X-band transmission evolution towards DVB-S2 for Small Satellites

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ABSTRACT

DVB-S2 is a CCSDS adaptation standard fully reusing the ETSI DVB-S2 mass-market telecommunication standard, thus providing the advantage of a wide diversity of very robust commercial mass market receivers, cheaper than the receivers dedicated to space telemetry links. CNES is currently upgrading with Syrlinks an existing X Band Transmitter for cube & nanosatellites (TRL 9) to use DVB-S2 CCSDS telemetry standard. The Variable Coding and Modulation (VCM) mode will provide 60% increase of the downloaded data compared to Constant Coding and Modulation (CCM), a link budget improvement of about 2 dB in QPSK for the same transmitted power and a better spectral efficiency.

INTRODUCTION

Today, earth observation or spectrum monitoring or astronomy or technological payloads can be embarked on very small platforms but they require the capability to download a large volume of data with a high telemetry bit rate subsystem. Syrlinks' EWC27 High Data Rate Transmitter combined with a miniaturized COTS antenna solves this problem and enables to download up to 17 GB per day on a 3.4 m X-band station with an omnidirectional antenna on board the cubesat. Higher data amounts are possible thanks to the use of directive antenna on board.

The EWC27 High Data Rate Transmitter has already been presented in recent conferences [1,2,3]. The Transmitter operates in the 8025–8450MHz frequency range. When used in Variable Bit Rate (VBR), it provides three different data rates up to 50Mbps. In Constant Bit Rate (CBR) or Constant Coding and Modulation (CCM), it provides up to 100Mbps input data rate with Convolutional Coding (7, ½) and OQPSK modulation. The RF output power of the Transmitter is adjustable from 30 to 33dBm with 1-dB step and can be programmed in flight.

Validation results of Syrlinks's X-band EWC27 transmitter and X-band patch antenna on board of GOMX-3 satellite are presented in the first part of the paper. Secondly, the paper will present the evolution of the X-band transmitter which will use a new and more powerful FPGA allowing a maximum data rate higher than 100 Mbps.

The 4 main interests of the CCSDS DVB-S2 telemetry standard are:

-its high end performances

-its compatibility with mass market allowing the procurement of very low cost receivers as long as the data rate is compatible with the (growing) space telecom needs

-the possibility of Variable Coding and Modulation (VCM) as well as Automatic Coding and Modulation (ACM) increasing the downloaded data amount, while CCM remains still possible.

-its growth potential with DVB-S2x, provided with new features and backward compatibility with DVB-S2.

All the CCSDS DVB-S2 features have already been coded by Syrlinks, they include the necessary DVB-S2 blocks: baseband encapsulation, channel coding, mapping, physical layer encapsulation and filtering. Different steps of the X-band DVB-S2 transmitter development will be described as well as intermediate validation results and use examples with related link budgets. Finally, the paper will present the next step for higher CubeSat data rate, like 200 Mbps in X-band, especially using directive high gain on board antenna, eventually deployable, to precisely point toward the ground stations as it is the case for EYE-SAT and for SKYBOX spacecrafts. The paper will also present insights of evolutions of the Payload Data Rate Telemetry transmitters for Nanosatellites, like the future Syrlinks DVB-S2 Ka-band High Data Rate Transmitter.

SYRLINKS EWC27 PERFORMANCE VERIFICATION

EWC27 on GOMX-3 mission

The GOMX-3 mission is a collaboration between ESA (European Space Agency) and GomSpace of Aalborg, Denmark to demonstrate new capabilities of nanosatellites focusing on attitude control, RF sensing, and high-speed data downlink.

The mission aims to demonstrate aircraft ADS-B signal reception and to characterize geostationary telecommunication satellite spot beam signal quality.

The satellite was developed, integrated, tested, and delivered over a period of 13 months using off the shelf components available from GomSpace. GOMX-3 uses the next generation of CubeSat OBC (NanoMind A3200) and UHF radio (NanoCom AX100). Both of these subsystems use a motherboard-daughterboard system designed to minimize stack height to fit more capability in a smaller volume. A P31us EPS and a BP4 battery pack complete the CubeSat bus.

The satellite uses a combination of advanced sensors (coarse sun sensors, IR horizon sensors, magnetometers, fine sun sensors, NovAtel GPS receiver) and actuators (in-panel magnetorquers, Astrofein momentum wheels) controlled by a dedicated ADCS A3200 computer. The payload ADS-B receiver is a software-defined radio module developed by GomSpace.

For telemetry data downlink, the satellite uses the Syrlinks EWC27 CubeSat X-band transmitter as well as an X-band patch antenna that has been designed by Syrlinks specifically for the GOMX-3 mission needs.

Figure 1: The GOMX-3 satellite showing Syrlinks X-band patch antenna

The GOMX-3 3U CubeSat was launched on the HTV-5 cargo flight to the International Space Station on 19 August 2015 and deployed on October 5, 2015. The satellite continues to operate since then with no loss of functionality.

X-band experimental patch antenna

Syrlinks has developed an X-band patch antenna for the GOMX-3 mission considering the following initial requirements: Frequency band between 8.025 and 8.4GHz, RHCP polarization, <3dB axial ratio between -/+60°, >0dBi gain between -/+30° from boresight, <12dB return loss in 400MHz bandwidth.

The available volume on the GOMX-3 platform for the antenna was limited, especially the thickness which was restricted to 7 mm. EM simulations have been performed (both 2.5D and 3D) in order to help optimizing the gain and axial ratio of the antenna. The final dimensions of the active part were 73.5 x 73.5 x 6.8 mm.

The radiated patterns of the antenna were measured in anechoic chamber. The performances were in line with the simulations results. The antenna gain was about 7dBi and the axial ratio was lower than 3dB in the frequency band 8025-8400MHz as shown in Figure2.

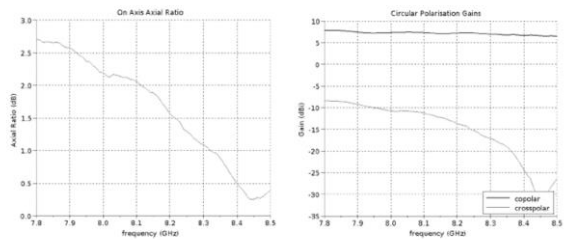

Figure 2: Syrlinks X-band patch antenna measurement results

Some qualification tests (temperature cycling, vibration, thermal vacuum) were finally made in order to check the evolution of the performances after environmental testing.

Telemetry download results

CNES has participated in the GOMX-3 project by providing two X-band ground stations. The first station, located at the French Guyana Space Center (CSG) in Kourou, has an antenna diameter of 11 meters and was used for experimental passes till end 2015. It. The second station, located at the French National Civil Aviation Engineering School (ENAC), Toulouse, France, has a 3.4-meter antenna and was used in a second step for satellite signal demodulation and data extraction.

Several telemetry download tests have been conducted in February 2016. The GOMX-3 satellite has been configured to transmit in a bursty manner (tens of seconds range) during each pass of the satellite over the X-band ground station.

The results were overall satisfactory [4]. Despite a few transmission losses, the signal to noise ratio was noticeably better than expected and the signal has been successfully demodulated and processed. An example of a successful pass is given in Figure 3. The amount of received data was 115.5Mo for a pass duration of 5min 46sec and average data rate of 3Mbps configured before flight in the equipment. The number of received good frames was 89150, and the number of received bad frame was 7. The bad frames are explained by some imperfection of the used old 3.4 meters ground station hosted and retrofitted by ENAC.

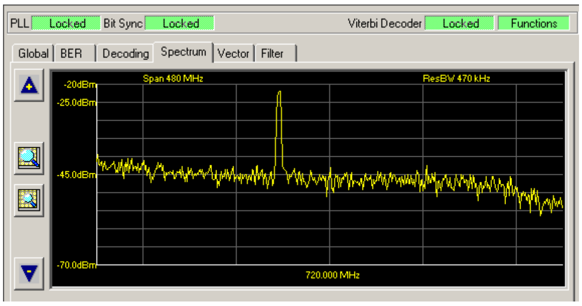

Figure 3: Spectrum of the received X-band signal from the GOMX-3 satellite

These results validate the correct operation of the Syrlinks X-band Transmitter (EWC27) and patch antenna that were used on board of the GOMX-3 satellite.

DVB-S2 IMPLEMENTATION

An FPGA implementation of a DVB-S2 encoder has been developed, compliant with the related CCSDS space telemetry DVB-S2 standard use. [5]

The DVB-S2 encoder as described in the standard can be divided in blocks as follows: baseband encapsulation, channel coding (BCH and LDPC coding), mapping, physical layer encapsulation, filtering. [6]

The CCSDS recommendation sets a few more rules. The input data shall be single input continuous Generic Streams. ASM (Attached Synchronization Marker) headers shall be inserted before going through the transmitter.

The following sections provide details about the different DVB-S2 encoding blocks implemented.

Mass memory interface

The data to be transmitted are considered to be contained in a mass memory. It is connected to the FPGA via a data link with bidirectional flow control: a data validation signal and a request signal.

ASM check

According to CCSDS, the data shall be composed of CADU (Channel Access Data Unit), which are a concatenation of an ASM and a Transfer Frame. The role of this block is to verify that this format is respected.

Baseband encapsulation

The CRC-8 encoder mentioned in the DVB-S2 standard is not used in this case because the data comes as a continuous stream, not a packetized stream.

The data flow is divided into Data Fields of length Kbch-80, where Kbch is the size of a codeword at the input of the BCH encoder, depending on the selected MODCOD.

Before each Data Field, a baseband header is inserted. It consists of 80 bits and contains information about the data format and the DVB-S2 encoder configuration: data flow type, CCM/VCM/ACM, roll-off, User Packet length, Data field length (DFL), etc. The last byte of the header is a CRC computed from the first 9 bytes.

In the CCSDS configuration, considering a given roll-off value, the only varying parameter in this header is the DFL, depending on the MODCOD. The header, including the CRC byte, is therefore computed beforehand, not dynamically.

The baseband header together with the data field are called a BBFRAME.

It is then scrambled with a pseudo-random sequence, identical for every BBFRAME, and generated by a 15^{th} degree polynomial. This is implemented using an LFSR register (linear-feedback shift register).

Channel coding

The FEC (Forward Error Correction) scheme consists of an outer BCH encoder, an inner LDPC encoder and an interleaver. It is viewed frame by frame.

The BCH encoder concatenates 128, 160, 168 or 192 bits to the BBFRAME, depending on the MODCOD. The parity check bits BCHFEC are serially computed by an LFSR register, based on a polynomial of degree 128, 160 or 192 for long FECFRAME (168 for short FECFRAME). The 4 polynomials to be used are computed beforehand from the indications of the standard and stored in the FPGA.

LDPC encoding is then performed. At its input the LDPC encoder takes a BBFRAME concatenated with BCHFEC bits. It delivers an output frame of 64800 bits (or 16200 for short FECFRAME mode).

The DVB-S2 standard provides an explanation of the encoding principle for the low-density parity code. The selected family of codes are systematic IRA (irregular repeat-accumulate) codes. This feature shall be taken into account for the implementation algorithm.

LDPC encoding is a key-point of the DVB-S2 transmitter implementation: it requires numerous accumulations of bits along a whole BBFRAME, and therefore needs significant amounts of both logical resources and memory resources.

An efficient algorithm has been developed to address that. It uses accumulation of the input bits as mentioned in the standard, serially.

FEC encoding chain is completed by a bit interleaver for 8PSK, 16APSK and 32APSK modulation. However, the implementation has been developed first in a QPSK mode, which doesn't require any interleaving. In that case, BCH and LDPC encoding are enough to define FEC, and the output of the LDPC encoder constitutes a FECFRAME.

Mapping

The binary frame is then converted into a complex sequence of modulation symbols, XFECFRAME. This is realized with serial-to-parallel conversion and bit mapping.

The QPSK constellation is described by I=MSB and Q=LSB. The bits are simply gathered 2 by 2. In that case, the XFECFRAME consists of 32400 modulation symbols (or 8100 symbols for short FECFRAME).

Physical layer encapsulation

A header and optional pilot blocks are added to the complex symbol frame, it goes through a scrambler, and thus a PLFRAME is encoded.

A PLHEADER of 90 symbols is inserted before each XFECFRAME. It is constructed with the chosen MODCOD, the size of the FECFRAME and the choice to use pilot insertion or no pilot insertion in PL framing. Knowing these information, the header computation requires: a bi-orthogonal (64, 7) coding; a binary scrambling with a given sequence; a BPSK symbols modulation.

As for the baseband headers, this whole computation is realized beforehand and the set of generated headers for different configurations is stored into the FPGA.

Pilot blocks might or might not be inserted then, depending on the user's choice of mode. If the pilot mode is selected, 36 pilot symbols are inserted for every 16 slots of 90 symbols each, making the frame 5760 symbols longer in a QPSK normal FECFRAME configuration.

Finally, the symbol frame is randomized by a scrambling sequence. PLHEADER is not randomized but the potential pilots are.

The complex scrambling sequence is a Gold sequence: it is constructed from two real sequences, themselves built with 18^{th} degree polynomials. The scrambling sequence has a length of 262141 symbols or order 2. It is parameterized by n, which can take values between, 0 and 262141. The parameter n determines which portion of the sequence should be used. The proposed implementation has n set to 0 (or any other fixed value), so that the sequence can be computed recursively, symbol after symbol, from a given starting point. Setting a value for n avoids having to either store the entire Gold sequence or compute it from scratch until the n^{th} value.

The computation of one Gold value at each step still requires storing 4 sequences of 18 bits and using a logical structure with 4 shift registers.

The PLHEADER concatenated with the scrambled sequence make a PLFRAME.

Filtering

The I/Q data of the PLFRAME are delivered outside the FPGA on LVDS wires. The last step of the DVB-S2 transmitter is shape filtering, with SRRC (square root raised cosine) filter. This is realized analogically with an I/Q modulator.

Prototyping

The FEC encoding blocks, BCH and LDPC, have first been prototyped with C. One Matlab prototype of the complete DVB-S2 encoder has then been realized and allowed validation of the developed VHDL code by comparing outputs.

Testing

A Cortex has been used to observe and validate the generated constellation.

The developed transmitter has been functionally tested with a commercial DVB-S2 receiver. That revealed compliance with the standard.

X-BAND DVB-S2 LINK BUDGET STUDY CASE

In this paragraph a preliminary link budget in X-band is computed to give order of magnitude of the transmitter achievable capacity.

The analysis is based on the use of DVB-S2 standard with a restriction on the available modulations and coding rates dictated by the transmitter features. The Variable Coding and Modulation (VCM) mode from the DVB-S2 is also considered.

Transmitter and antenna characteristics:

- DVB-S2 VCM QPSK 1/2 and 9/10
- RF output power: 30 dBm
- Filter roll-off: 0.5
- Antenna coverage: +/-65°
- Antenna gain @65°: 0 dBi (@0°: 7 dBi)
- Antenna axial ratio @65°: 1.5 dB
- Total losses: 3 dB
- Satellite altitude: 700 km

Ground station characteristics:

- Diameter: 5.5 m (Europe) or 13 m (Polar)
- G/T: 30 dB/K or 34 dB/K
- Total losses: 2 dB
- Overall C/I: 20 dB
- System margin: 2 dB

The link budget is computed for a worst case (border of antenna coverage) and a favorable case (good antenna pointing).

Some preliminary results are given in the Table 1.

First of all, the results are found similar for both antenna diameters meaning that the link budget limitations come from the satellite side. An optimistic interpretation of this is that a 5.5 m antenna is sufficient.

The results include the elevation from which each code rate is used, the average useful bit rate, passage duration and volume of transmitted data for one passage.

Table 1: X-band link budget outputs

	Worst case	Favorable case
RF AOS elevation (QPSK 1/2)	26°	8°
Coding rate change elevation (→ QPSK 9/10)	84°	21°
Average useful bit rate	122 Mbps	149 Mbps
Average passage duration	≈ 6 min	≈ 10 min
Volume of transferred data	≈ 40 Gb	≈ 90 Gb

The overall achievable capacity will depend on several parameters such as the number of dumps per day.

EWC27 X-BAND TRANSMITTER EVOLUTION

Syrlinks is considering starting Ka band telemetry predevelopment for cubesats, since it could be part of the smallsat telemetry market for some specific cases. Such cases could correspond to an X-band antenna too big for the considered cubesat, especially if the satellite face where is mounted this antenna is very occupied by other appendixes like mission and TT&C antennas, panels, optical sensors, …In other word, for highest data rates possible with a cubesat, Ka band allows a smaller on-board antenna than X-band. Such cases could also correspond to cases where reactivity of the payload telemetry is not a big driver of the mission, since attenuation in Ka band can highly be increased by the rain cells. Generally, when reactivity is needed for the mission telemetry, X-band is kept.

Ka-band HDR transmitter for nanosatellites

With increasing data rates asking for larger and larger bandwidths, the radio communication links have evolved from S-band to X-band over the last years and are now moving forward towards the Ka-band.

Syrlinks has anticipated the need for high data rate downlink transmitters in Ka-band and has already developed several prototypes over the past years. One example is a Ka-band transmitter operating in the 25.8-26.7GHz band and capable of 200 Mbps input data rate with convolutional coding (7, ½), OQPSK modulation and 1W-1.5W RF output power.

Adapting this prototype to a CubeSat form factor is one evolution that Syrlinks is currently considering for the EWC27 X-band transmitter. This new Ka-band transmitter would be answer to all Cubesat and Nanosatellite missions in need for a reliable and cost effective solution for data downloading in Ka-band.

The offered data rate, which would be in the order of 200-300Mbps, is believed to be a suited range for Cubesat and nanosatellite missions. Higher data rates would indeed require more power and/or higher gain antennas that would not be compatible with such kind of missions.

The Ka-band HDR transmitter for nanosatellite considered by Syrlinks should have a cubesat form factor, and be compatible with several DVB-S2 modcods, allowing usage in CCM, VCM or ACM according to the CCSDS standard.

Ka-band link budget

In this paragraph, a reflection is carried out on the link budget design in Ka band.

The Ka band is seen as the next step for high data rate transmission as the available bandwidth is four times larger. Nevertheless, it is well known that Ka band transmissions are very sensitive to propagation conditions in particular rain attenuation. As visible on Figure 4, the expectable levels on the link budget increase dramatically for low elevation angles where most of the data downloads are achieved. The results are given for a 1% unavailability.

The main impact of these higher propagation losses is that a higher EIRP is needed onboard to fulfill the link budget. The transmitter RF power cannot be excessively increased, for heat dissipation mainly, so the solution is to increase the antenna gain. The use of isoflux antennae with low antenna gain but wide beam width is no more conceivable. A pointed antenna with high gain in the axis, for instance a horn, becomes necessary and along with a pointing system, which can be the pointing of the satellite itself. The expectable delta gain between pointed and non-pointed antenna can be at least 15 dB.

The pointed approach involves constraints on the RF subsystem, satellite and mission design.

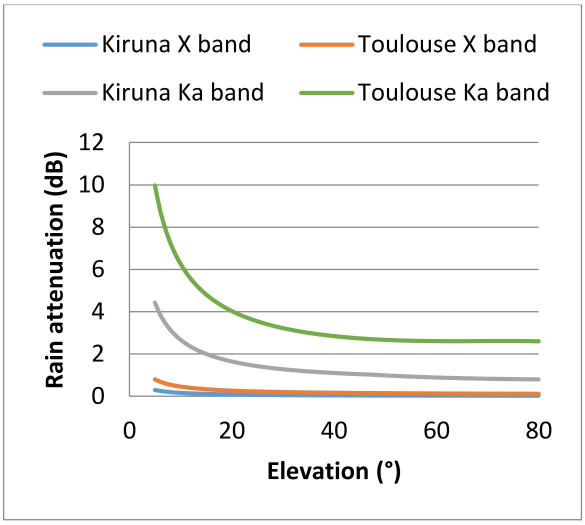

Figure 4: Rain attenuation for 1% of unavailability in X and Ka bands for Toulouse and Kiruna stations

In Ka band, the ground segment choice becomes crucial and humid regions with high rain frequency must be avoided as much as possible. On the other hand, Ka band equipment are smaller and so, more adapted for cubesats.

For high throughput missions, considering a Variable Coding rate and Modulation with elevation, like in X band, may be a complementary solution to better exploit the satellite passes. On the other hand, for less demanding mission, considering lower link availability, 95% for instance, would allow fulfilling the link budget with lower EIRP.

CONCLUSION

Syrlinks and CNES are working on the implementation of the DVB-S2 CCSDS telemetry standard in cubesat HDR transmitters, in X-band. Syrlinks is also considering to develop such an equipment in Ka band. These equipment, complementary to the current EWC27 X-band OQPSK CC (7,1/2) HDR transmitter validated in orbit on-board GOMX-3, could satisfy data rate needs lower and also higher than 100 Mbits/s

Thanks to its excellent performances, the DVB-S2 standard with adaptive coding and modulation is getting widely adapted. All the DVB-S2 features have been implemented in a baseband card, and validation is on-going, and future operational DVB-S2 HDR equipment for cubesat are therefore on a good track.

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