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SCOUTT

Executive Summary Report

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01.00	09/07/2018	First draft	All
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1 Introduction

This executive summary summarize the activities performed during this project. In this study project the new concepts of sampling and frequency conversion are studied in the system level for the requirement analysis. Later this requirement is translated to the subsystem requirements where each component is analysed for commercially availability and performance.

Intensive simulations and analyses are performed to justify the performance for different applications. Track-hold amplifier (THA) is studied as a baseline of the project. Along with this architecture, photonic based architecture and also high speed DAC are considered for different applications.

In this project the frequency bands that need to be covered are tabulated in the table below.

Table 1-1: Frequency bands required for coverage in this activity

Band	S		X			Ka	
Service/type of mission	SRS DS	EES NE	SRS DS	EES (TTC) NE	EES (Payload data) NE	EES NE	SRS DS
Downlink frequency (MHz)	2290-2300	2200-2290	8400-8450	8450-8500	8025-8400	25500-27000	31800-32300
Uplink frequency (MHz)	2110-2120	2025-2110	7145-7190	7190-7235		27500-31000	34200-34700

2 Related Documents

2.1 Applicable documents

DRL/CI	Document ID	Title	Issue
AD-1.	SC OUTT-AS-TNO-0002	Level 2 Specification Document	01.00
AD-2.	SC OUTT-AS-TNO-0008	Subsystem Specification Document	02.00
AD-3.	SC OUTT-AS-TNO-0013	Architecture Trade-off Document	02.00
AD-4.	SC OUTT-AS-TNO-0018	Hardware platform description	01.00
AD-5.	SC OUTT-AS-TNO-0017	Simulation tool documentation	01.00

2.2 Reference documents

DRL/CI	Document ID	Title	Issue
RD-1.	EPFC-AS-0093	Final report	01-00

2.3 Internal documents

A set of internal Antwerp Space documents describes the following topics:

DRL/CI	Document ID	Title	Issue
ID-1.	-		

3 Terms, Definitions and Abbreviations

3.1 Terms and Definitions

None.

3.2 Abbreviations

Abbreviation	Description
ADC	Analog-to-Digital Converter
AS	Antwerp Space
B	Bandwidth
Clk	Clock
COTS	Commercial Off The Shelf
DC	Direct Current
DS	Deep Space
DAC	Digital to analog converter
EMI	Electromagnetic Interference
EPFC	Electro-Photonic Frequency Converter
EES	Earth exploration satellite
IF	Intermediate Filter
Ka	Kurz above
LNA	Low-Noise Amplifier
LO	Local Oscillator
MLL	Mode Locked Laser
MSps	Mega sample per second
MZM	Mach Zehnder Modulator
PIC	Photonic Integrated Circuit
RF	Radio Frequency
SRS	Space research service
SoW	Statement of Work

Abbreviation	Description
THA	Track and Hold Amplifier
TTC	Tracking telemetry comment
TRL	Technology Readiness Level

4 Frequency conversion based on bandpass sampling

As per Nyquist sampling theorem, a signal must be sampled at a rate greater than twice its maximum frequency component in order to ensure unambiguous data. If the Nyquist criterion is not met, aliasing will occur. For example, if the maximum frequency of a sine wave is 70 MHz, then the minimum sampling frequency required is 140 MSps, as per Nyquist criteria.

If we use this Nyquist criterion, that is, the sampling frequency is sufficiently high which will not have any overlapped frequency components in the frequency domain; it is called normal sampling or oversampling. 2 × Fmax is called the **Nyquist sampling rate** where Fmax is the maximum frequency component in the signal. Also, the Fmax is called the Nyquist frequency. Nyquist rate is the minimum sampling rate to avoid aliasing.

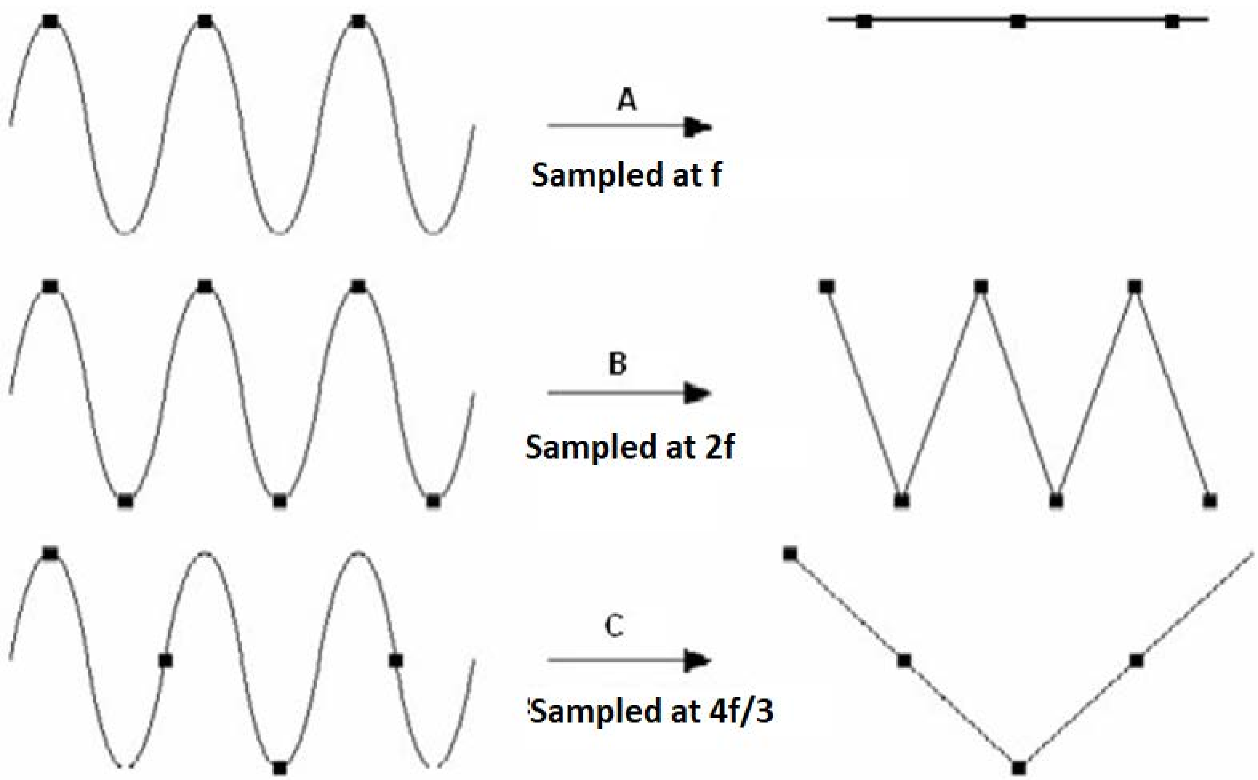


Figure 4-1: example of sampling a sin signal at different frequencies

If we use the sampling frequency less than twice the maximum frequency component in the signal, then it is called **undersampling**. Undersampling is also known as band pass sampling, harmonic sampling or super-Nyquist sampling. Nyquist-Shannon Sampling theorem, which is the modified version of the Nyquist sampling theorem, says that the sampling frequency needs to be twice the signal bandwidth and not twice the maximum frequency component, in order to be able to reconstruct the original signal perfectly from the sampled version. If B is the signal bandwidth, then Fs > 2B is required where Fs is sampling frequency. The signal bandwidth can be from DC to B or from f1 to f2 where B = f2 – f.

The aliasing effect due to the undersampling technique can be used for our advantage. When a signal is sampled at a rate less than twice its maximum frequency, the aliased signal appears at Fs – Fin, where Fs is the sampling frequency and Fin in the input signal frequency. In the above case, if we sample the 70-MHz signal with 100 MSps sampling rate, the aliased component will appear at 30

MHz (100 – 70). As we know in advance that the signal is aliased, we can recover the actual frequency by using the Fs – Fin relationship. The undersampling technique allows the ADC to behave like a mixer or a down converter in the receive chain. For a band-limited signal of 70 MHz with a 20-MHz signal bandwidth, if the sampling rate (Fs) is 100 MSps, the aliased component will appear between 20 MHz to 40 MHz (30 ±10 MHz).

4.1 Valid sampling frequency

We need to be careful with the valid sampling frequency, because this conversion should follow certain criteria. For the sampling frequency estimation, three criteria should be satisfied. The first requirement is that $f_{IF} \geq B/2$, to avoid aliasing around zero where B is the data bandwidth. Given a sampling rate f_s there are aliases of the band at integer multiples m*f_s. This means that f_s is:

$$f_s = \frac{f_c - f_{IF}}{m}$$

Another requirement is that $f_s \geq 2B$ which makes sure that the complete bandwidth can be translated and not only the central frequency. The last criterion is to avoid overlap between aliases and given by:

$$\frac{2f_h}{n} \leq f_s \leq \frac{2f_l}{n-1}$$

Where $f_h = f_c + B/2$ and $f_l = f_c + B/2$. Considering these criteria the frequency plan can be made to verify the correct sampling rate for given frequencies. Since there is always a mirror image of the band at negative frequencies, we can use the relation $-f_{IF} = f_c - m'f'_s$ to create a second possible sampling rates for each m′.

An example of such analysis to find the right sampling frequency is provided in the table below for a few satellite standard RF frequencies:

Table 4-1: Frequency plan for ground station receiver for downconversion to 530 MHz (Downlink)

Green box: valid; orange box: valid for half BW; red box: not valid frequency

f_{RF} (MHz)	n = 2	3	4	5	6	7	8	9	10	12
	f_s (MHz)									
2245	2775	1715	1387.5	925	857	693.75	/	/	462	396
2295	2825	1765	1412.5	941	882	706	/	/	470	403
8213	8743	7683	4371.5	3841.5	2914.3	2561	2185.75	1920.75	1748.6	1457.2
8425	8955	7895	4477.5	3947.5	2985	2631.7	2238.75	1973.75	1791	1492.5
8475	9005	7945	4502.5	3972.5	3001.7	2648.3	2251.25	1986.25	1801	1500.8

4.2 Track & hold bassed sampling

The Sample and Hold circuit is an electronic circuit which creates the samples of voltage given to it as input, and after that, it holds these samples for the definite time. The time during which sample and hold circuit generates the sample of the input signal is called sampling time. Similarly, the time duration of the circuit during which it holds the sampled value is called holding time. The diagram below shows the circuit of the sample and hold circuit with the help of an Operational Amplifier. It is evident from the circuit diagram that two OP-AMPS are connected via a switch. When the switch is closed sampling process will come into the picture and the capacitance will charge with the sampling value and when the switch is opened holding effect will be there (the capacitor will hold the value for the holding time).

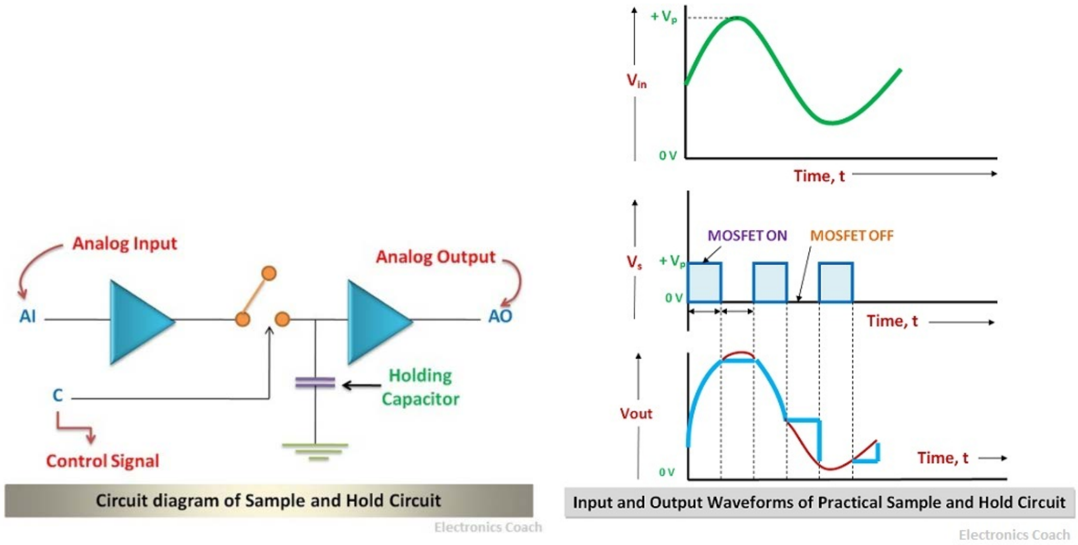
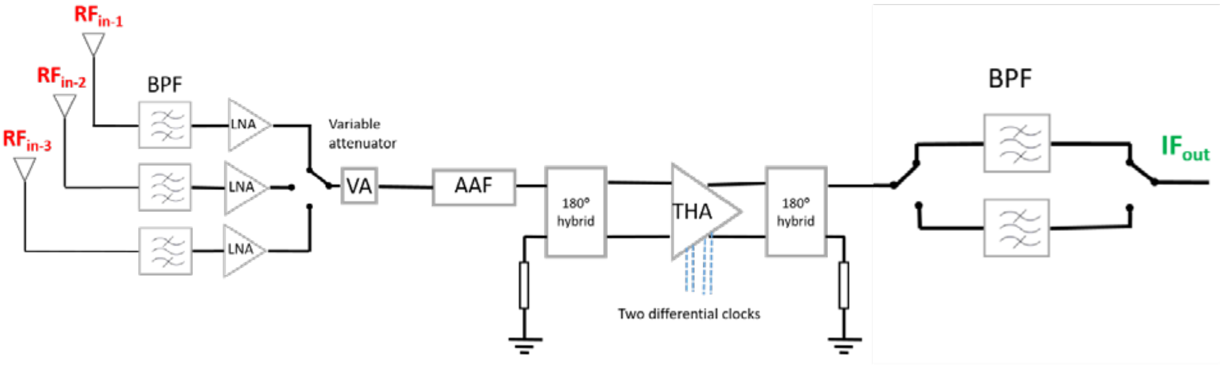


Figure 4-2: Sample and hold device operation principle

The architecture based on this device presented. The high level simulation, analyses and component selection has performed to validate the architecture performance. The figure below shows the suggested architecture and its simulated spectrum.



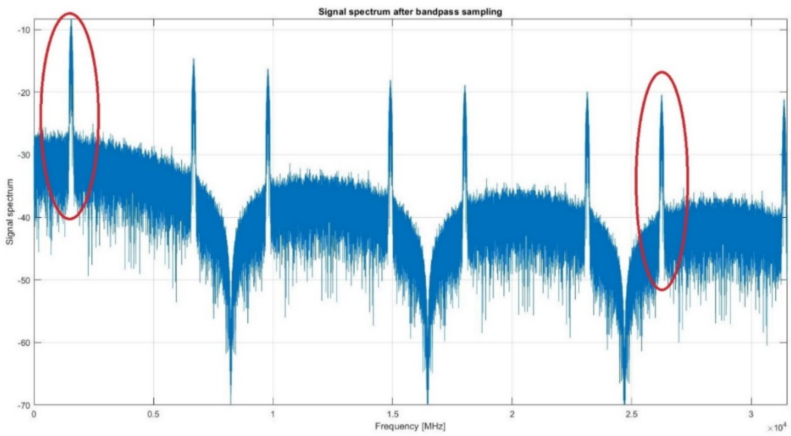


Figure 4-3: Dual Rank THA-based sampling front-end receiver (top), Full spectrum after bandpass sampling at 8233 MHz. The RF signal (26250 MHz) and the IF signal (1550 MHz) are indicated in the figure (bottom).

For this architecture simulation is carried out by taking into account the additive white noise and clock jitter. QPSK modulation format is used to verify the link performance. The THA based architecture theoretically proved to fulfil whole frequency band of interest from S-band up to ka-band. This has demonstrated with the developed simulation tool in Matlab. However, the commercially available THA devices up to now are able to work up to 25 GHz with degraded performance.

This device is the active component and at its maximum sampling rate can consume about 2 W which should be treated carefully if intended to be used in a payload. Another issue which should be considered when using a THA device is the noise folding effect. From Noise consideration point, wide-band noise such as thermal noise introduced by the relevant hardware is all combined into each of the $f_s/2$ bands. Therefore, the main difference between a classical mixer and bandpass sampling is that a mixer (at least an ideal one) preserves the SNR, while bandpass sampling changes the SNR according to the noise folding expression:

$$SNR = \frac{S}{N_p + (m-1)N_0}$$

Where S is the signal spectral power density, N_p is the in-band noise power density, N_0 is the out-of-band noise power density and m is the multiplier. If out-of-the-band noise level is not filtered sufficiently, this effect can be problematic as shown in the figure below for the noise figure.

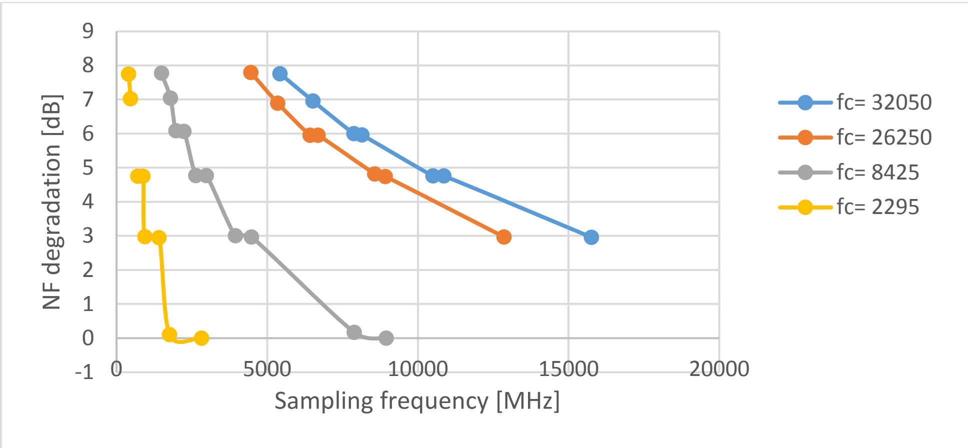


Figure 4-4: Noise folding effect as a result of the passband sampling

In order to see the effect of the additive white noise on the received signal quality, we performed a QPSK signal link simulation for different noise levels. For the S-band signal the sampling frequency of 2775 MHz is chosen. The constellation points' divergence shows the link performance for the given noise level. It is clear that a decrease in the SNR results in a low signal quality.

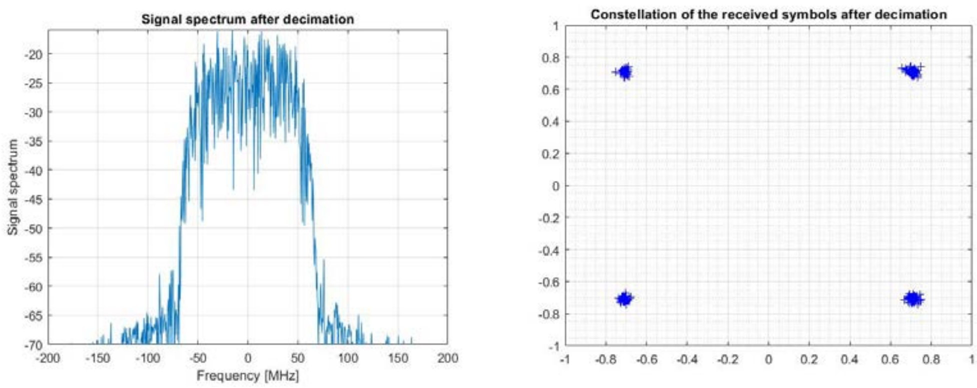


Figure 4-5 : Output spectrum after being translated to the baseband, SNR = 40 dB. Constellation is clean (RF = 2245 MHz, Fs = 2775 MHz).

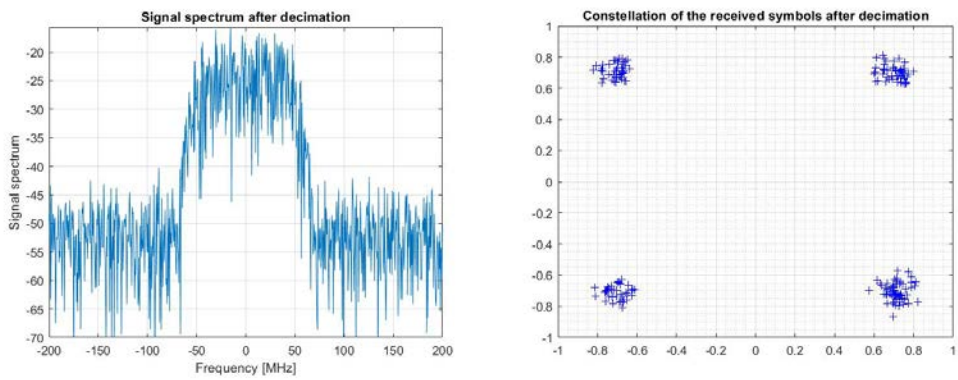


Figure 4-6 : Output spectrum after being translated to the baseband, SNR = 20 dB. Constellation is clean (RF = 2245 MHz, Fs = 2775 MHz).

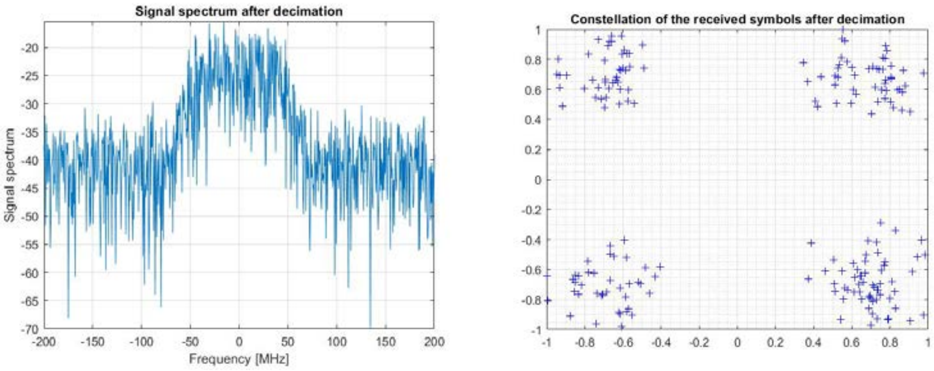


Figure 4-7 : Output spectrum after being translated to the baseband, SNR = 10 dB. Constellation is clean (RF = 2245 MHz, Fs = 2775 MHz).

5 Frequency conversion based on the photonic mixer

Here, a brief introduction is given for the photonic applications for the space-related projects. The Electro-Photonic Frequency Converter is going to be a key enabling architecture for flexible and high performance frequency conversion systems. Characteristics such as mass saving, power saving, room saving, EMI immunity, available bandwidth and routing/switching is proved to be beneficial for space applications, especially for on-board units. Of course, when this technology is mature enough to be implemented in the space application it can benefit both the ground station unit and the on-board system. The frequency converter system consists of a laser to generate the light carrier signal, a modulator to apply the RF signal on the optical carrier, an amplifier to boost the signal in order to compensate the losses and a photodiode to convert back the optical signal to the electrical one.

An EPFC-based architecture which is capable of handling frequencies up into the Ka band realm is envisaged as an alternative to the limitations which one faces with the bandwidth limited THA technology or with the mass and the power consumption of such fully electronic circuits. The schematic of such an architecture is illustrated in Figure 5-1.

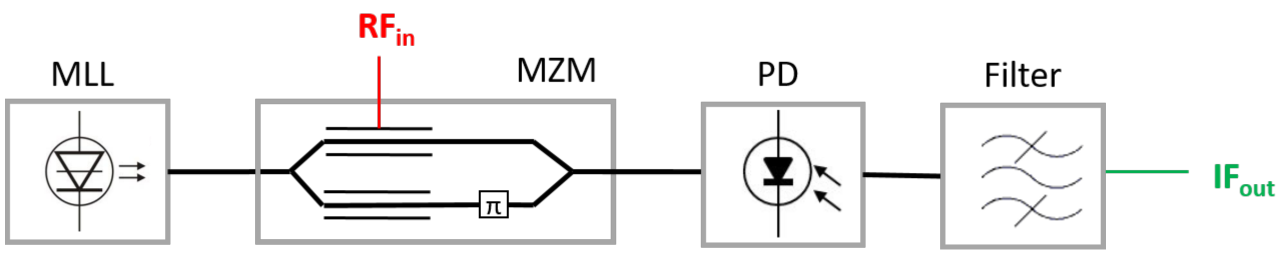


Figure 5-1: High-level Concept of the Electro-Photonic Frequency Converter (EPFC)

This architecture consists of a mode-locked laser that generates a series of short optical pulses in the time domain. This can be seen as sampling pulse of the RF input signal. This optical LO signal is injected to a high-speed optical modulator that is driven by the RF signal to be downconverted.

The output of the modulator is the RF sampled signal which contains replicas of the original RF signal. This optical signal would then be applied to the input of a photodetector to have it converted again to the electrical domain. Since the photodetector's output is a current as a function of optical input power this can be converted to a voltage through a trans-impedance amplifier such that an amplified voltage waveform can be applied to an IF filter.

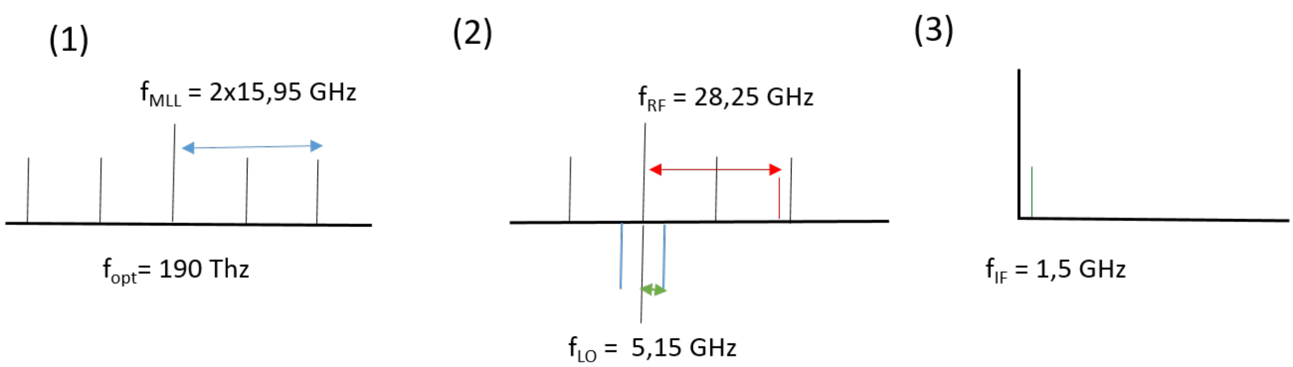


Figure 5-2: (1) optical spectrum of the MLL output, (2) optical spectrum after RF phase modulator and LO, (3) electrical spectrum obtained at the output of the PD.

The same mixer principle applies to the upconversion where an IF signal can be up converted to a high frequency carrier signal the following schematic illustrates the concept (Figure 5-3). By virtue of the photonic technology, it is possible to have a very wideband system available that can perform frequency conversions for all frequency bands so stated in the SoW.

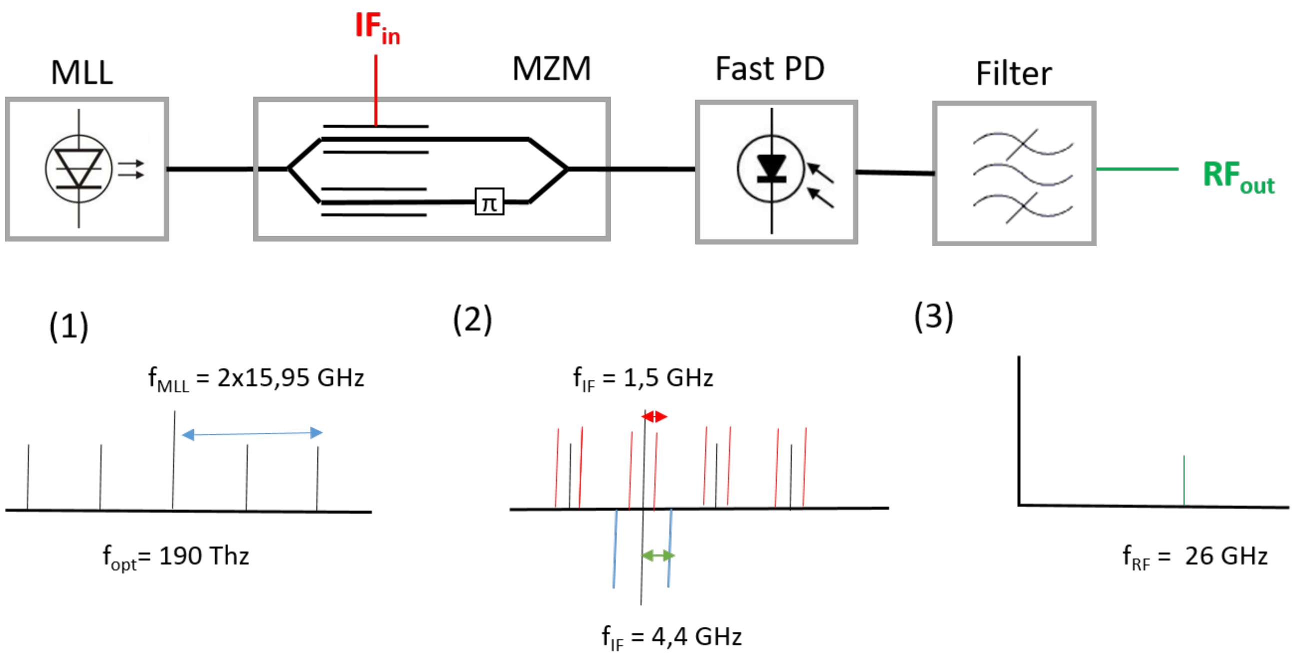


Figure 5-3: EPFC employed as a Frequency Upconverter and the waveform plot to upconvert the IF from 1.5 GHz to 26 GHz without LO signal

Here, an example of the frequency conversion simulation using a photonic based sampler is illustrated.

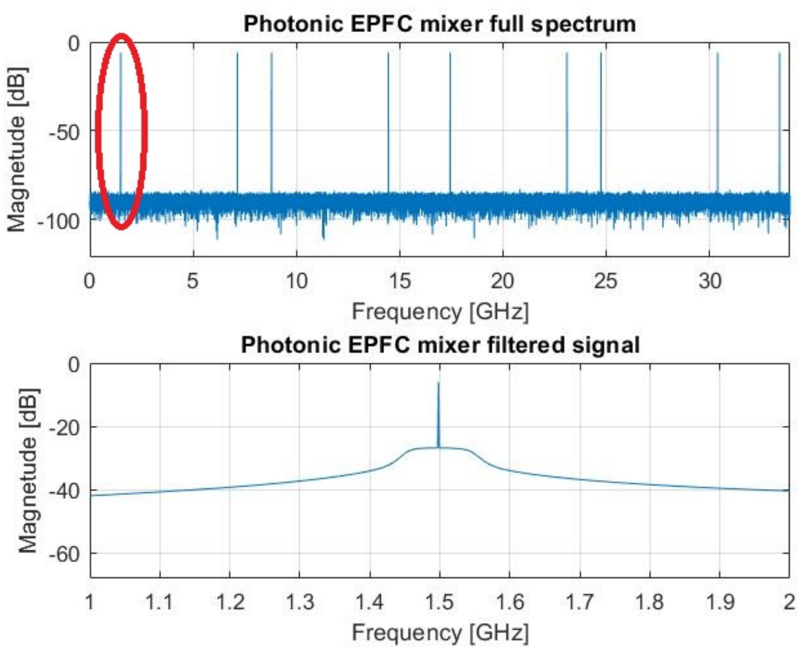


Figure 5-4: Full spectrum of the mixing optical product (top), the filtered IF signal after the Rx filter (bottom).

Actually this idea of the frequency conversion using a photonic architecture has been studied by AS within an ESA ARTES 5.1 project called "Electro-Photonic Frequency Conversion (EPFC)" and we demonstrated Ka-band (28.25 GHz) to 1.5 GHz downconversion with -20 dB conversion efficiency over 800 MHz bandwidth.

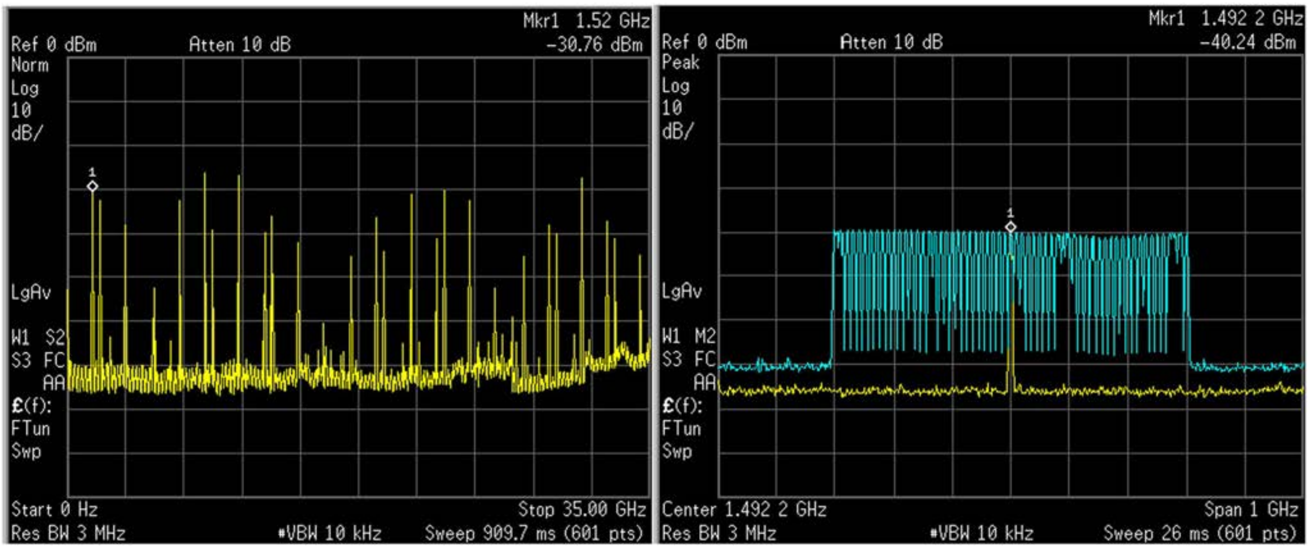


Figure 5-5: (Left) Electrical output spectrum after the photodiode from 0 to 35 GHz. (Right) IF output of Channel 2 swept 800 MHz in frequency for an RF input signal of – 20 dBm [RD1]

Our results from SCOUTT project (simulation and theoretical analysis) and also experimental results from the EPFC project shows a huge advantage of moving toward the photonic based architecture for Space application. EMI immunity, low mass, low power consumption and ultra-wide modulation bandwidth makes this technology appealing.

6 Conclusion

In summary, simulated and analysed parameters for each component are used to define the requirements for each application. For the flight model, the most important parameters are **power consumption, cost** and **mass** of the components. The power consumption and mass of components are acquired from the datasheets. Since Space qualification is needed for these components the cost estimation is a difficult task to do. For example even for the passive component the price difference between non-qualified, qualifiable and qualified devices is rather high. In this document, we tried to fairly estimate the price for either qualifiable or qualified components. The **THA based technology** is analysed in details as the best match for flexible frequency conversion technology. The main results based on this architecture are listed as follow:

- Broadband frequency conversion solution up to 25 GHz using existing technology
- Up to 4 GHz sampling frequency
- Down and up conversion from S, X and K band is possible to the IF frequency
- Power consumption and noise folding should be carefully considered
- For upconversion, high speed RF DACs are a suitable solution up to X-band

For the ground station, the similar analyses are done and commercially available components are listed. For these devices the price range is estimated from the acquired datasheets and quotes. Here, the power consumption is not a big issue and can be a secondary priority. Since the Space qualification is not required for these devices, the price range is considerably lower than the flight ones.

Ka-bands transceiver are becoming demanding bands for the satellite communication. More data bandwidth and data channels are possible in these frequency ranges. However, as mentioned throughout this document, standing alone electronic approach faces a difficulties to cope with the frequency requirement. On the other hand, **optical inter satellite link** is getting lot of attention because of its distinct advantages such as transmission security, high throughout and its power and mass saving capability.

Regarding both mentioned Space needs (high frequency communication and inter satellite communication), the advent of the **photonic assisted frequency converter** is becoming economically appealing. For the photonic components, the devices selection is performed and the list of the available components are provided. Since these devices are mainly used for the telecom applications, the price range for the Space application (qualified devices) is not provided from the foundries. The research is already initiated for this application by European and American big players such as NASA, ESA, EU, Airbus, TAS and DAS photonics. It is just matter of time which we will see this technology commercially in Space. The recent study by Thales Alenia Space (TAS) as an ESA project (contract number: N 4000111857/14/NL/WE) with title of “Roadmap for the introduction of photonic technologies based payloads” discusses the high level aspects of the photonic application in Space more precisely and specifically. The main results for the photonic based architecture are listed as follow:

- High speed frequency conversion up to Ka-band and even further to Q/V band is possible using the photonic technology
- Both down and up conversion are considered and analyses and simulation are performed

- Capability of doing conversion within predefined requirements has been verified by cascade analyses and simulation.

- Proof of principle measurement in ESA-EPFC project was performed together with this theoretical project to justify the simulation results.

To conclude, regarding highly competitive environment of the Space market and particularly constrain over developing of flexible and efficient Space systems, satellite industries rely on the support and collaboration from both electronic and photonic ecosystems to push the technology to higher frequencies and efficient architectures.

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