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X Band Downlink for CubeSat : From Concept to Prototype

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ABSTRACT

This paper starts with a remind of the main performances of the transmitter which is able to modulate data up to 50 Mbps (up to 100Mbps with technical restriction), deliver 2 Watts with no more than 10W DC/DC consumption in only 0.3U dimensions. Then, the architecture of the transmitter is presented with all the key functions such as the power amplifier, synthesizer, IQ modulator, filters. Some results achieved on the prototype are presented with particular attention to the consumption, BER measurements and transmitter quality losses. The process used to select and qualify the key components is also described.

INTRODUCTION

Today, more and more complex and miniaturized payloads for CubeSat or NanoSat are in development for earth observation, astronomy or space spectrum survey missions. Such instruments generate large amount of data and require much higher data rate telemetry solutions than those which are currently available.

If UHF and S bands are well adapted to usual telemetry needs, the channel bandwidth which is limited to maximum 6 MHz in S band can hardly fit with future high data rate telemetry needs, even with high spectral efficiency options.

In these conditions, X band appears to be a good solution as the gain at system level is really significant, in particular with variable bit rate option. Nevertheless, the feasibility of such subsystem for CubeSat is not trivial because the energy and size are again more restricted than on micro satellite platforms where X band is already tricky.

Fifteen years ago, the design of S band equipment with COTS was a real challenge because most of the existing ground wireless applications were limited to UHF. Today, many wireless applications exist up to 5-6 GHz. But only a few are located close to 8-9 GHz and almost no highly integrated chipsets exist that could ease the design of a miniaturized X band telemetry transmitter.

Despite these difficulties, a first high performance X band transmitter was developed by Syrlinks in 18 months for CNES and ESA for PROBA-V mission.

In the follow up of this development, Syrlinks has started to study for CNES a highly integrated micro transmitter, with a form factor and consumption compatible with 3U CubeSat or NanoSat.

The miniaturization is achieved both thanks to smart choices of modulation, coding and architecture but also to a selection of high performances circuits and components.

After the development of a first prototype which has showed promising performances, an Engineering Model realisation is now on the way. It will be followed by a qualification campaign.

The qualification tests will be executed both at component level for the most critical parts and at the board level for rest of the equipment.

The system aspects were already exposed in reference 1 where link budgets are presented. They show the capability of this solution to download several gigabytes per day with 3.4 or 5m diameter antenna ground stations and with 0 dBi gain board antenna.

TRANSMITTER OVERVIEW

Specifications

The system study has allowed to define a first level of specifications which are summarized in Table 1. The frequency band and the waveform are compliant with the ECSS standard. The key figures are the RF output power of 2 W, the power consumption of 10 W and the size which fits with the CubeSat constraints (10 cm x 10 cm). It is also important to note that the data rate may be programmable in flight authorizing the VBR (Variable Bit rate) feature to maximize the downlink capability.

Table 1: Transmitter specifications

Item	Typical value
Frequency band	8025 to 8400 MHz
RF Output power	2 W typical tunable from 30 to 33 dBm (with an option up to 34 dBm)
Waveform (modulation, coding & filtering)	OQPSK / convolutional coding 7 ½ / 6th order Butterworth
Data rate (user)	Programmable from 3 to 50 Mbps
Implementation losses	< 1 dB @ BER = 10^{-9}
Data & clock input format	LVDS
Input DC voltage	8 to 32 V (no galvanic isolation)
Power consumption	~ 10 W for +33 dBm RF
Volume	< 10 x 10 x 3.0 cm^3
Weight	~ 300 g
Operating temperature	-40 to +50°C
Life time	2 to 5 years (depend upon qualification tests)
Radiation tolerance	5 to 10 kRad (depend upon qualification tests)

Prototype Bloc diagram

The prototype architecture is presented in Figure 1. Input digital data are encoded, mapped and filtered within the base band subsystem. Then a homodyne up-converter allows to translate the signal in X band. This elementary RF structure uses a reduced number of components in order to miniaturize the transmitter. The synthesizer part includes a TCXO, an X band VCO, a PLL IC and a prescaler. The last RF stage includes three amplifiers to reach the desired gain and to get up to 34 dBm at the RF output. Moreover a pass band filter is settled inside this chain essentially to limit the out of band noise floor.

The prototype also integrates a digital logic function to setup and to control the equipment. It provides likewise a HKTM link. Today a RS422 format is used but I2C bus might be considered to fit with CubeSat platforms. Finally some power supply functions (LDO…) provide the required voltage levels.

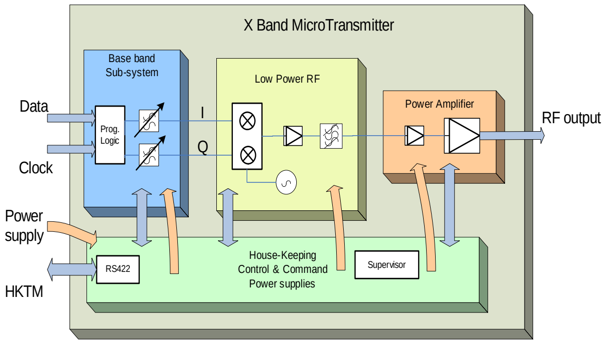

Figure 1: Micro-Tx prototype Bloc Diagram

Functional description

At power-on, equipment initialization starts with transmitter warm up during a few seconds. This timeframe is necessary for transmitter stabilization. Transmitter is in stand-by mode, with no RF output signal.

When HKTC of RF output power and data rate are received and when clock signal appears, transmitter becomes active and data are transmitted. Each time new data rate command is received or when clock signal disappears, transmitter goes back to stand-by mode.

A supervisor function manages the transmitter functioning modes (active, stand-by, safety). It monitors internal sensors parameters (such as RF output power, currents and internal temperature) and programs synthesizer frequency. It controls amplifiers biasing values from temperature compensated tables, to optimize power consumption over the complete RF output power range. It manages the communication protocol with the OBC for HouseKeeping TeleMetry (HKTM), based on a serial link.

COMPONENTS SELECTION AND QUALIFICATION

Components selection

COTS component selection is one of the most critical steps of the development, as the transmitter is fully based on components used for ground commercial telecommunication applications. Some components are based on the heritage of X band PROBA-V transmitter (validated in space environment), but others are new.

Each active component is supplied in one shot with same manufacturing batch number. All procurements include parts for qualification, flight models and (tens) equipments foreseen for future missions.

Components are stored in neutral atmosphere.

Each COTS components choice is justified. Components technology is described and reliability data from manufacturer are provided. This process will allow identifying specific tests to be performed on components – or component family – such as Destructive Part Analysis (DPA), burn-in, cumulated-dose radiation test, heavy ions radiation test. The goal is to verify components reliability and compatibility for space application.

Most components are procured with a non-pure tin termination. Nevertheless some Restriction of the use of certain Hazardous Substances (RoHS) active and passive components had to be processed in order to obtain leaded terminations. Traceability of all components is performed.

Manufacturing

The unit will be almost completely assembled on an industrial manufacturing line. All manufacturing steps are traced from purchase orders up to product delivery to customer.

Qualification and flight model boards will be built following the same manufacturing process than the one used for Myriad TTC and Proba-V TMHD. Flight model boards will be stored in neutral atmosphere, waiting for their integration into equipment boxes.

To fit with mission calendar, qualification and flight model boards could be manufactured at the same time. Such approach has already been applied successfully by Syrlinks on X band PROBA-V transmitter.

Qualification of equipment

Critical components will be analysed individually, but aggravated tests will be done at unit level in order to demonstrate robustness and to evaluate margins for comparison with mission constraints. Several qualification models will be manufactured. First they will be tested by applying qualification levels as defined in mission requirements: temperature cycles, life tests, on/off cycles, mechanical trials, vacuum tests, radiation tests. More severe conditions levels might be then applied to stress the equipment in some cases up to destruction. This principle was successfully applied on 2 products developed by Syrlinks:

- Myriad TTC transceivers in S band: 44 transceivers delivered to CNES, EADS Astrium and Thales Alenia Space

- Proba V X band transmitters: 2 FM delivered to ESA with GaAs RF amplifier and 1 FM delivered with GaN RF amplifier) + products under manufacturing for new customers

STUDY AND DESIGN OF THE POWER AMPLIFIER

One of the major challenges of the project is to meet the specification of consumption (below 10W for +33 dBm). Special efforts were made to improve the power amplifier efficiency. In fact, the PA often contributes up to three-quarters of a transmitter consumption.

The selected component is a high performance MMIC housed in a small SMT package. To optimize its performances, it was decided to make a campaign of characterizations on a load pull test bench. In that way, a dedicated test board was realised (cf. Figure 2)

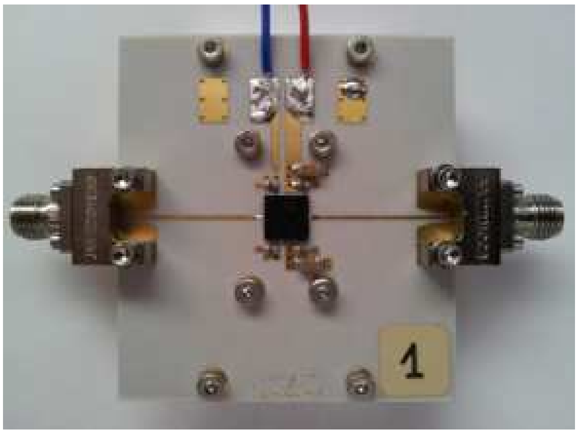

Figure 2: Test board of the PA

The aim of these measurements is to determine optimum PAE. The influence of several parameters was analyzed as the drain voltage (Vd), quiescent current (Idq), gain compression and frequency.

At the end of this phase of characterization, a summary was made to choose, for this component, the best possible trade-off and to design the matching circuits with microstrip lines.

Finally, the desired power of 2 W was obtained with an efficiency close to 40%. These figures meet our expectation and are compliant with system requirements. Nevertheless, reaching these values was only possible thanks to the technical know-how Syrlinks developed during the TMHD Proba-V development.

DESCRIPTION OF SOME RF & ANALOG FUNCTIONS OF THE μ-TRANSMITTER

This section provides the description and key results of the main functions of the transmission chain.

Driver amplifier

To optimize the overall performance of the transmission chain it is also important to choose a driver which fits well with the PA. In fact, a driver oversized in terms of output performance will penalize the efficiency while a driver undersized will induce prematured gain compression. In this context, a transistor was selected because it offers a good flexibility for the polarization compared to a multistage MMIC amplifier. Indeed, the drain voltage and the quiescent current of a transistor may be adjusted as a function of the desired output power.

The selected transistor is chosen from a GaAs FET foundry and is packaged in a non-hermetic ceramic package. Linear simulations were carried out to adjust the transistor in the frequency band [8-8.5] GHz. Then measurements on a prototype have verified the performance of the amplifier, the low level measured gain reaches 11 dB and the output power at 1 dB compression is 21 dBm. These results are in line with expectations.

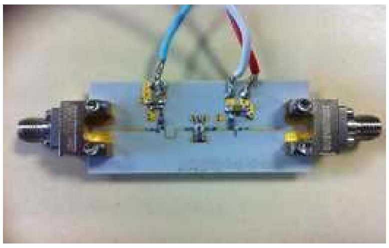

Figure 3: Test board of the driver

X band filter

To save up space on the PCB, we have chosen a filter structure as compact as possible and which presents some good performances in X band. Moreover we have here no severe constraints in terms of rejection due to homodyne architecture of the transmitter. So a third order filter is convenient to suppress out of band noise.

Two filters have been designed and realized: an interdigital filter and a hairpin version. Their layout is presented in Figure 4. The intergital size is around 3 x 6 mm² and the hairpin is ~ 6.5 x 5,5 mm². As theirs performances are finally similar, the small one was chosen for the transmitter prototype. Measurement results fit very well with simulations and are presented in Figure 5. The 15 dB return loss bandwidth is around ~[7800-8800] MHz, insertion loss at 8.3 GHz is roughly 3.5 dB.

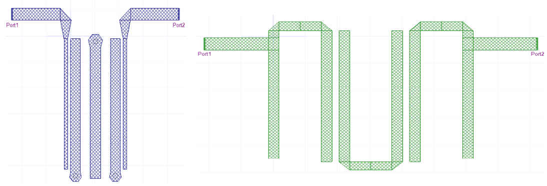

Figure 4: Layout of the 2 X band filters

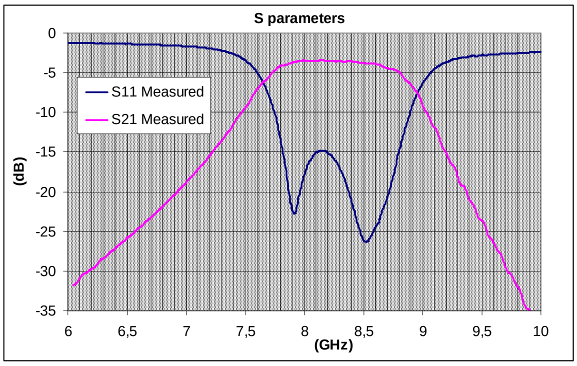

Figure 5: Measured S parameters of the interdigital X band filter

Tunable analog base band filter

As stated previously, it is important to have the ability to vary the bandwidth of the analog IQ filter in order to use the benefits of VBR. To fulfill this function Syrlinks experts worked on a dedicated scheme. A 6th order Butterworth transfer function was chosen to deliver superior stop band rejection while maintaining both a flat passband and minimal group delay variation. Likewise its cutoff frequency is programmable between 3 et 100 MHz. As an example, Figure 6 shows the transmission parameter for five different filter cutoff frequencies (5, 15, 25, 37.5 and 50 MHz). The theoretical slope of 36 dB per octave is properly obtained and the precision of the cuttoff frequency is around ± 2%. Another interesting property of the used scheme is the good matching between the both channels of the filter.

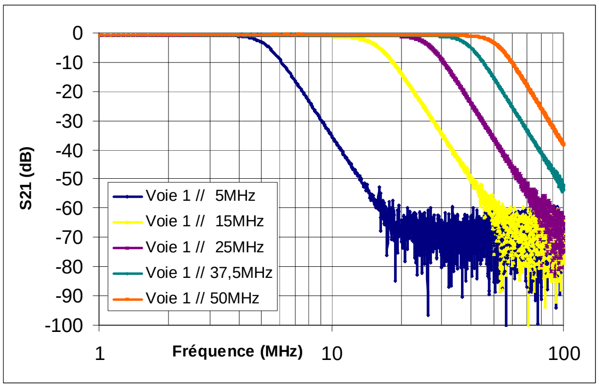

Figure 6: Measured S21 parameters of the tunable filter

IQ Modulator

To minimize the EVM of a homodyne transmitter, it is important to have an accurate IQ modulator. This can be complicated in X-band so Syrlinks has developed a specific hybrid well suited to the required bandwidth and the working frequencies. This hybrid is able to operate with a LO frequency ranging from 7.5 to 9 GHz and a bandwidth of 500 MHz for I&Q inputs. Through its integrated OL buffer, it only requires a level of 0 dBm at the LO input. Without adjustments, the rejection OL typically reaches 40 dB but can be improved to more than 60 dB by adjusting setting resistors. The value of the rejection of the image frequency is typically 40 dB. To illustrate these values a Single Side Band (SSB) spectrum is given in Figure 7 for an OL frequency of 8200 MHz.

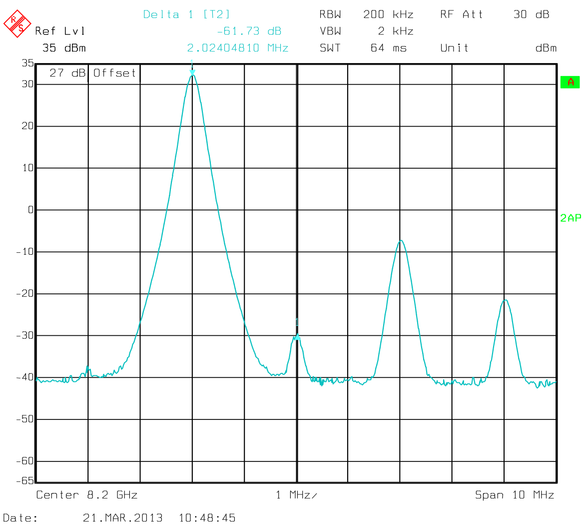

Figure 7: Typical SSB output spectrum (OL @ 8200 MHz)

RF Synthesizer

To design the X band synthesizer of the µTransmitter, a compromise was to be made between the phase noise performance, consumption and dimensions. Finally a monolithic VCO was chosen because it takes less space than a hybrid VCO or a dielectric resonator oscillator. Then a frequency divider by 4 is used to transform the X-band frequency to a compatible range of the PLL used. A fractional PLL is used to obtain a relatively fine frequency resolution. As the reference frequency, still to optimize size and consumption a TCXO is used instead of an OCXO. The synthesized frequency can be programmed via the serial connection from 8000 to 8500 MHz.

The global footprint including the future top part will be less than 100 x 100 x 30 mm^3.

COMPLETE PROTOTYPE DESIGN

Integration and mechanical presentation

The current version of transmitter mechanical structure is defined with by two stacked parts (Figure 8).

The bottom part includes base band and RF sections and Control/command functions. The thermal power is drained to the platform with an aluminium base plate. All RF and critical analog functions are shielded into with a cover which contains dedicated cavities.

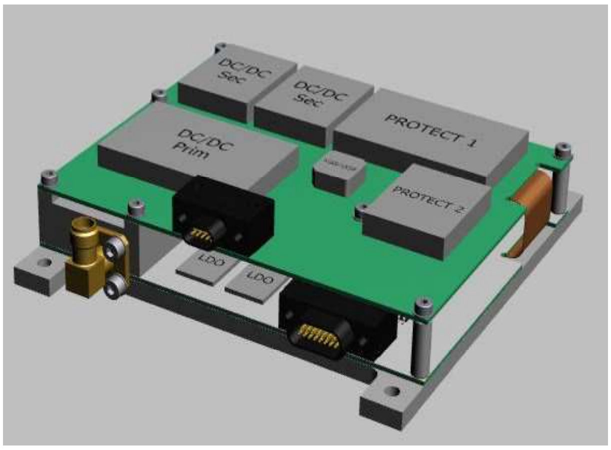

Figure 8: 3D mechanical preview of the µTransmitter

The top part contains power supplies functions (DC-DC converters) and protections circuits against latch up. Both parts will be interconnected with a flexible polyimide harness. As a first hypothesis, 9 pins micro sub-D connector will be used for the power supply and a 15 pins connector will be used for the data and clock LVDS input signals and for the housekeeping telemetry. A SMA or a SMP connector will be used for the RF output. Some discussions are on-going with some CubSat platform providers to define the most relevant mechanical (connectors, …) and electrical (Electrical Power, Datas, Control/command) interfaces.

Today Syrlinks realized only the bottom part of the transmitter which includes all the functions except power management (LDO, DC/DC, …). A prototype photo of this prototype is presented Figure 9. Its overall dimensions are 100 x 80 x 14 mm^3 without connectors and fastener points. To achieve this level of integration a 4 layers PCB was used. RF traces are built on a hydrocarbon ceramic substrate which offers relatively low losses (tan δ =0,003).

Figure 9: Photo of the µTransmitter prototype

Power consumption analysis

During architecture, an estimation of consumption was made in order to check whether the objective was reachable. Consumption of key function is shown on Figure 10. Note that the consumption of PA is more than three quarters of the total which is equal to 8.6 W. To this must be added the performance of DC-DC converters that would bring the total consumption to 10.0 W if their yield is equal to 85%. We must therefore design the DC-DC converters with a particular care for their efficiency in order to reach or exceed 85%.

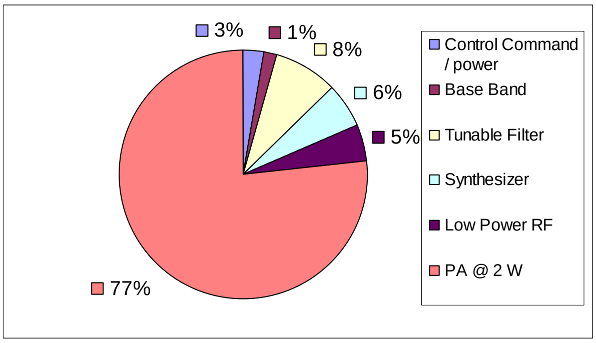

Figure 10: Power consumption distribution

RESULTS MEASURED ON THE PROTOTYPE

Output power, linearity and efficiency of the RF chain

To characterize the RF chain some power measurements were made by injecting a variable level at analog inputs I & Q and by measuring the output power of the prototype with a powermeter. In this way all the elements of the RF chain are taken into account from IQ modulator to PA. This test provides the AM-AM curve, consumption and PAE as a function of output power. The results are presented in Figure 11. The point of operation of the transmitter is fixed for an input power of +6 dBm, which corresponds to a voltage level of about 450 mVpeak-peak on paths I & Q. In this case the output power reaches the desired power of 2 W with compression of the gain of around 3 dB. A 2 W (33 dBm) the overall efficiency is about 30%, which represents approximately a current consumption of 1.2 A at 5.5V.

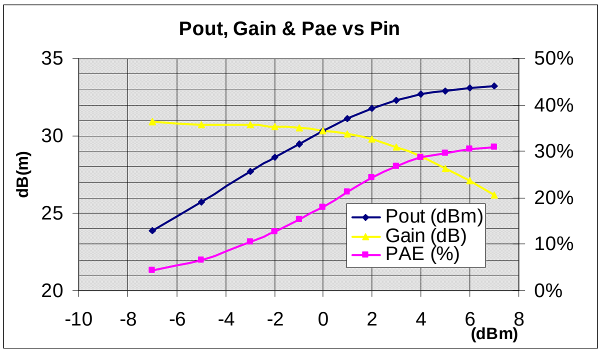

Figure 11: RF chain characteristics @ 8200 MHz

Moreover, it is also useful to know the behaviour of the RF chain within temperature range. Thus measurements were made between -40°C and +50°C, Table 2 summarizes the results, focusing on the operating point of 2 W for RF output power. Through a mechanism of temperature stabilization of the RF gain, the measured differences remain relatively low: 33 dBm ± 0.3 dB is obtained for an input power of 7 dBm ± 1 dB and a consumption of 6.8 W ± 3%.

Table 2: Output power vs temperature

Item \ T°	-40°C	+25°C	+50°C
Pout @ P3dB	33,4 dBm	33,3 dBm	32,8 dBm
Pae @ P3dB	33,1 %	30,5 %	28,1 %
Pin @ P3dB	6 dBm	7 dBm	8 dBm
PA DC Power	6,6 W	7,0 W	6,75 W

Emitted spectrums for different data rates

To check the operation of the µTransmitter prototype, the output spectrum was measured at different data rates between 3 and 50 Mbps. Two examples are given in Figure 12 at 28 Mbps and in Figure 13 at 50 Mbps for a carrier frequency of 8200 MHz and an output power of 2 W. In each case, the green spectrum is recorded when the I & Q channels filter is bypassed, obviously this mode is not operational. The cyan spectrum is recorded when the filter is activated, for example, a cutoff frequency of 28 MHz is programmed for 28 Mbps (50 MHz for 50 Mbps). The red outlined template represents the spectrum mask from the ECSS standard.

The two examples show that the filter provides a comfortable margin on the required mask. It is even quite possible to slightly increase the cutoff frequency of IQ filters to improve the EVM and therefore the quality loss.

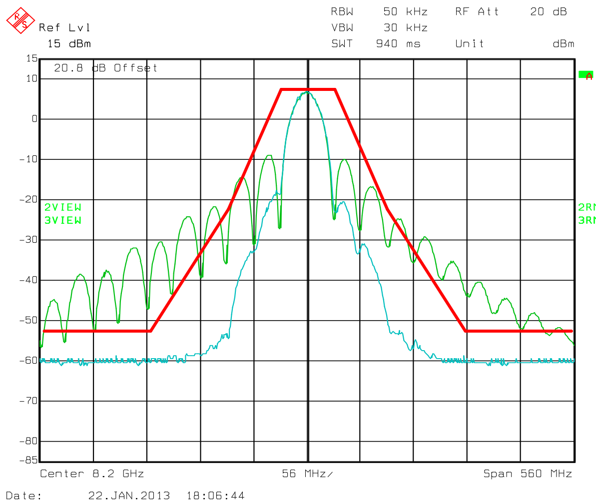

Figure 12: Emitted spectrum @ 28 Mbps

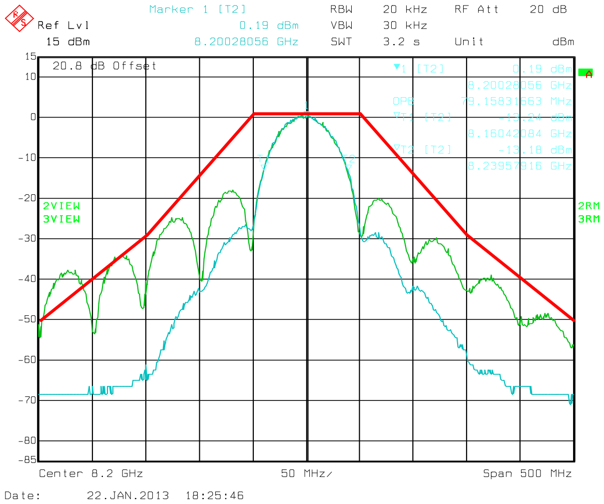

Figure 13: Emitted spectrum @ 50 Mbps

µTransmitter quality loss

It is useful to measure RF performances of an equipment but the aim is still to get a good transmission quality in order to improve the link budget. This is why the final validation measures are performed by demodulating the signal using a receiver in order to make BER measurements as a function of Eb/N0 (the energy per bit to noise power spectral density ratio).

On our test bench we use a sophisticated High Data Rate test bench receiver with Viterbi feature as the receiver and we use a noise source to add noise over the signal. It allows to have the required Eb/N0. It is also important to note that the result is not only technological losses of the transmitter but is the performance of the assembly formed by the transmitter and the receiver.

In Figure 14 some measurements are given for data rates between 3 and 50 Mbps. They show a difference of about 0.75 dB with the theoretical curve for a BER of 10^{-6} and 1 dB for a BER of 10^{-9}. Performance could be slightly improved by increasing the cutoff frequency of the tunable IQ filters.

The differences observed between the different data rates are not significant and are actually in the order of the measuring accuracy.

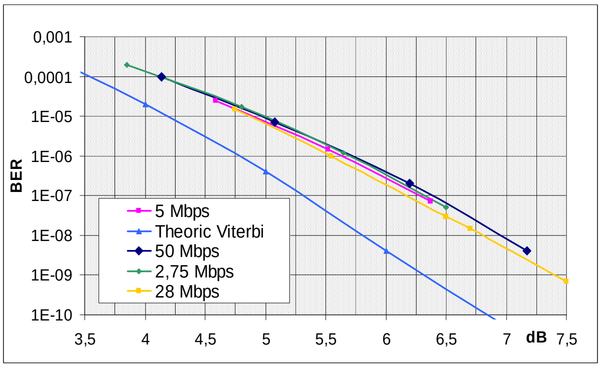

Figure 14: BER vs Eb/N0 for some data rates

The Figure 15 shows results within the temperature range at a rate of 28 Mbps. We can notice a performance degradation of about 0.2 dB at -40°C. This is probably due to the phase noise of the synthesizer, which also degrades at cold temperatures.

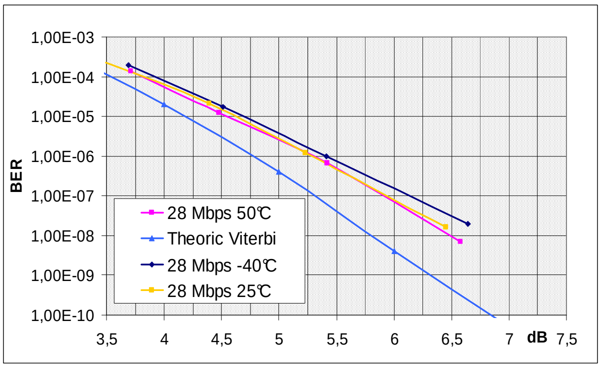

Figure 15: BER vs Eb/N0 from –40°C to +50°C

NEXT STEPS

Following the development of the prototype, the next steps are to continue the development of an EM which incorporates all functions of the µtransmitter including power management and anti latch-up protection. Today it is planned to supply the equipment with a single voltage between 8 and 32 V. But this figure could change depending on discussions with manufacturers of CubeSat platform. The definition of interfaces is an essential prerequisite before realizing an EM.

Another step of research would be to identify some ground and onboard solutions which be able to interface with the transmitter. Indeed it is not obvious to find an OBC or a mass memory capable of delivering data rates of up to 50 Mbps. Regarding the ground segment, it is also necessary to identify or develop a receiver capable of demodulating the received signal and that is economically consistent with the budget of a CubeSat mission. The protocol to manage the variable rate mode (VBR) is also to specify and implement.

Protection against single event latch-up

A single heavy ion or high energy proton passing through semiconductor junctions can lead to excessive power supply current and loss of device functionality. Semiconductor device can burnout unless current is limited.

An electronic fuse is implemented in order to protect equipment in case of over-current situation. This device is located just after main DcDc converter. The design uses as few components as possible, as reliability should not be degraded due to this protection unit. Components used for are protected against latch-up thanks to power resistors in series with their supplies.

Electronic switch is opened when over-current is detected in one of the main branches. A flip-flop memorizes the switched-off state. The equipment has to be switched-off then -on, for being operational again. This function can be inhibited by the user, but over-current remains detectable and flip-flop memorizes the switched-off state.

CONCLUSION

The realization on this prototype confirms the feasibility of X band transmitter for CubeSat or NanoSat.

Although standard COTS technology is used, the prototype presents very interesting performances which are very closed to those of usual X band modulators for bigger satellites.

With a DC consumption of 10W, a volume of 0.3U and a mass of 300g, this transmitter allows to download telemetry to ground stations at data rate between 3 to 50 Mbps with less than 1 dB system transmission losses.

The transmitter can be operated in fixed or variable bit rate in flight. The VBR is very interesting because it allows roughly doubling the damping capacity but this operating mode requires a flexible data rate mass memory solution to operate this transmitter option.

The EQM model in development should present the same performances than the prototype. Thanks to PROBA-V qualification campaign and specific pre evaluation tests, risk of product qualification is low. No critical element is identified today that could impact the development program. Flight models should be available in Q3 2014.

Last but not least, a C band version of this MicroTransmitter would be easily achievable, as most of components would be the same ones as the X-band one. This product might be interesting for specific missions (AIS, …).

References

1. E. Peragin , “X Band downlink for CubeSat” Proceedings of 26th Annual AIAA/USU Conference on Small Satellite, Logan (USA), August 2012.