EVOLUTION AND OPTIMISATION OF SMALLSAT DOWNLINK PERFORMANCES

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ABSTRACT

The number of satellite launches is foreseen to grow by around 20% per year and throughout the next decade. Half represents small satellites under 10 kg, so-called Nano/CubeSats. This significant growth is driven by several key factors such as miniaturization of electronics and sensors, capital expenses (CAPEX) decrease thanks to Commercial-Off-The-Shelf component (COTS) based designs, higher volume production with satellite constellations and last, but not least, the benefits of the technological innovation such as High-Data-Rate downlink.

First, this presentation introduces the evolution of the data transmission architecture and performances over the last decade for small satellites, recapping key success ESA missions with Syrlinks radios onboard such as Proba-V, GOMX-3, etc. Secondly, a focus will be provided on the expectations and requirements as today expressed by (Earth Observation) satellite operators with regards to High-Data-Rate downlink implementation. We will explain how the Software-Defined-Radio (SDR) architecture combined with the latest modulation technologies come as the perfect candidate to meet expectations. Finally, the main future technological trends and challenges to make data transmission more efficient and more "intelligent" will be discussed.

PAPER

1 INTRODUCTION

Earth Observation Space Missions where few dozens of Mbps were sufficient are ending and giving the floor to much more powerful transmission. Nevertheless, they constitute a key heritage and have provided some positive feedbacks concerning the efficiency of using COTS component based design as well as the benefits of miniaturization in the context of small satellites and nanosats.

As payloads are becoming more and more efficient in terms of integration and capabilities, the need of high data rate is becoming a key factor to satellite design to meet downlink capabilities and business targets.

From the historical needs of a few Mbps to the current needs of several hundred Mbps, the architectures of high data rate transmitters had to evolve to meet these new requirements. X-Band frequency range is currently the baseline for downlink, however as the 375 MHz bandwidth is a limitation factor, transmitter are exploring new possibilities with more efficient coding and modulation technics but also to match other frequency bands with higher bandwidth.

2 MARKET TRENDS

The global nano satellite market size was USD 220.4 Million in 2020 and is expected to reach USD 1,336.9 Million in 2030 with a revenue Compound Annual Growth Rate (CAGR) of 20.4% over the forecast period, according to the latest report by Emergen [1]. On their side, Euroconsult [2] has estimated the number of nano satellites <10 kg estimated to be launched by 2030 in the range of 3000 units with 30% representing Earth Observation (EO) applications. Therefore, we are witnessing a very significant growth of the small nano satellites to be used for EO.

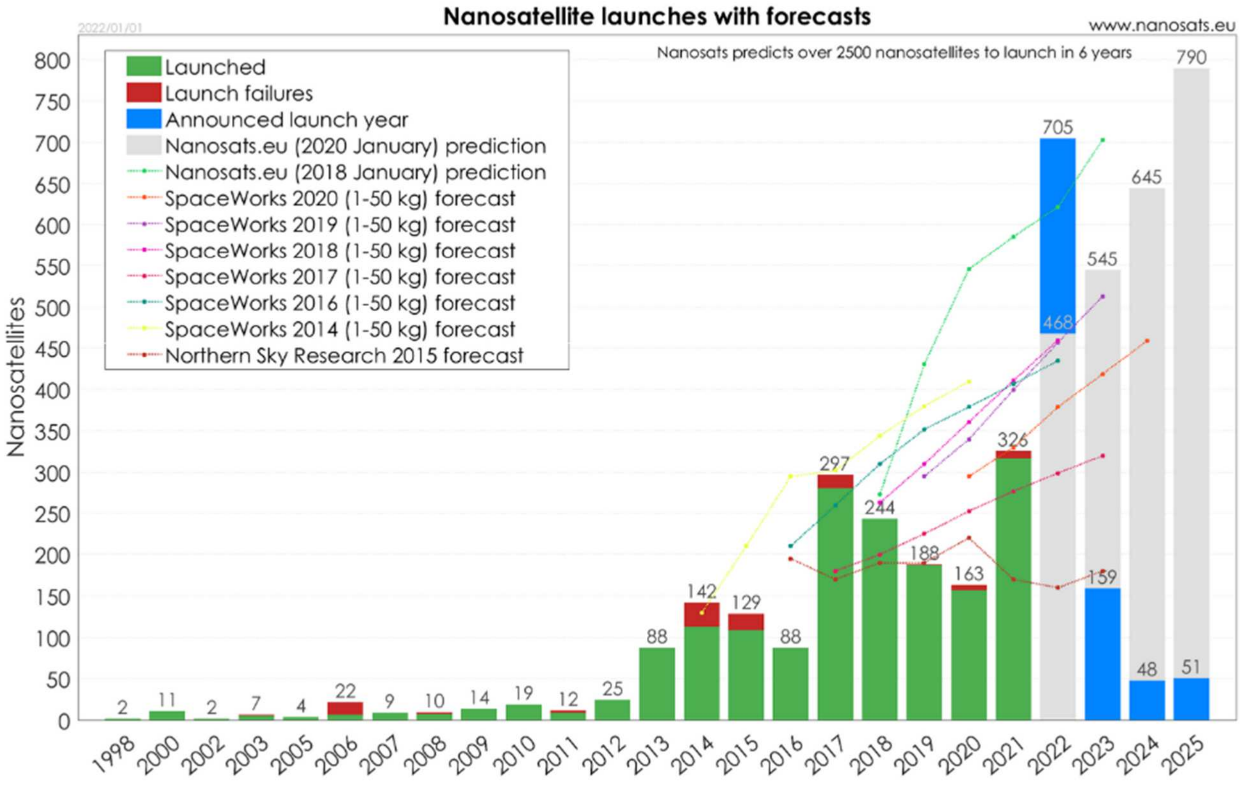

Figure 1. Nanosatellite forecast 01/01/2022 Erik Kulu, Nanosats Database, www.nanosats.eu

Several factors are driving this growth such as the growing interest and needs to use EO data to increase various service efficiency and accuracy. Indeed, far from limited to the military or governmental realms, nowadays the data from EO satellites are more and more sought out and exploited by private players in agriculture, insurance, finance or even in the oil industry, thanks to the considerable technological progress made in the aerospace sector and in data processing. The requirement to get real-time EO data has impacted the space industry with need to exponentially increase the number of satellites to operate in constellation mode. In addition, there are also key factors at the technological level such as miniaturization of electronics and sensors, capital expenses (CAPEX) decrease thanks to Commercial-Off-The-Shelf component (COTS) design and higher volume production and last, but not least, the benefits of the technological innovation with respect to the data downlink transmission.

3 SYRLINKS MISSION FEEDBACKS

3.1 PROBA-V

In the scope of ESA, European Space Agency, PROBA-Vegetation satellite, Syrlinks designed and provided two 100 Mbps (used at 42.22 Msps) X-Band transmitters [3]. PROBA-V was launched in 2013 in order to map land cover and vegetation growth across the globe every two days. The initial life-time for the satellite was 2.5 years with a possible extension to 5 years. The end-of-life date of PROBA-V has been extended several times and on 30th June 2020 and about 7 years after initial launch, the satellite reached the end of its operational life. The satellite has shown good performance throughout its life.

Figure 2. PROBA-V 100 m image of the Mississippi River, Louisiana (© ESA-BELSPO 2022 – Produced by VITO)

For PROBA-V, Syrlinks delivered mid-2012 to ESA two COTS-based X-Band transmitters (one primary unit XBT1, and one redundant unit XBT2) using a Gallium-Arsenide (GaAs) RF Power Amplifier and one COTS-based X-Band experimental transmitter (XBT3) using a Gallium-Nitride (GaN) RF Power Amplifier.

After 7 years of operation in orbit, all the initial performances of the 3 transmitters were unchanged: no variation or no major drift were observed. The in-orbit success of these X-band High Data Rate Payload Data Transmitters (ref: Syrlinks EWC28) validated the successful use of COTS-based solutions and of the GaN technology for space application for a lifetime in orbit **greater than 5 years**.

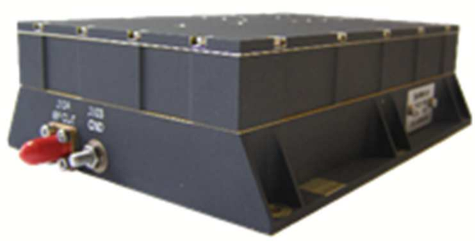

Figure 3. Proba-V X-Band transmitter

3.2 GOMX-3

The GOMX-3 mission is a collaboration between ESA and GOMSPACE in order to validate new concept and capabilities on Nano/Cubesat. One mission is to demonstrate aircraft ADS-B (Automatic Dependent Surveillance-Broadcast) signal reception. In order to increase the data rate usually limited by UHF-band or S-band on nanosats, CNES and ESA have explored X-Band for nanosat for this mission.

GOMX-3 satellite was launched on August 19, 2015 with a miniaturized version of Proba-V X-Band transmitter architecture designed by Syrlinks and suitable for nanosat size.

During the year of exploitation of the satellite, the X-Band transmitter showed great performances with a successful demonstration on Toulouse ground station. The system was capable to transmit 115 MB in 5 minutes during a pass [4]. Insertion loss of the equipment is less than 1dB and has great stability from few Mbps to dozens of Mbps.

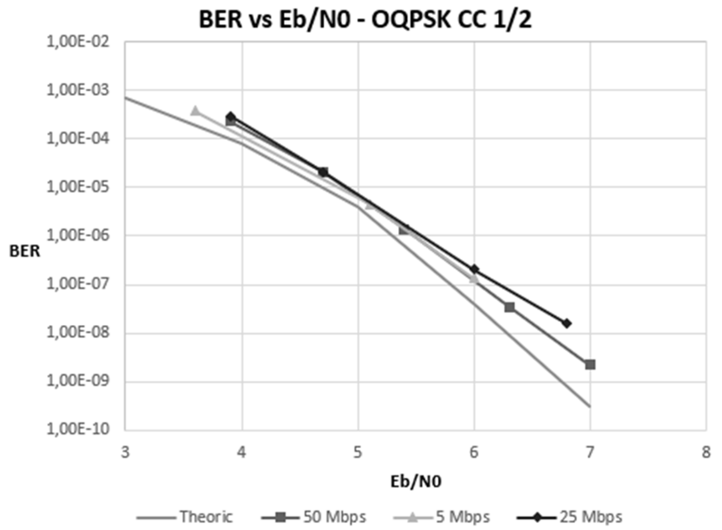

Figure 4. BER performance on Syrlinks nano X-Band transmitter

This X-Band transmitter (ref : Syrlinks EWC27) has since been used on dozens of missions with data rates up to 100 Mbps coded showing good performances over lifetime.

3.3 PLEIADE NEO

Pléïades Neo, initiated, financed and operated by Airbus Defense & Space, is a constellation of four high-performance earth observation satellites with a 30 cm resolution images in real time.

In order to reach the downlink target of 600 Mbps, the X-Band transmitter (ref: Syrlinks EWC34) uses advanced architecture with CCSDS four Dimension 8-ary Phase Shift Keying Trellis Coded Modulation (4D-8PSK-TCM) compatibility. The first satellite was launched on board the Vega 18 rocket from the European Space Center in Kourou, French Guiana, on Wednesday 28 April 2021. First images are already available on Airbus website and can be ordered.

Figure 5. Syrlinks X-Band transmitter for Pléïades Néo

4 ARCHITECTURE EVOLUTION

4.1 FIRST GENERATION ARCHITECTURE

The EWC27 and EWC28 X-Band transmitters are based on a CPLD architecture. The frequency range is from 8025 to 8500 MHz with a maximum input bit rate of 100 Mbps. The modulation used is filtered OQPSK (CCSDS compatible) 1/2 with convolutional coding R=1/2.

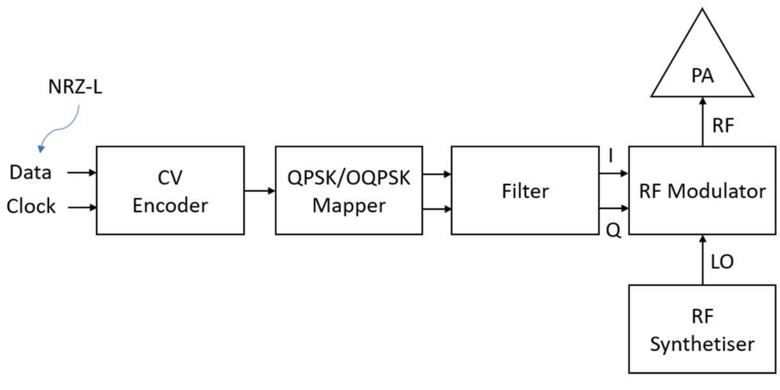

Figure 6. CPLD based architecture

In this architecture, the internal clock is generated and synchronised with input clock. Digital input data are coded with a convolutive code - 7 constraint length, ½ puncturing rate, [171]octal and [133]octal polynomial generators. OQPSK block provides I and Q signals. A 7^{th} order Butterworth analog filter shapes I and Q pulses. The data/clock input path is based on single LVDS line suitable for the required maximum input data rate at had the best compatibility with on board computers on the market.

Main challenge was to match expected low power consumption for nano/cube satellite with an integrated system. This was possible with a smart use of fractional PLL coupled with a MMIC VCO and by fine selection of COTS components. The power amplifier matching was also a key point to match the power consumption requirement. Typical measured consumption for this implementation is 10W for 2W RF output power.

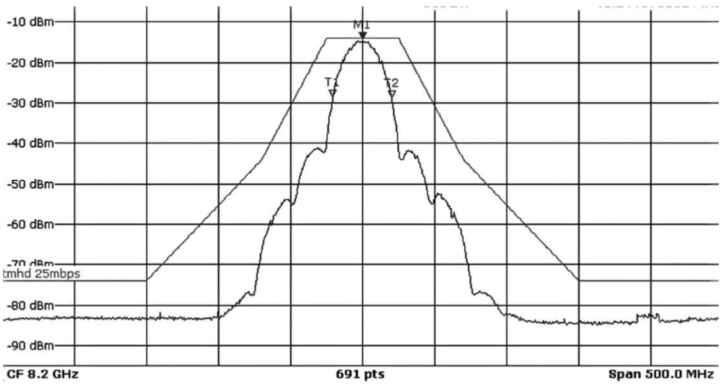

Figure 7. ECSS mask compatibility on nanosat X-Band transmitter

4.2 SDR ARCHITECTURE

In order to address the increasing throughput demands as well as to make the platforms more and more flexible but also powerful, an evolution of the historical architectures was necessary. In relation with CNES and in the scope of research and technology activities a new system was developed.

The new architecture is based on System on Chip (SoC) with Processing System (PS) and a Programmable Logic (PL) unit. The X-band function generates an X-band modulated signal from data supplied by a mass memory unit (MMU) thanks to digital to analog converter (DAC). In combination with the DAC, a PLL with integrated VCO is used to generate the clock signal for the DAC. Numerical functions and IPs are hosted by an FPGA.

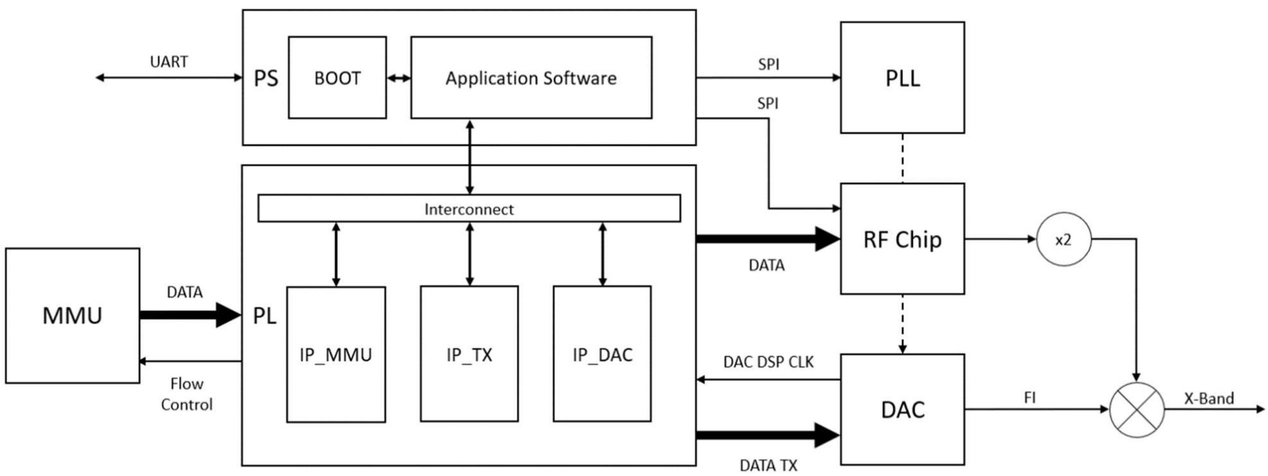

Figure 8. X-Band SDR architecture

A flow control management is dedicated to data bus regulation and is mandatory for specific modulation and coding. This system makes the architecture compatible with non-framing input mode and CCSDS framing input mode. The architecture allows to address symbol rates up to 400-600 Mbauds. Thanks to this architecture, the possibilities of evolution are numerous: integration of new IPs, software update in flight, configurability , adaptative coding and modulation, flexibility according to the needs. The system can also be adapted to address other frequency bands.

In the use case of small satellite X-Band transmitter, the numerical system is coupled with a radio frequency board which aims to generate the X-Band signal and filter it. The block diagram of this RF board is depicted below.

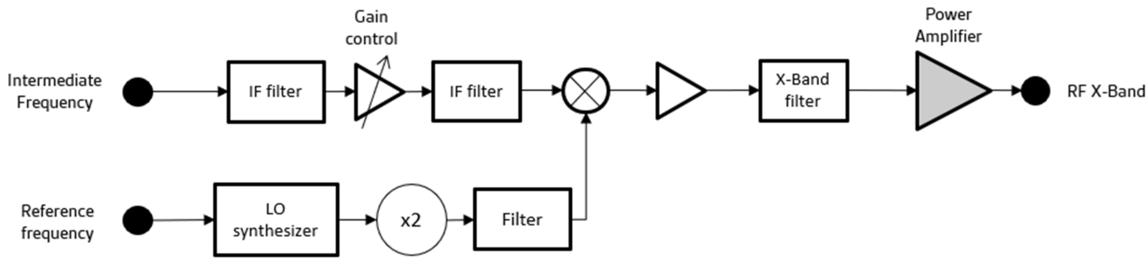

Figure 9. RF bloc diagram of the X band transmitter

First the IF signal from the DAC is filtered and amplified. Dedicated IF filter were designed in order to have great rejection with a small size. Indeed, many spurious are present at the DAC output and especially the sampling frequency. The Local Oscillator (LO) is generated with a synthesizer (PLL & VCO). This LO is then multiplied by 2 with a MMIC. Thereafter, the IF signal is upconverted to get a 8.2 GHz carrier. At last, the X band signal is filtered to eliminate the leakage and image frequencies. Then the signal is amplified to reach +33 dBm thanks to the power amplifier (PA). For this device a GaN process was selected in order to get a good efficiency. Also, a great derating is used on the drain voltage in order to get an excellent reliability with a low junction temperature.

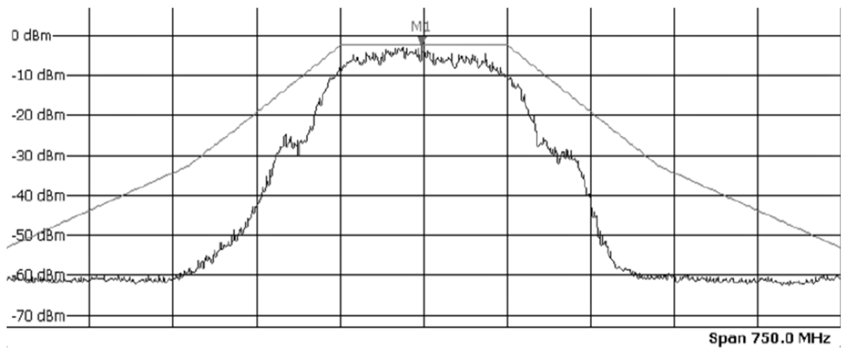

Figure 10. ECSS mask compatibility on small satellite X-Band transmitter, 150 Mbauds, DSN filter

5 DVB-S2 IMPLEMENT

The latest architecture allows to address more complex and efficient coding methods. This makes possible high throughputs while maintaining a spectral spread consistent on X-band. For this purpose, DVB-S2 standard was implemented.

DVB-S2 standard (ETSI EN 302 307-1) describes a scheme for forward error coding and modulation, proposing solutions for satellite communications with a variable link quality but a constant symbol rate (variable useful bit rate). The FEC is composed of BCH and LDPC encoders. The modulations are phase modulations QPSK, 8PSK, 16APSK or 32APSK. It offers great flexibility, with a spectral efficiency between 0.5 and 4.5 bit/s/Hz, corresponding to 28 MODCODS. MODCODs are combinations of coding rates and modulation orders.

Mode	MOD COD	Mode	MOD COD	Mode	MOD COD	Mode	MOD COD
QPSK 1/4	1_D	QPSK 5/6	9_D	8PSK 9/10	17_D	32APSK 4/5	25_D
QPSK 1/3	2_D	QPSK 8/9	10_D	16APSK 2/3	18_D	32APSK 5/6	26_D
QPSK 2/5	3_D	QPSK 9/10	11_D	16APSK 3/4	19_D	32APSK 8/9	27_D
QPSK 1/2	4_D	8PSK 3/5	12_D	16APSK 4/5	20_D	32APSK 9/10	28_D
QPSK 3/5	5_D	8PSK 2/3	13_D	16APSK 5/6	21_D	Reserved	29_D
QPSK 2/3	6_D	8PSK 3/4	14_D	16APSK 8/9	22_D	Reserved	30_D
QPSK 3/4	7_D	8PSK 5/6	15_D	16APSK 9/10	23_D	Reserved	31_D
QPSK 4/5	8_D	8PSK 8/9	16_D	32APSK 3/4	24_D	DUMMY PLFRAME	0_D

Figure 11. DVB-S2 MODCODs table

CCSDS 131.3-B-1 recommended standard proposes to use DVB-S2 in space links and defines an interface with CCSDS Space Link Protocols. It lists configurations that define the encoder capability (transmission mode, roll-off factors, scrambling code numbers, list of MODCODs, FECFRAME sizes, pilot insertion status). Syrlinks proposes a subset of these configurations in its products. The DVB-S2 standard implementation was performed with the following parameters:

- No framing for the input data, considered as continuous stream.
- Baseband padding, implemented to complete user data with padding before the encoding in case of a lack of data, although not considered by CCSDS recommendation CCSDS 131.3-B-1
- Dummy frames, implemented to maintain a continuous output flow
- Pilots mode, which is necessary to the DVB-S2 demodulators to maintain good performances.

On small satellite X-Band transmitter, QPSK and 8PSK MODCODs are implemented and show implementation loss with less than 1dB at 2W output power. The measurement below presents results in nano product X-band transmitter, with pilots, normal frames, QPSK ½ and QPSK ¾.

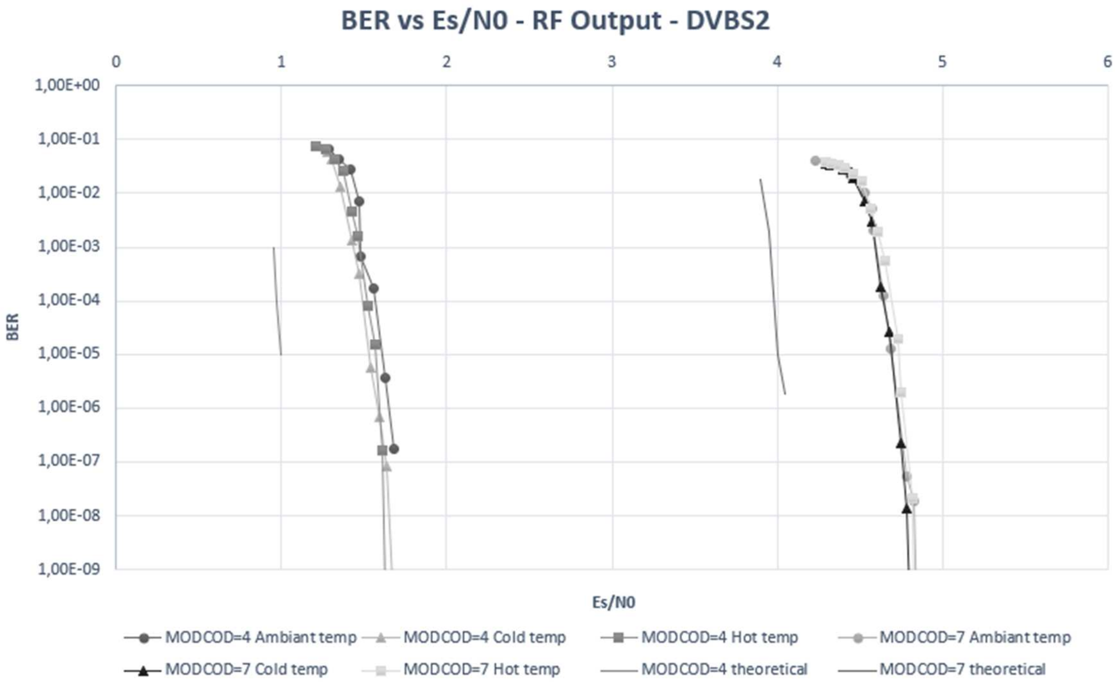

Figure 12. DVB-S2 implementation on small satellite X-Band transmitter

In addition to simple MODOCDs use, variable coding and modulation (VCM) allows to define a passage plan for the mission, adapting the user data rate to the foreseen link quality during the satellite pass over the Earth stations. VCM is implemented in the SDR architecture and is illustrated below.

In the following example, we propose a dynamic link budget scenario, associating an elevation angle with a satellite-to-station distance, a link budget margin and therefore with a recommended DVB-S2 MODCOD. In this scenario, the transmission starts with QPSK 3/5 at 5° and reaches 8PSK 9/10 at 30°. Between 30° and 90°, the most efficient MODCOD is used.

Elevation angle	Modcod
5-6°	QPSK 3/5
6-8°	QPSK 2/3
8-9°	QPSK 3/4
9-10°	QPSK 4/5
10-11°	QPSK 5/6
11-14°	8PSK 3/5
14-18°	8PSK 2/3
18-23°	8PSK 3/4
23-28°	8PSK 5/6
28-30°	8PSK 8/9
30-90°	8PSK 9/10

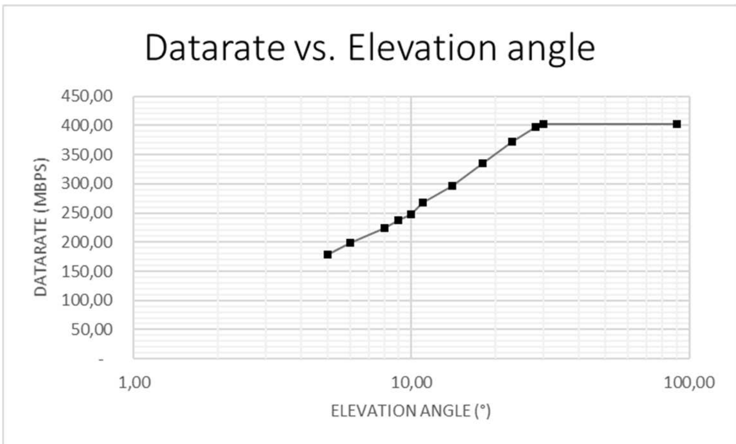

Figure 13. Passage plan on dynamic link budget scenario, zenith pass. rising half

6 FUTURE AND CHALLENGE

In addition to the many possibilities offered by the new architectures and their evolutions, solutions are already being explored to achieve higher throughputs to meet market new needs while solving frequency band congestion. Technical solutions are already being proposed to meet these needs.

6.1 ADAPTATIVE CODING AND MODULATION

Adaptive coding and modulation (ACM) allow real-time adaptation of the user data rate to the link quality conditions, without a pre-defined mission plan (VCM). It supposes to have a return channel that retrieves a link quality metric, and to dynamically select the most appropriate DVB-S2 MODCOD according to this metric (which could be the signal to noise ratio).

The return path can be the TT&C equipment of the satellite or a solution offered by a more modular architecture with integrated S-band receiver possibilities. The SDR architecture presented in chapter 4.1 is already compatible with this method.

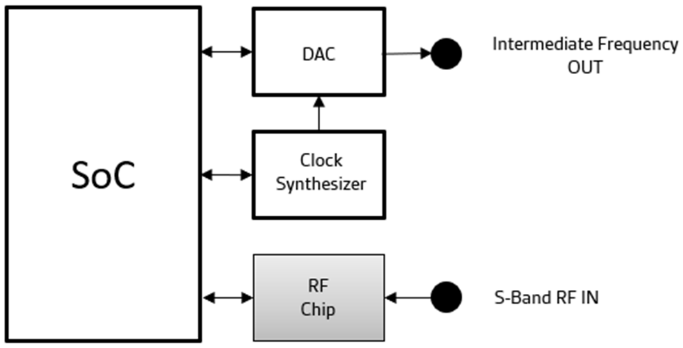

Figure 14. ACM use case with SDR architecture

The system, with an ACM application software is then capable to change dynamically the DVB-S2 MODCODs. This enables the system to be autonomous and to address optimal flow rates and send the maximum data to earth in a single path.

6.2 16APSK and 32APSK

Another approach to increase the amount of useful data to the earth is the use of higher modulation orders. These modulations are offered by the DVB-S2 standard with 16APSK and 32APSK. The difficulty of using these modulation orders is shifted to the radio frequency part rather than to the digital part which is already compatible thanks to SDR architectures.

In the case of systems with high power output and in order to maintain linear operation, the input signal to the amplifier must not exceed a certain level characterized by the compression point. The margin kept within this zone is called the input back-off. In order to use power amplifier with optimum efficiency, linearization techniques based on digital pre-distortion (DPD) are commonly used.

Using 16APSK modulation, Figure 14 shows the improvement that predistortion can bring based on Syrlinks simulations and analysis.

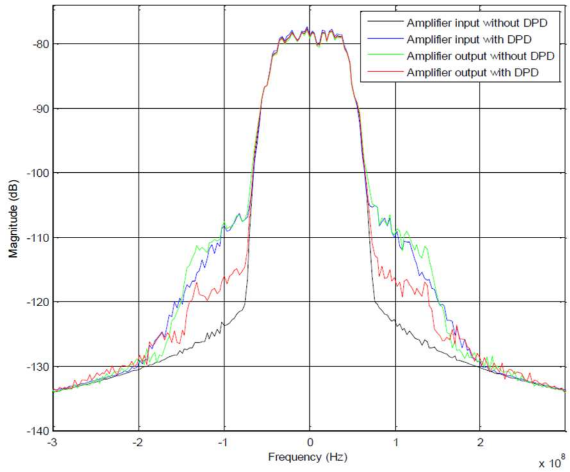

Figure 15. Normalized input and output spectrums of a PA with and without predistortion on 16APSK modulation

6.3 KA-BAND

To compensate for X-band congestion, small satellite systems are now turning to Ka-band to deliver the amount of data given by advanced payloads. The allocated band for Ka-band according to ECSS-E-ST-50-05C is between 25.5 GHz to 27 GHz that allows a 1.5 GHz bandwidth. As ground stations growing with more compatibility to Ka-band, the need for Ka transmitters is becoming more and more of a priority on the market.

In this framework, a TRL-5 prototype of a Ka band transmitter for small satellite was designed and realized. For the base band subsystem, the same system than for X band is used: The DAC provides an IF modulated signal. For the microwave subsystem two frequency translations are used to get an output RF signal between 25.5 and 27.0 GHz (see Figure 16). Thanks to the RF synthesizer a LO signal is generated. The two translations allow to reach 25.8 GHz. This prototype has an RF output power of +33 dBm in Ka Band. The next step would be to design an integrated Ka front-end which would embed a waveguide filter and the antenna. This work is already planned for the next coming months.

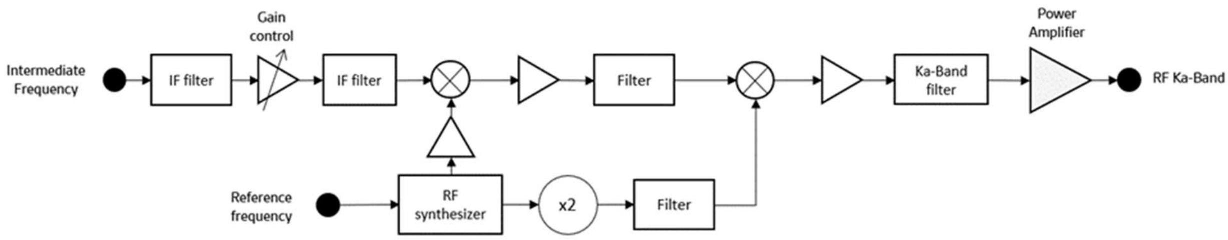

Figure 16. RF bloc diagram of the Ka band transmitter

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