz satellite will be used as baseline for our laboratory testbed.

Other works demonstrate a full gNB on board the satellite. Petry et al. use a System-on-Chip (SoC) platform for hardware acceleration of lower layer computations and an additional CPU for higher layer processing [1].

Unfortunately, implementation details of commercial systems are not publicly available. However, it is assumed that most novel satellite constellations are deploying regenerative satellite payloads with strong on-board processing capabilities such as SpaceX Starlink or Eutelsat OneWeb.

B. Functional Splits

A functional split in mobile communications separates the radio access network (RAN) functionalities into several components. The split options are numbered in the opposite order from ISO/OSI layers, starting with 8 at the transmitted radio frequency (RF) signal to 1 at the interface to the core network [4]. An overview of the split options is shown in Figure 1.

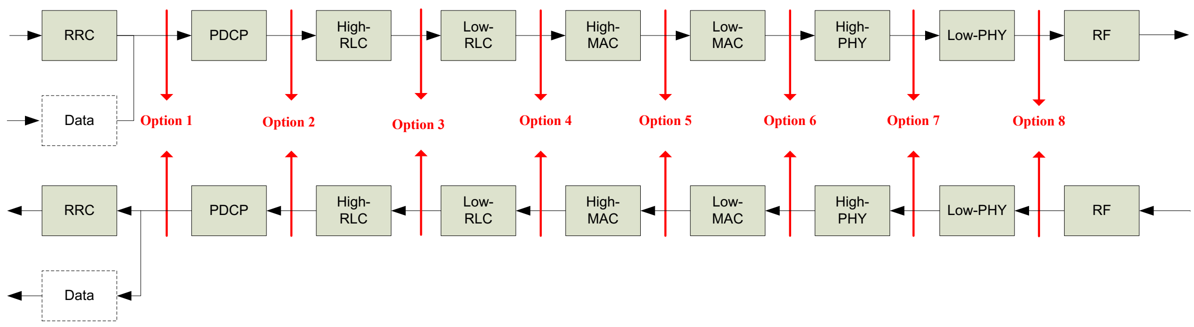

Figure 1: Protocol stack with layers and sublayers, including the numbered functional split options proposed by 3GPP as presented in [4].

Functional splitting can enable load balancing across the RAN as some functionalities can be shared between multiple cells. However, computationally intensive tasks, such as the lower physical layer, do not depend on the load and do not benefit from this resource sharing.

Currently, split option 2 is standardised by 3GPP [5] and 7-2x by the Open-RAN (ORAN) alliance [6]. To evaluate candidates for Non-Terrestrial Networks (NTN), previous work analysed the different split options [7]. Based on those results, split option 8 and 7-1 are deemed impractical for NTN scenarios. Generally, lower layer splits lead to higher data rate requirements between ground and space segment but reduce computational complexity on the payload.

III. ARCHITECTURE AND SCENARIO

We investigate a regenerative satellite architecture with minimal complexity and power consumption on board the satellite. To minimize processing requirements of the regenerative satellite payload, we select split option 7-2x, which balances computational complexity and required feeder link data rate. In this case, the waveform generation and demodulation - components of the Lower Physical (PHY) Layer - are shifted to the satellite.

Thus, as depicted in Figure 2, the 5G core network and the upper layers of the gNB are implemented on ground in software using OpenAirInterface (OAI). The SRI is realized through a bidirectional DVB-S2X link, a robust and reliable satellite communication protocol [8]. On ground, we employ a commercial off-the-shelf (COTS) modem.

The regenerative satellite payload is emulated using an RFSoC evaluation board. This versatile chip integrates ADCs and DACs. Even though there are more powerful chipsets available, the RFSoC provides an excellent example of a modern regenerative payload. It offers high power efficiency, high level of integration and exceptional performance in bandwidth-intensive tasks. Its programmable logic handles the lower PHY for 5G and the SRI counterpart, i.e. the FPGA implementation of a DVB-S2X modem. The processing system supports the SRI with software adaptations enabling efficient encapsulation and processing of the feeder link.

For the user equipment (UE), the system utilises an OAI-based software-defined radio (SDR) implementation. This combination enables flexible and rapid development compared to purely hardware-based solutions.

To replicate realistic conditions, satellite parameters are derived from the Heinrich Hertz satellite. The given system operates in the Ka-band, with an uplink frequency of approximately 30 GHz and a downlink frequency of about 20 GHz. The demonstration considers a small gateway antenna, reflecting the constraints of limited power on ground as well. On the user side, a compact dish antenna is employed, aligning with automotive or nomadic use cases. The channel emulator replicates the satellite link parameters, including non-linear distortions in all transmission paths. In the regenerative scenario, the processing payload generates and demodulates the 5G NR signal onboard. This effectively decouples the feeder link and user link and can lead to an improved signal quality received by the user. For the proof-of-concept, the 5G NR implementation is kept at a reduced feature set. A 5 MHz channel bandwidth is realized using a subcarrier spacing of 15 kHz and 25 physical resource blocks (PRB). Not-applicable features for our scenario such as beamforming, multi-connectivity, and MIMO are not considered.

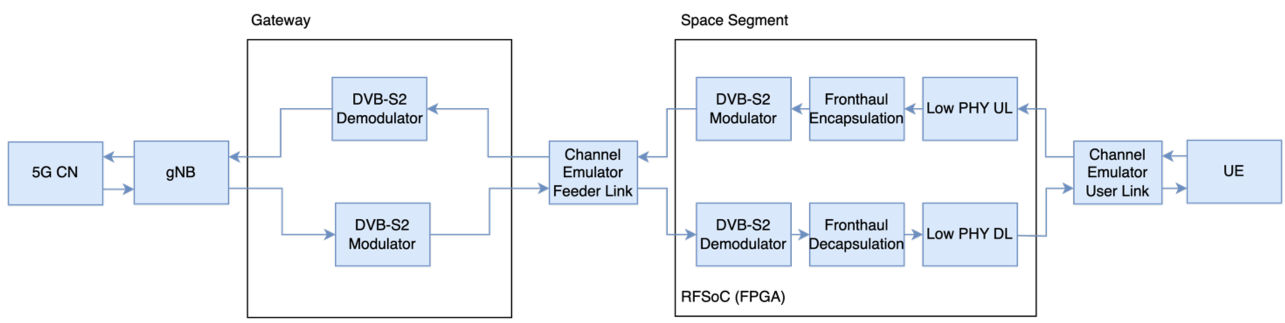

Figure 2: From left to right: Signal flow from the core network through gateway and satellite to the user equipment (downlink) and back (uplink). Between the gNB on ground and the low PHY processing in space, DVB-S2 is employed as satellite radio interface.

As reference scenario, we compare the presented regenerative system to a conventional transparent satellite payload using the same key RF parameters for the space and ground segment. The key differences between the reference scenario and the regenerative demonstration include the placement of the gNB and the nature of the transmitted signal between gateway and satellite. In the reference case, the gNB resides on the ground as the satellite operates transparently. Conversely, in the regenerative scenario, the SRI can use a different waveform as the lower PHY for 5G NR is implemented on-board. One advantage of this is that the SRI waveform, being single-carrier, is inherently more robust and better suited for satellite transmission [9]. Its low peak-to-average-power ratio (PAPR) allows for a smaller output back-off (OBO), enabling higher transmission power while mitigating the impact of non-linearities in the gateway's amplifier. In contrast, the reference case relies on 5G NR, which uses an Orthogonal Frequency Division Multiplexing (OFDM) waveform. These signals are more vulnerable to distortions caused by non-linearities due to their high PAPR. As a result, higher OBOs are necessary to maintain modulation quality, limiting transmission efficiency.

IV. Demonstration

In order to compare performance, we set up both scenarios in the laboratory and perform the same measurements.

A. KPIs and Measurements

During our demonstration we compare transparent and regenerative modes. The considered measurements are as follows: throughput in uplink as sent by the UE and received by the gNB and vice versa. For this, the Linux tool iperf is used with maximum throughput in UDP mode. Also, latency and jitter are measured as experienced by the user. Finally, modulation error rate measurements are used to assess the downlink signal quality on the physical layer.

B. Expected Results

The talk will present the results of the comparison, which will be executed during November and December. Based on simulations, a gain of several dB is expected for the SNR of the user link in the regenerative case, as only half the analogue signal processing and transmission path contributes to distortions. This allows the gNB to switch to a modulation and coding scheme (MCS) with higher spectral efficiency so that the throughput can be increased by up to 25%. Latency is expected to be dominated by the GEO transmission delay in both cases, but the delay and jitter should not be influenced by the additional processing.

V. Conclusion

In this paper, we presented our architecture for a regenerative payload implementing a lower layer functional split, that could become part of future 5G or 6G NTN systems. The developed laboratory implementation demonstrates the feasibility of delay tolerant fronthaul links. Furthermore, simulation results show that for certain scenarios gains can be achieved by functional splitting.

This testbed implementation represents a valuable starting point to continue developments to also support other architectures like a full gNB in space or a functional split distributed between satellites as proposed in [7]. Furthermore, these experiments also allow to qualify new approaches for standardisation.

Acknowledgment

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