An Analytical Method for Performance Evaluation of Digital Transparent Satellite Processors

- PhD students' presentations

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Subject

- This work, that has been developed in collaboration with **Thales Alenia Space Italy**, takes as its starting point the perspective of introduction of a **new generation of satellites** based on **semi-transparent transponder** architectures.
- The aim is to use the satellite communications in the perspective of **supporting also terrestrial networks**.
- There is the need to manage on board large portions of bandwidth in which a **large number of users** can be allocated.
- It is required a careful **system modeling and accurate digital hardware design** in order to enable feasible **trade-offs** between **hardware efficiency** and overall **link-budget performance**.

Summary

i. Introduction and system model;

ii. Causes of non ideal behavior;

iii. Noise model of the digital on-board processor;

iv. Model verification;

v. Application example of the DTP extended **noise figure** concept in a typical link-budget;

vi. Conclusion and perspectives.

INTRODUCTION

There are four possible architectures for satellite transponder:

- Fully transparent payload
- Fully regenerative payload
- Translucent (Digital Transparent Processing)
- Semi-transparent transponder

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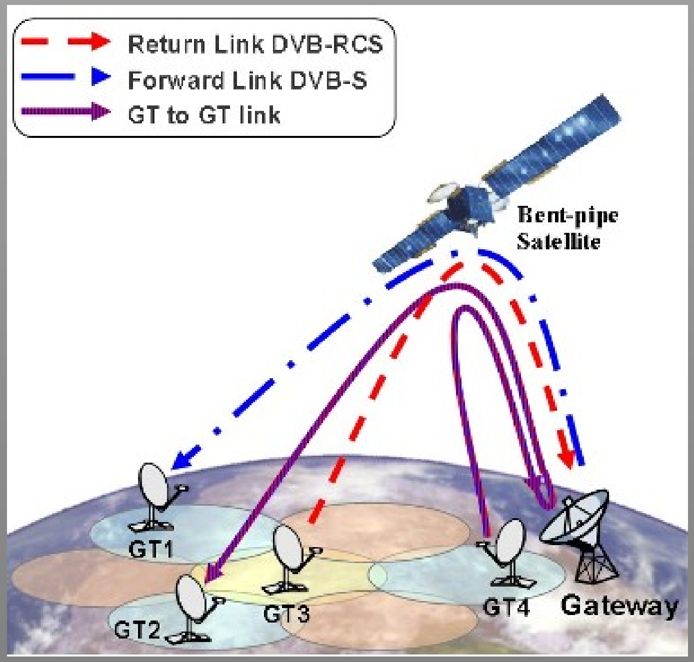
- **Fully transparent payload**
- Fully regenerative payload
- Translucent (Digital Transparent Processing)
- Semi-transparent transponder

- Simple relay with frequency shift from the up-link to the down-link range;
- For a peer-to-peer communications is required a double access to the satellite and the routing is fully managed by the gateway;
- **Simple but not flexible architecture. High latency.**



INTRODUCTION

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- Fully transparent payload
- **Fully regenerative payload**
- Translucent (Digital Transparent Processing)
- Semi-transparent transponder

- Demodulation and decoding, extrapolation of the headers of the packets and routing;
- The routing is carried and managed on-board;
- **Maximum flexibility in the routing but high complexity and risk of obsolescence.**

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- Fully transparent payload
- Fully regenerative payload
- **Translucent (Digital Transparent Processing)**
- Semi-transparent transponder

- Digital transparent process (**no Decoding**);
- The routing is carried on-board but the management is implemented by the gateway;
- **Trade-off solution between flexibility and complexity.**

INTRODUCTION

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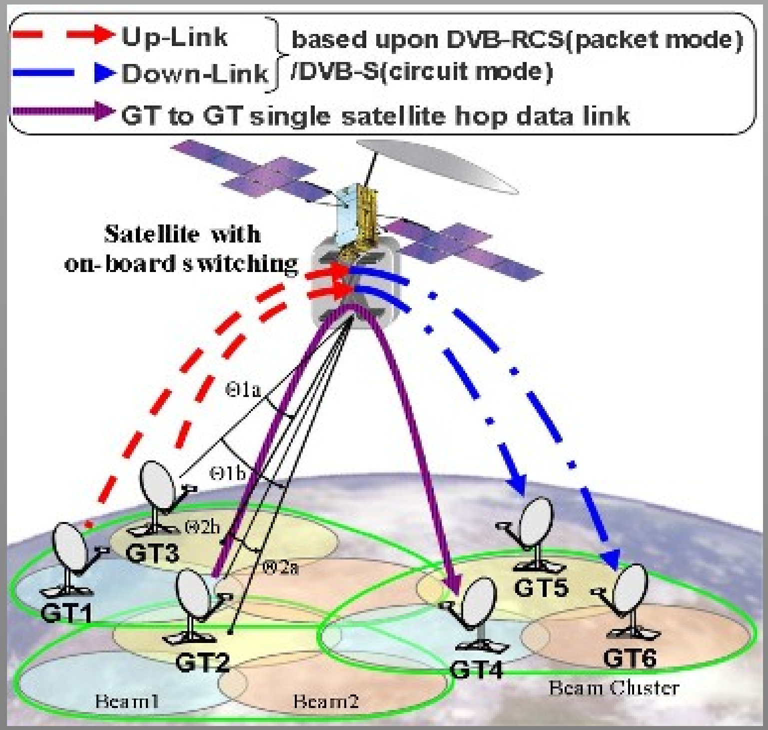
- Translucent (Digital Transparent Processing)
- **Semi-transparent transponder**

- Digital transparent processing in the traffic and regenerative section for the signaling information;
- The routing is carried and managed on-board;
- **Good performance in terms of flexibility with reasonable complexity.**



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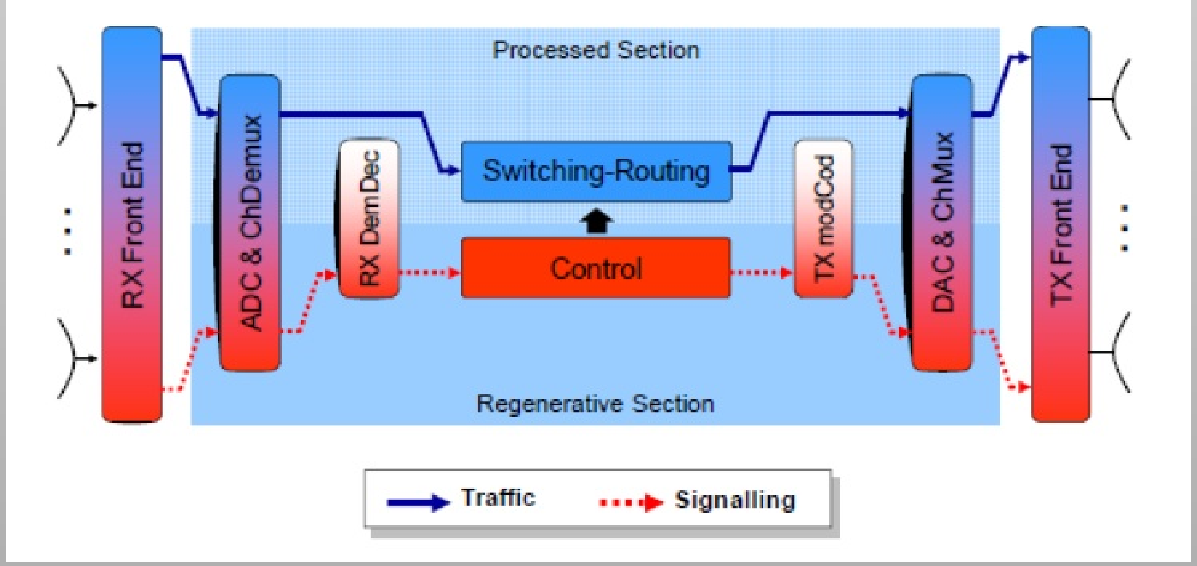
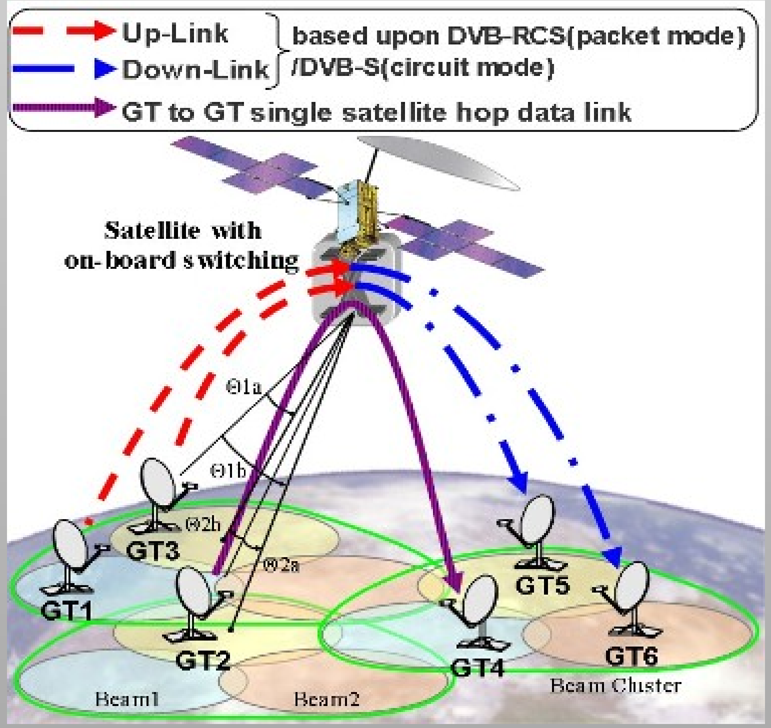
Note: both in the translucent and in the semi-transparent architecture a DTP is included.

INTRODUCTION





Semi-transparent satellite architectures are proposed as the enabling technology allowing to efficiently deliver (i.e. without loss of flexibility in the management of traffic) a broadband connectivity to a large and differentiated number of users.

Note that, with the particular constraints in the granularity of bandwidth allocation, the choice of fully regenerative architecture could result in a unacceptable complexity.

INTRODUCTION

In this field of research (i.e. Digital Transparent Satellite Processors) we mainly consider three aspects:

- Trade-off analysis between flexibility in the allocation of bandwidth and complexity;
- Modeling and implementation of additional blocks useful to improve the hardware efficiency of the processing chain;
- Definition of an analytical method for the evaluation of the performance, in terms of processing accuracy, depending on the implementation parameters (i.e. FIR Filter order; number of bits for the coefficients and data representation).

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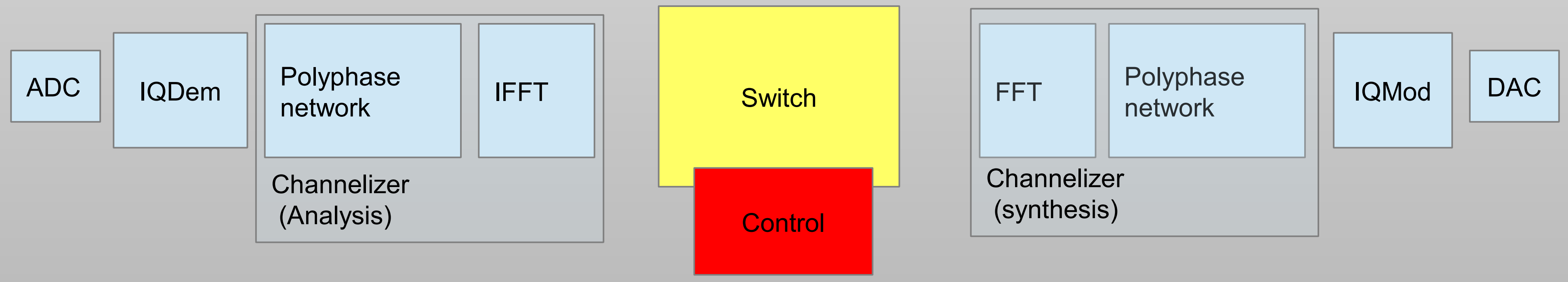
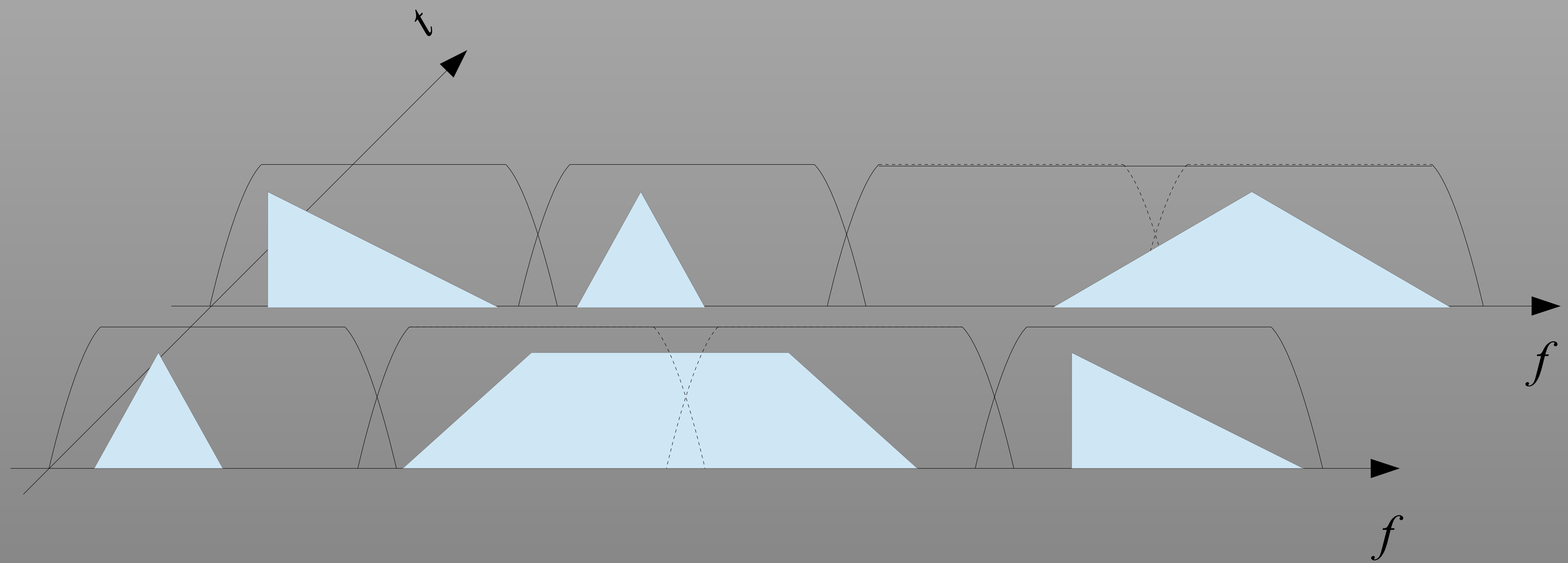
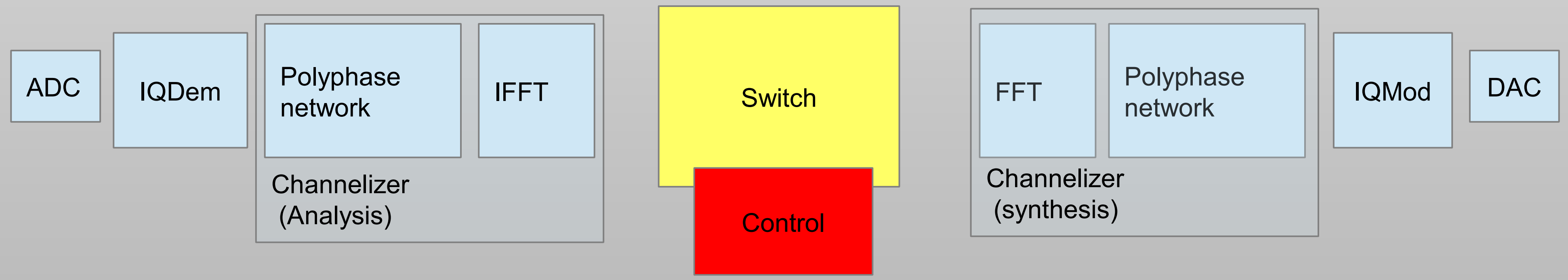
TRADE-OFF BETWEEN FLEXIBILITY AND COMPLEXITY



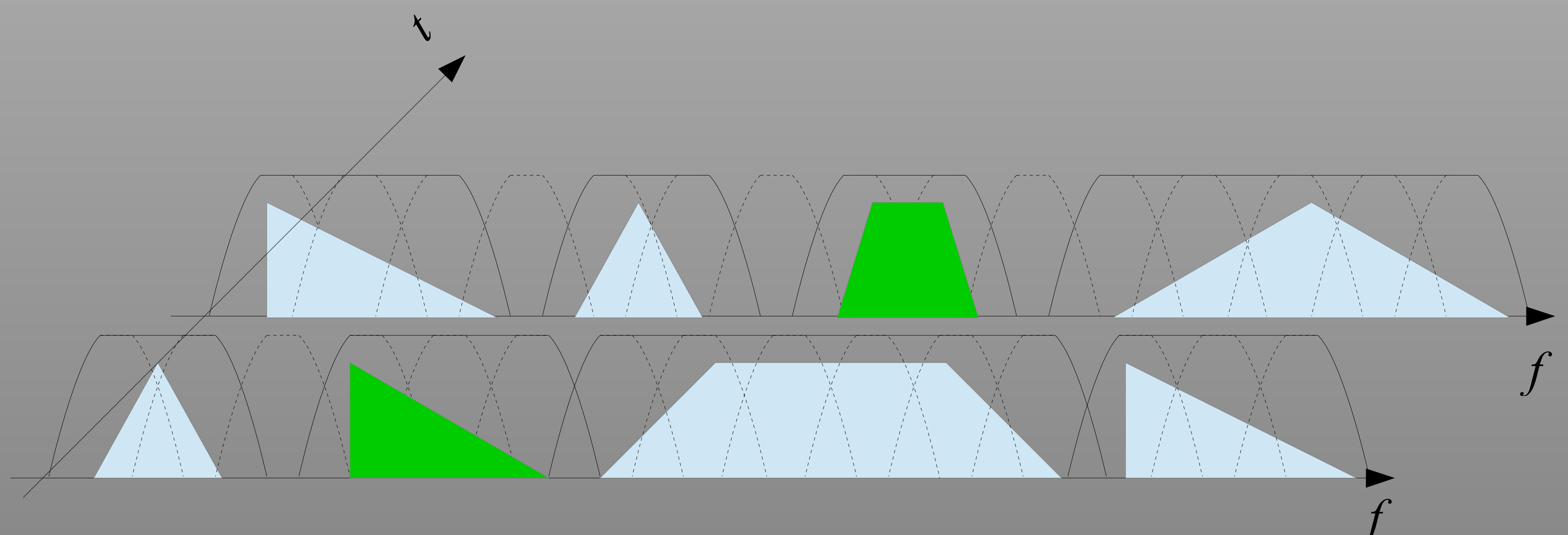
- Trade-off analyses are needed to define the best solution in terms of flexibility while maintaining a reasonable complexity.
- A typical trade-off analysis regards the choice of the channelizer granularity.



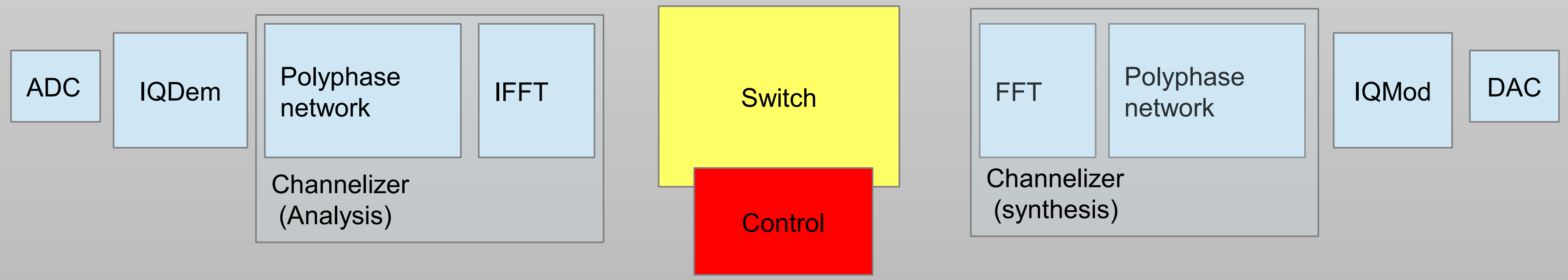
TRADE-OFF BETWEEN FLEXIBILITY AND COMPLEXITY



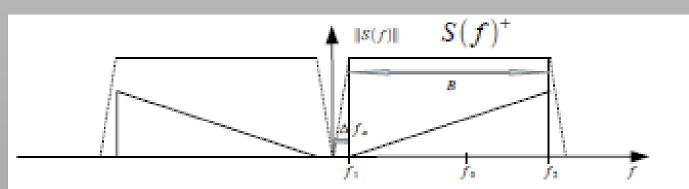
Through a more dense channeling it is possible to manage in an efficient way a greater number of different users, but more hardware resources are required.



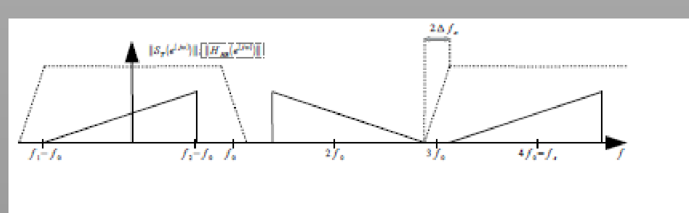
DTP MODEL



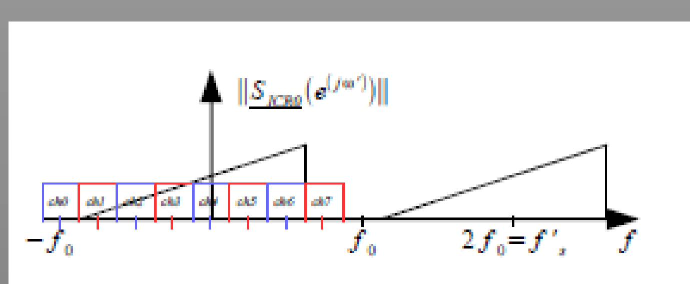
IF signal

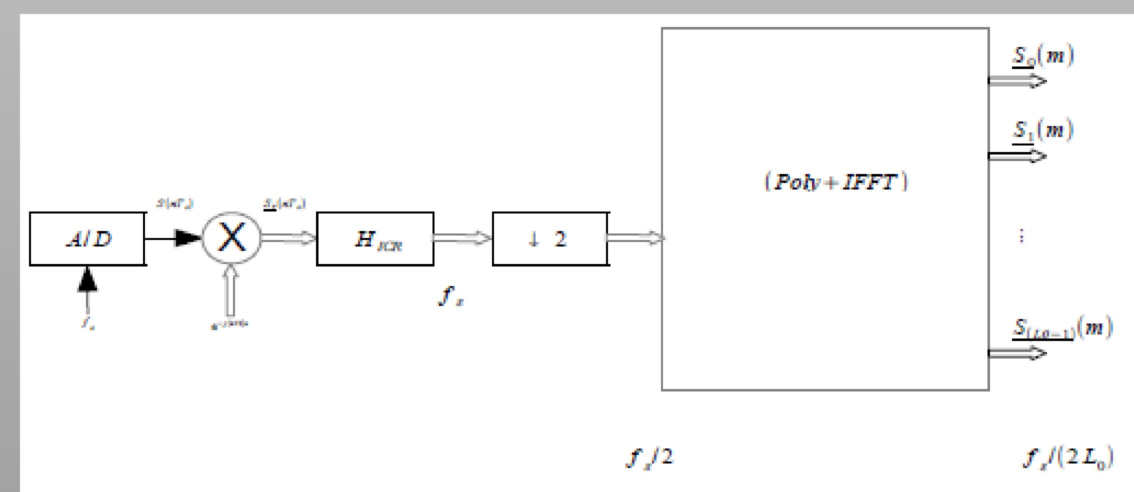


Complex envelope



Channelizer (analysis)

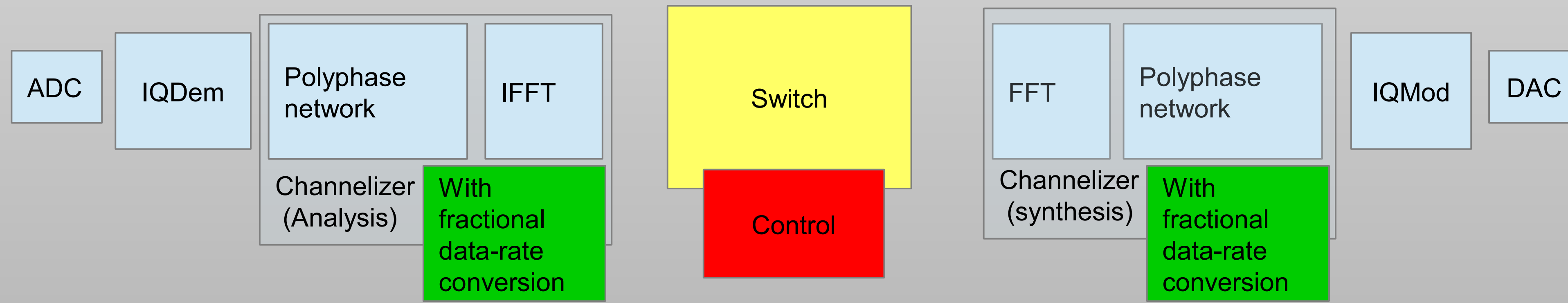




The DTP processing chain is composed by:

- A/D converter;
- Block of Complex envelope extrapolation;
- Channelizer (analysis);
- Switch;
- Their dual blocks.

DTP IMPROVED MODEL



Channelizer (analysis)

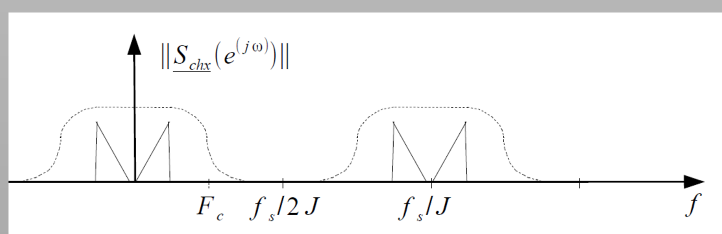


Fig.1 Non critically sampled solution.

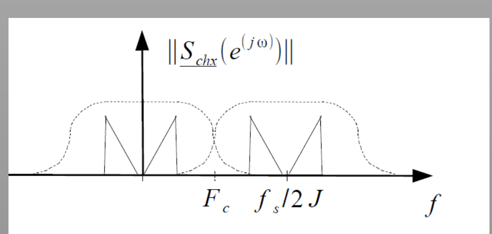


Fig.2 Critically sampled solution.

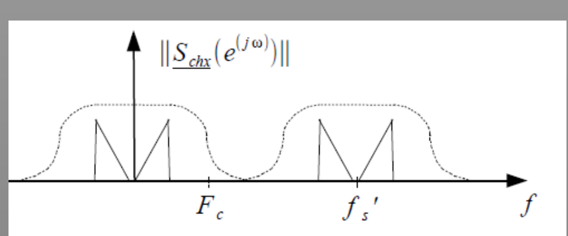
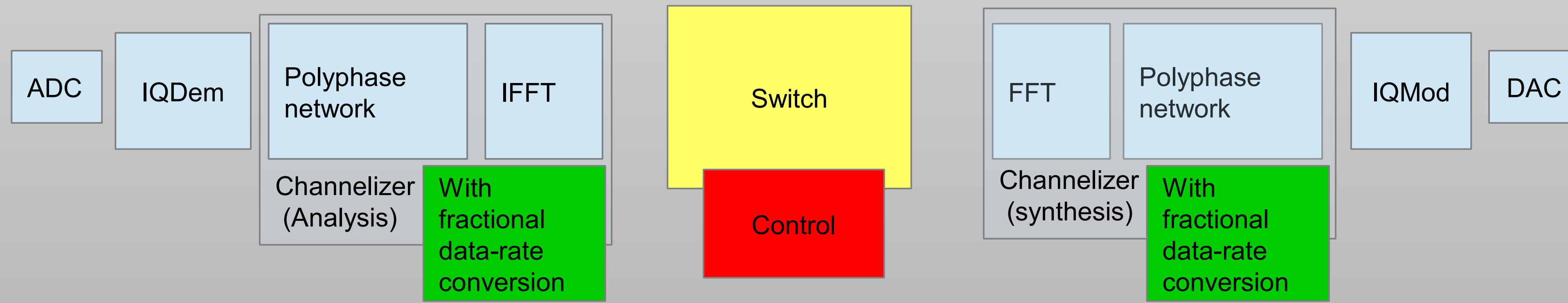


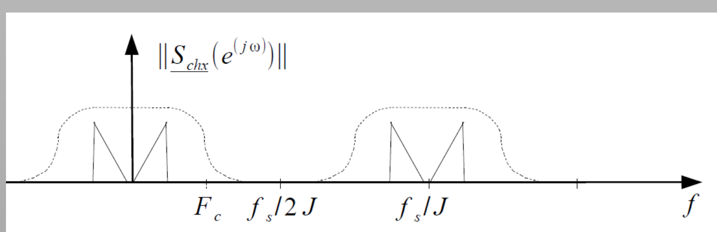
Fig.3 Fractional Decimator output.

- For the purposes of the Digital Transparent Satellite Processors taken into account, the channelizer can not be in a "critically sampled" solution (Fig.2).
- In order to avoid the introduction of aliasing "non critically sampled" solutions are often proposed and they allow to represent the signals with sampling frequency that are integer multiples of the Nyquist frequency (Fig.1).
- However, these solution produces an inefficient spectral representation.
- For this reason a particular architecture of channelizer has been proposed. This architecture is characterized by a fractional data rate conversion for a spectrally efficient representation of the channel signals (Fig.3).

DTP MODEL



Channelizer (analysis)



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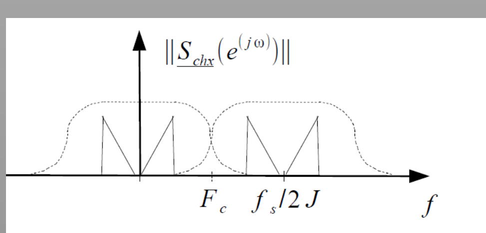

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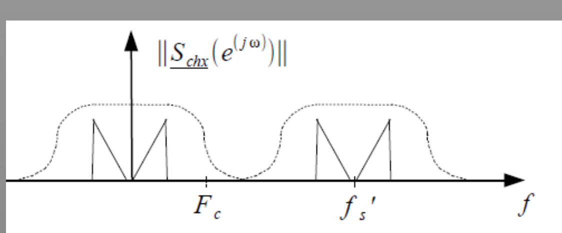


Fig.3 Fractional Decimator output.

- Introduction of the fractional data rate conversion.
- Increase in the required logical hardware resources.
- Reduction of the amount of memory required in the switch (critical issue for satellite applications).

EQUIVALENT NOISE MODEL

- A digital transparent satellite payload is composed by analog receiving and transmission chains with a fully digital but non regenerative chain between them.
- Performance characterization of the analog sections is well consolidated in the radio communications community, and a remarkable amount of literature also exists for modeling the sources of non idealities in single digital processing blocks.
- Nevertheless, digital blocks are considered in a stand-alone way with respect to analog sections and typically combined with subsequent detection stages in digital regenerative receiver chains.
- In this frame we propose to characterize the performance of the digital section by resorting to an **extended notion of noise figure** to qualify the behavior of various components **of the digital chain**.

EQUIVALENT NOISE MODEL

We start by analyzing and modeling the following sources of degradation:

- Quantization errors caused by the Analog-to-Digital (ADC) conversion;
- Non idealities in filters' implementation, namely the adoption of finite length impulse responses due to windowing and the finite number of bits for representation of their coefficients; these effects can also be cast in terms of linear distortion with respect to a reference (ideal) behavior:
- Use of a fixed-point arithmetic in the registers operating within the whole processing chain.

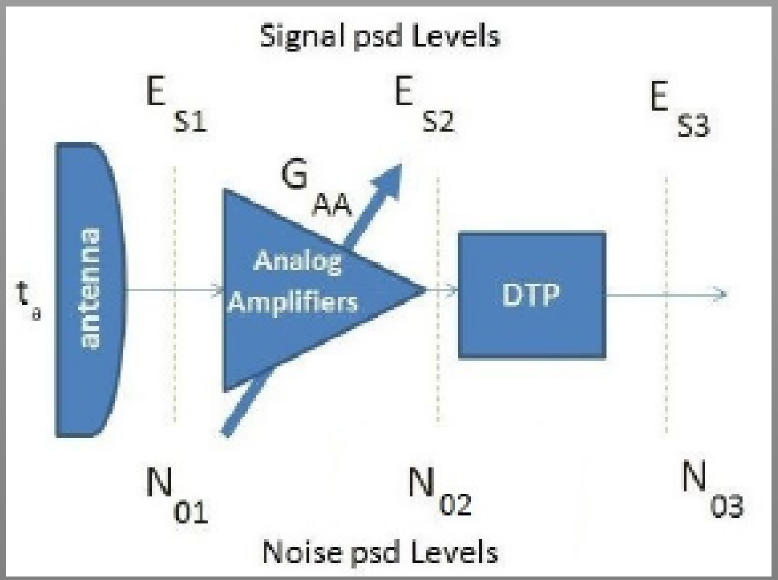
EQUIVALENT NOISE MODEL

The sources of degradation in the DTP can be characterized, according to a typical and widespread assumption, as AWGN components and we denote the flat power spectral density of the resultant as follows:

$$N_{DTP} = N_{0\mathrm{R}} + \delta^2 E_{S2} \qquad (1)$$

where the first term is used to denote the **power spectral density related to the overall rounding and quantization** noise along the whole DTP chain, and the second term is intended to account for the **linear distortion noise in FIR filters** implementation and is proportional to the useful signal power spectral density.

Note : "Analog Amplifier" (AA) block is actually intended to denote the whole RF analog receiving front-end and typically includes an LNA (Low Noise Amplifier), a mixer, an AGC (Automatic Gain Control) stage and an AAF (Anti-Aliasing IF Filter).



EQUIVALENT NOISE MODEL

By taking the noise at the antenna output as a reference, the overall noise figure can be defined as:

$$F_t = F_{AA} + \frac{F_{DTP} - 1}{G_{AA}} \qquad (2)$$

where the noise figure of the DTP is given by:

$$F_{DTP} = \frac{N_{01} + N_{DTP}}{N_{01}} \qquad (3)$$

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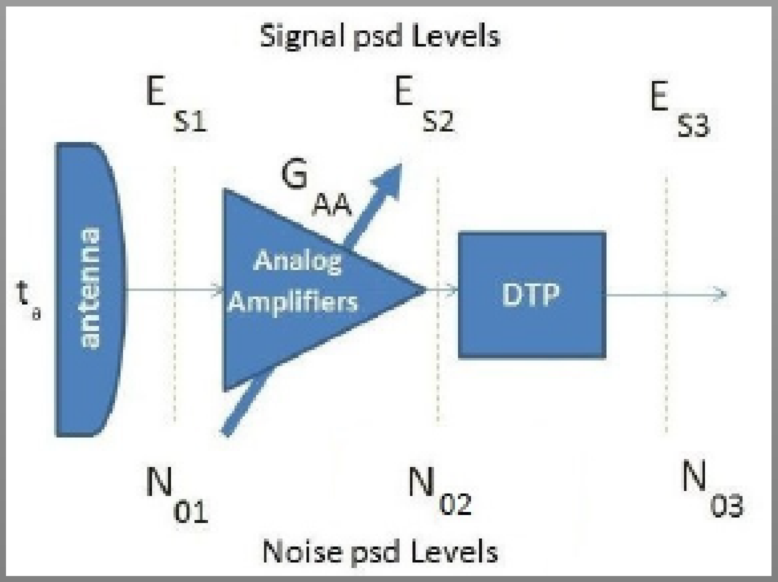


Noise Contribution from Linear Distortion in FIR Filters

When the impact of DTP internal blocks on the linear distortion noise is concerned, the blocks may be considered as sampling rate conversion blocks. We derived the following general expression for the power spectral density of the related noise components at the output of each generic block 'k' that applies both for interpolators and decimators:

$$N_{Lk} = S_i \delta_k^2 F_{sk} T_{ok} \qquad (4)$$

where $1/T_{ok}$ is the sampling frequency at the output of the kth block and F_{sk} is the filter design frequency, S_i is used to denote the (flat) signal power spectral density and $\delta_p = \delta_s = \delta_k$ accounts for ripple, which is assumed to contribute in the same way for both passband and stop-band regions of the filter design.

The Impact of Coefficients Quantization in FIR Filters

After the filter design has been made in order to limit the linear distortion noise, the number of bits for filter coefficients quantization n_h is addressed.

$$N_{opt} = \frac{-20\log_{10}(\delta) - 7,5}{14,8\,\Delta F} \qquad (5)$$

$$n_{opt} = 2,25 - 3,4\log_{10}(\delta) - 1,9\log_{10}(\Delta F) - \log_2(A_h) \qquad (6)$$

The above expressions allow to estimate the order of the optimal Chebyshev low-pass FIR filter (with infinite precision coefficients) that with given high probability (say 0.95) meets the specifications also for coefficients quantized by n_{opt} bits.

Noise Contribution from Quantizations and Internal Round-off

The quantization error can be modeled by an additive white noise that is due to the impact of the A/D conversion and to the rounding effects introduced in the subsequent processing blocks.

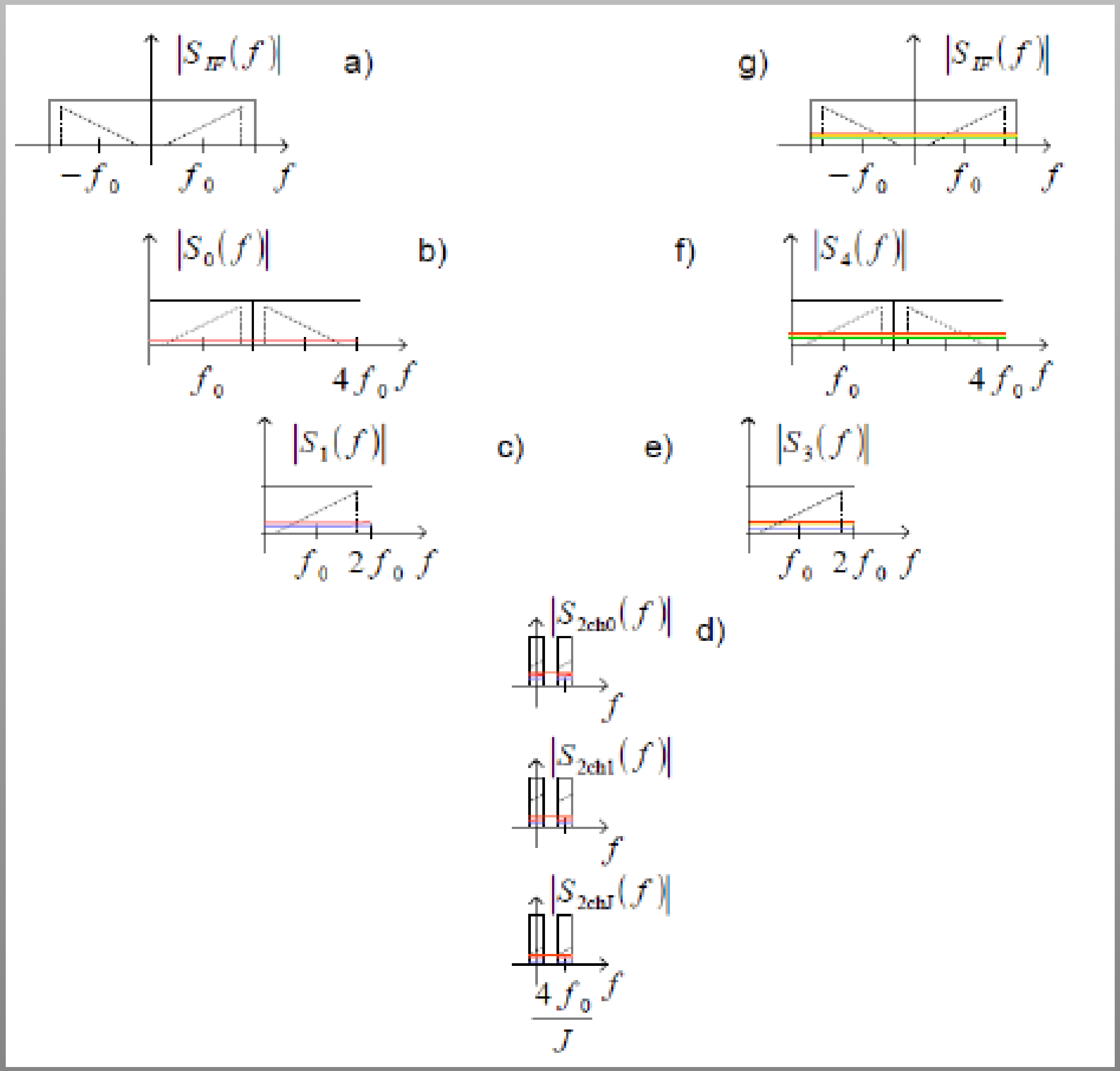
$$N_{R-ADC} = T_{ok} \frac{q^2}{12} \tag{7}$$

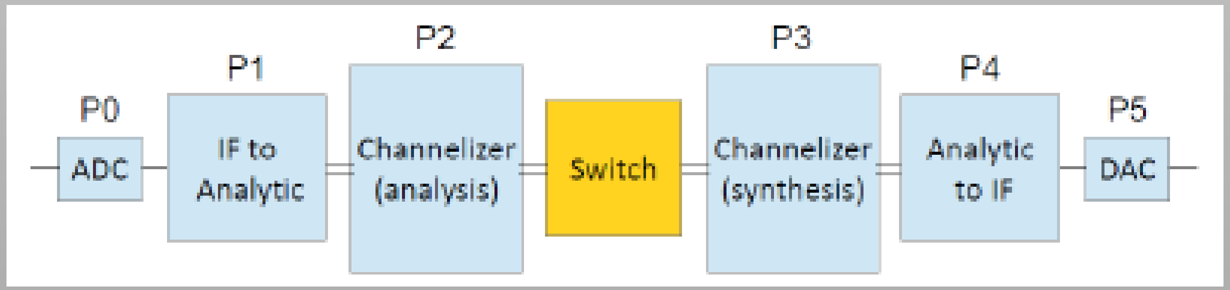
$$N_{R-FIR} = T_{ok} \left[(N+1) \frac{q_m^2}{12} + \frac{q_s^2}{12} \right] \tag{8}$$

$$N_{R-FFT} = T_{ok} J \frac{q_{fft}^2}{3} \tag{9}$$

Performance Analysis of the DTP

The DTP model is composed of an ADC, a “IF to Analytic” block, a channelizer of analysis (working on J-channels), the switch, and their dual blocks.





For the purpose of definition and verification of the analytical method the **signals flow across the switch in a transparent way**, and the input signal is regarded as noiseless and characterized by a constant and uniform value of power spectral density (Si (f)=Si).

Performance Analysis of the DTP

Processing Block (Pn°)	Noise contribution	Overall noise at the block output
P0: ADC	$N_{R0}=\frac{q_0^2}{12}\frac{1}{4f_0}$ $N_{L0}=0$	$N_{R0}^T=N_{R0}$ $N_{L0}^T=N_{L0}=0$
P1: "IF to Analytic"	$N_{R1}=(\frac{N_1}{2}\frac{q_m^2}{12}+\frac{q_s^2}{12})\frac{1}{2f_0}$ $N_{L1}=(A_1^2S_i)\delta^2(4f_0)\frac{1}{2f_0}$	$N_{R1}^T=(A_1^2N_{R0}^T)+N_{R1}$ $N_{L1}^T=(A_1^2N_{L0}^T)+N_{L1}$
P2: Channelizers (analysis)	$N_{R2}=J(\frac{N_2}{J}\frac{q_m^2}{3}\frac{1}{A_2^2}+\frac{q_s^2}{6}+\frac{q_{fft}^2}{3})\frac{J}{4f_0}$ $N_{L2}=(A_1^2S_i)\delta^2(2f_0)\frac{J}{4f_0}$	$N_{R2}^T=N_{R1}^T+N_{R2}$ $N_{L2}^T=N_{L1}^T+N_{L2}$
P3: Channelizers (synthesis)	$N_{R3}=(J\frac{q_{fft}^2}{3}+\frac{N_3}{J}\frac{q_m^2}{3}+\frac{q_s^2}{6})\frac{1}{2f_0}$ $N_{L3}=\frac{1}{2}J(A_1^2S_i)\delta^2(2f_0)\frac{1}{2f_0}$	$N_{R3}^T=N_{R2}^T+N_{R3}$ $N_{L3}^T=N_{L2}^T+N_{L3}$
P4: "Analytic to IF"	$N_{R4}=(\frac{N_4}{2}\frac{q_m^2}{12}+\frac{q_s^2}{12})\frac{1}{4f_0}$ $N_{L4}=(A_1^2S_i)\delta^2(4f_0)\frac{1}{4f_0}$	$N_{R4}^T=\frac{1}{A_4^2}(N_{R3}^T+N_{R4})$ $N_{L4}^T=\frac{1}{A_4^2}(N_{L3}^T+N_{L4})$

In TABLE the column "noise contribution" **summarizes the expressions** of quantization, round-off and linear distortion noise contributions of **each block**.

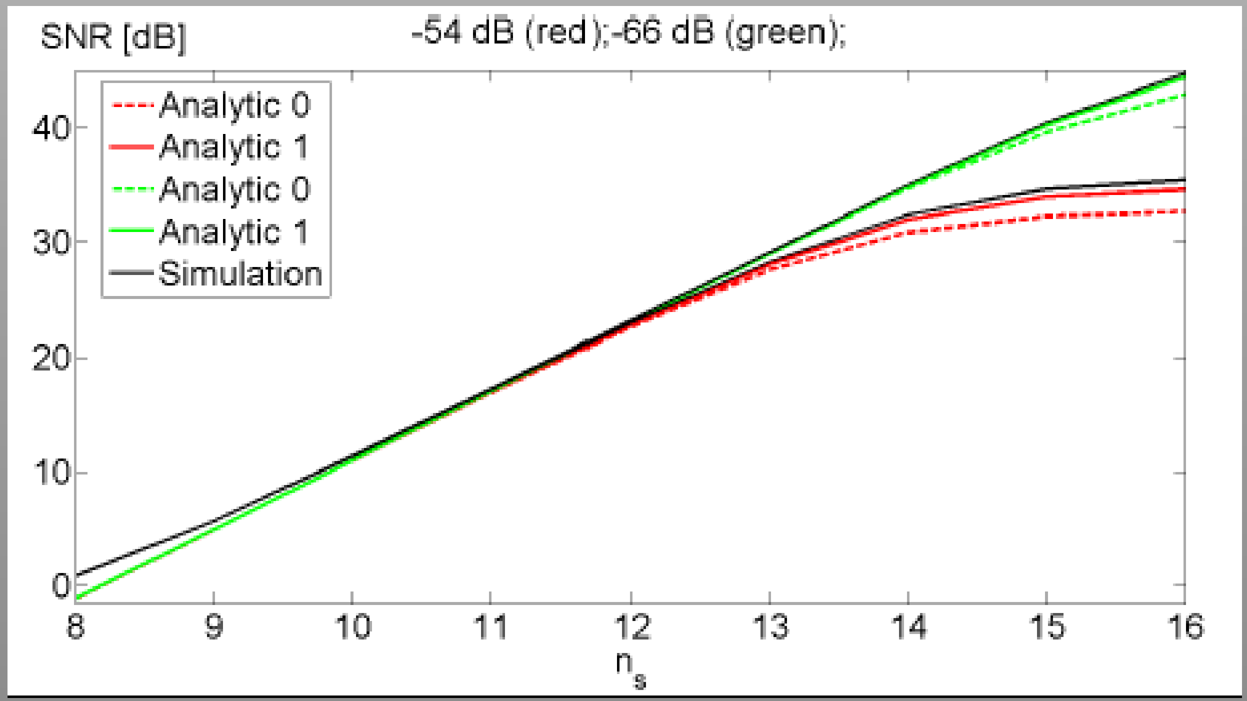
[] V.Sulli, D.Giancristofaro, F.Santucci, M.Faccio - "An Analytical Method for Performance Evaluation of Digital Transparent Satellite Processors", submitted and accepted to the IEEE GLOBECOM 2016.

Model Verification

In order to validate the proposed analytical method a C software module has been implemented to support the behavioral simulation of the DTP.

The signal-to-noise ratio obtained in simulation has been then compared with the values obtained through the analytical method.

The comparison has been made for different data path widths and for two different values of accuracy of the amplitude response of the filters (20 log10(δ)=−54 dB and 20 log10(δ)=−66 dB).



Example of Application and Numerical Result

To evaluate the DTP performances in an up-to date application scenario, the near-to-Shannon bound MHOMS modulation and coding scheme has been assumed.

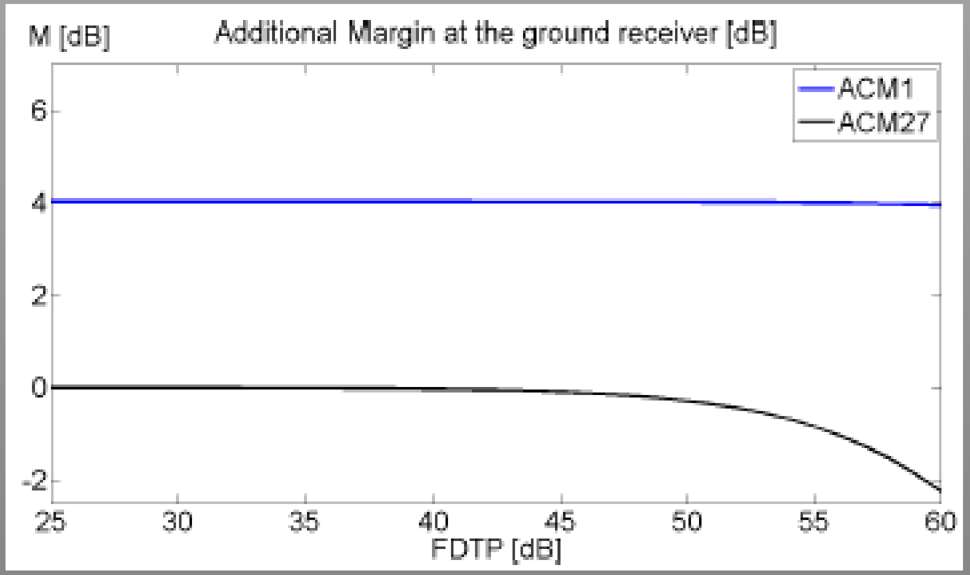
In this frame a link budget analysis has been carried out for the path from a ground gateway to an end user installation.

The **two limiting cases of modulation** and coding modes allowed by the adopted ACM modulation and coding scheme, namely mode **ACM1** (**QPSK** with Rb/Rs efficiency 0,71) and mode **ACM27** (**64 APSK** with Rb/Rs efficiency 5.39) have been considered.

Example of Application and Numerical Results

Case 1	Uplink:	
Up-Link Frequency	28,5000	[GHz]
Tx Antenna Gain	64,20	[dBi]
Per-Carrier HPA Power	50,0	[W]
Ground Station EIRP	81,19	[dBW]
Free Space Attenuation	213,06	[dB]
Atmospheric Suppl. Att.	8,80	[dB]
Sat. RX antenna Gain	41,30	[dBi]
Onb. RX G/T (w/o DTP)	13,70	[dB/K]
C/No Up (w/o DTP degr.)	101,63	[dBHz]
Single Channel Rs	27.5	[MHz]
Es/No Up (w/o DTP degr.)	27.74	[dB]
No. of Uplink Carriers	22	
SRRC roll-off	0.2	
	Downlink:	
Downlink Frequency	19,9500	[GHz]
Per-Carrier HPA Power	12,73	[W]
Onboard TX Ant. Gain	39,75	[dBi]
EIRP	50,80	[dBW]
Atmospheric Suppl. Att.	6,7	[dB]
Free Space Attenuation	209,96	[dB]
Ground Receiver G/T	15,2	[dB/K]
Ground RX Antenna Gain	41,3 [dBi]	
C/No Downlink	77,94	[dBHz]
Modulation and Coding:		
MHOMS ACM Mode:	ACM1;	
Modulation:	QPSK;	
Rb/Rs (modulation and coding eff.)	0,71;	
Required Es/No for a 10E-7 BER	-0.5	[dB]
Additional margin	4	[dB]
Onboard ADC biasing:		
ADC Biasing (50 OHM)	0.5*1.41	[Veff]
LNA + analog ampl. chain gain G_{AA}	59.92	[dB];
Case 2 Different parameters (only those different from case 1 are reported):	**Uplink:**	
Atmospheric Suppl. Att.	0,0	[dB]
C/No Up (w/o DTP degr.)	110,43	[dBHz]
Single Channel Rs	27.5	[MHz]
Es/No Up (w/o DTP degr.)	36.04	[dB]
	Downlink:	
Atmospheric Suppl. Att.	0,0	[dB]
Ground Receiver G/T	24,29	[dB/K]
Ground RX Antenna Gain	50.39	[dBi]
C/No Downlink	93,65	[dBHz]
Modulation and Coding:		
MHOMS ACM Mode:	ACM27;	
Modulation:	64 APSK;	
Rb/Rs (modulation and coding eff.)	5,39;	
Required Es/No for a 10E-7 BER	19.25	[dB]
Additional margin	0	[dB]
LNA + analog ampl. chain gain G_{AA}	51,12	[dB]

It is our goal to exploit the developed DTP noise figure in the classical link budget by including the DTP noise contribution in the overall receiver G/T. In this regard, the figure shows the additional margin that the extended link budget makes available at the ground receiver as a function of the DTP noise figure for the ACM1 and ACM27 modes.

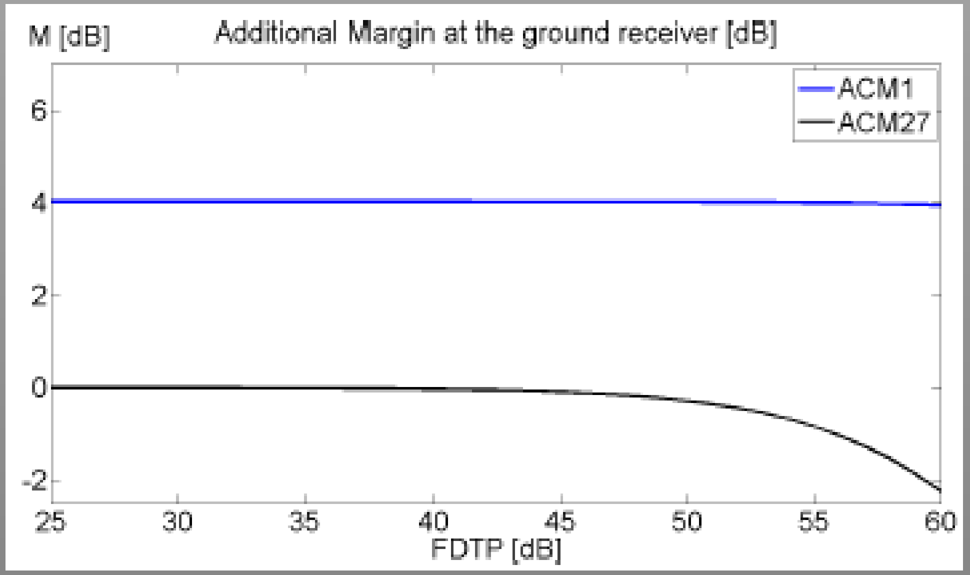


Example of Application and Numerical Result

The choice of the DTP parameters can be crucial in the identification of the operating point and the impact of the DTP performances is more evident for the ACM27 mode.

However, also for this worst case it is possible to impose a DTP noise figure that produces minimum variations on the link budget parameters.

For example, it can be argued from the figure that the DTP noise figure does not induce any degradation in the margin for ACM1, while for ACM27 a DTP **noise figure below 35 dB would be required to avoid additional margin degradations.**



As an example, a **DTP noise figure of 30 dB** can be obtained by implementing the DTP with a pair (**ns=13 bits,20 log10(δ)=−68 dB**).

Conclusions

In the context of an industrial research project driven by Thales Alenia Space Italia, this discussion has presented a comprehensive framework for **performance analysis of novel satellite payloads that rely on semi-transparent transponder architectures**.

A relevant feature is represented by an **extensive use of the classical metrics of noise figure** and equivalent noise temperature to characterize the performance of the various blocks of a digital transparent on-board processor.

Our current work is focused on **further developments and adaptations of the developed framework to several scenarios of interest in satellite communication,** while it is quite evident that the framework is of interest in all relay-based and non regenerative wireless contexts.

References

[1] R. Suffritti et al. – A Mesh Network over a Semi-Transparent Satellite –Global Telecommunications Conference(GLOBECOM 2011), 2011 IEEE.

[2] C. Haardt, N. Couville – Internet by satellite: a flexible processor with Radio Burst Switching – Satellite and Space Communications, 2006 International Workshop on – 14-15 Sept. 2006, IEEE.

[3] H. G. Gockler and H. Eyssele. Study of on-board digital FDMdemultiplexing for mobile SCPC satellite communications (part I and II). Europ. Trans. Telecommunic., ETT-3:7-30, Jan./Feb. 1992.

[4] X. Weiguan, B. Guoan, L. Po-Ching - An efficient multirate FDM demultiplexer for satellite communication systems - Communications and Networks - 3-7 Jul 1995, IEEE.

[5] T.Neu - Direct RF conversion:From vision to reality - Texas Instruments Incorporated, May 2015, SLYY068

[6] W. Kester - "ADC Noise Figure—An Often Misunderstood and Misinterpreted Specification" - Analog Devices, 2014.

[7] G. Mian – Elaborazione numerica dei segnali – Università degli Studi di Padova –2006 – Pag. 189 – 262.

[8] G. Mian, A. Nainer - "On the performance of optimum linear phase lowpass FIR digital filters under impulse response coefficient quantization"- IEEE Transactions on Acoustics, Speech, and Signal Processing, vol.ASSP-29, pp. 928-932,1981.

[9] S. Benedetto, C. Berrou, C. Douillard, R. Garello, D. Giancristofaro, A. Ginesi, L. Giugno, M. Luise, G. Montorsi, “MHOMS: High Speed ACM Modem for Satellite Applications”, IEEE Wireless Communications Journal, Vol. 12, No. 2, April 2005, pp. 66-77.

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