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CLEANRF Project Final Presentation

July 14th 2022

Agenda

1. The motivation
2. The requirements
3. The market approach
4. The detailed scenarios
5. The design solutions
6. The implementation aspects
7. The testing approach
8. The testing results
9. The technical conclusions
10. Demo

CLEANRF motivation

- Serve the growing *protected satcom* market with a new “plug-in” product providing active protection against RF intentional and unintentional interference (RFI)
  - Key market users are critical infrastructures owners, government agencies, security forces etc., as well as operators of space assets (satellites/payloads/ground stations)
  - Current protections (e.g. redundancy, nulling antennas protected waveforms) can be expensive and/or just partially effective
- Unintentional RFI being a daily concern today of commercial satellite/service operators with new threats expected due to new constellations
- Company-specific motivations
  - Direct petition from existing and potential customers for a product with very few competitors
  - (challenging) adquisition of new technology capabilities, from signal-trace (monitoring) domain to strict real-time (processing) domain
  - Enabler for new products/applications

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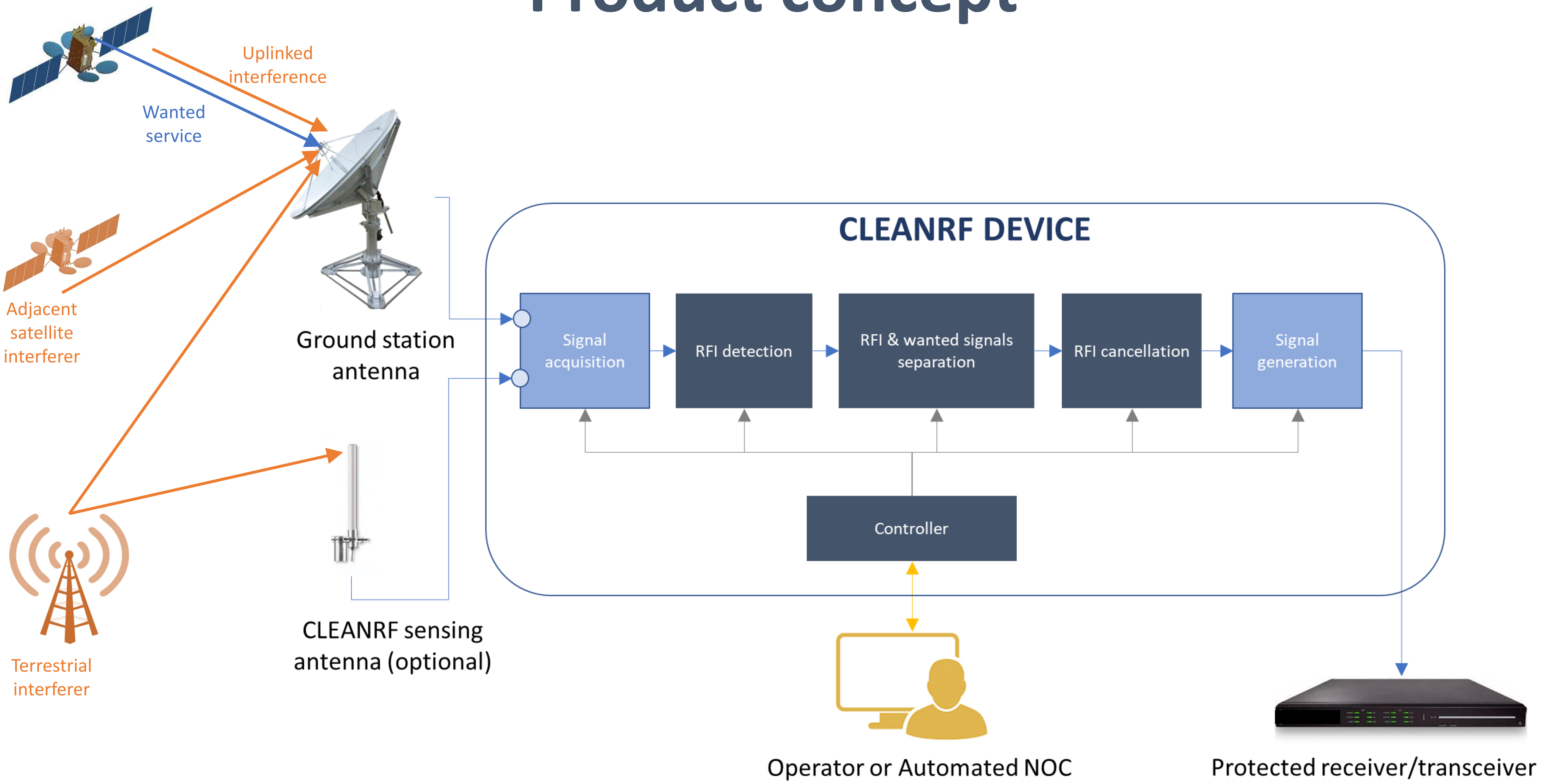
Product concept



Product requirements

ID	Description
PR1	The canceller device will aim to remove RFI in the forward-link (**CASE1**) and return-link (**CASE2**) of SatCom GEO satellites and the telemetry link of EO satellites (**CASE3**)
PR2	RF input/output interfaces for CASE1 and CASE2 canceller devices will in IFL frequency range (**950-2150 MHz)** and in S-band directly **(2200-2290MHz**) for CASE3
PR3	**Bandwidth** of the protected signal up to **36MHz** in CASE1 and CASE2 and up to **10MHz** in CASE3
PR4	**Target interference signals in CASE1**: static tone CW (up to two) or swept CW tone (up to 100KHz/s)
PR5	**Target interference signals in CASE2**: in-band modulated DVB-S2
PR6	**Target interference signal in CASE3**: in-band terrestrial fixed service signal with generic QPSK/16QAM modulation
PR7	**Implementation losses** of cancellation processes of 2dBs with respect to ideal cancellation conditions
PR8	Use of the existing **antenna for the wanted service**. An **auxiliary omnidirectional antenna** is allowed only for CASE3
PR9	Maximum **latency** of two signal frames duration (longest frame out of wanted or interfering)
PR10	Minimum **input parameters** given through Web GUI: wanted centre frequency, symbol rate and roll off
PR11	Store RFI events statistics for at least 1 week including at least: start, duration, and technical characteristics of the interference (central frequency, bandwidth, roll off, MODCOD, estimated ASI)
PR12	Implement a live RFI monitoring interface so traces can be visualised through the web interface with an update rate of at least 1 trace per second

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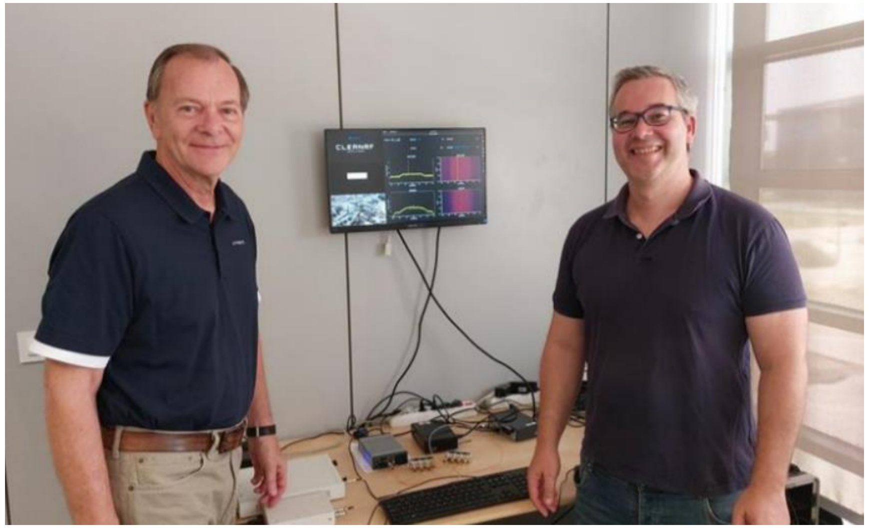
Business actions

Integrasys booth at SATELLITE 2022

Integrasys booth at AUSTRALASIA 2022



Kymeta VP visiting Integrasys for CLEANRF discussion

MSUA Satellite Mobile Innovation Awards 2022

Customers feedback

- Massive interest from the Security satcom market and selective interest from professional satcom markets on particular applications
- Very positive opinions from both integrators and modem manufacturers familiar with competiging products or techniques
- Many demands for IP Licensing for integration in existing systems
- New applications mentioned
  - Cancellation of (terrestrial) mobile services interference into satellite bands
  - Improvement of RFI geolocation
  - Self-cancellation for co-site radios interoperability

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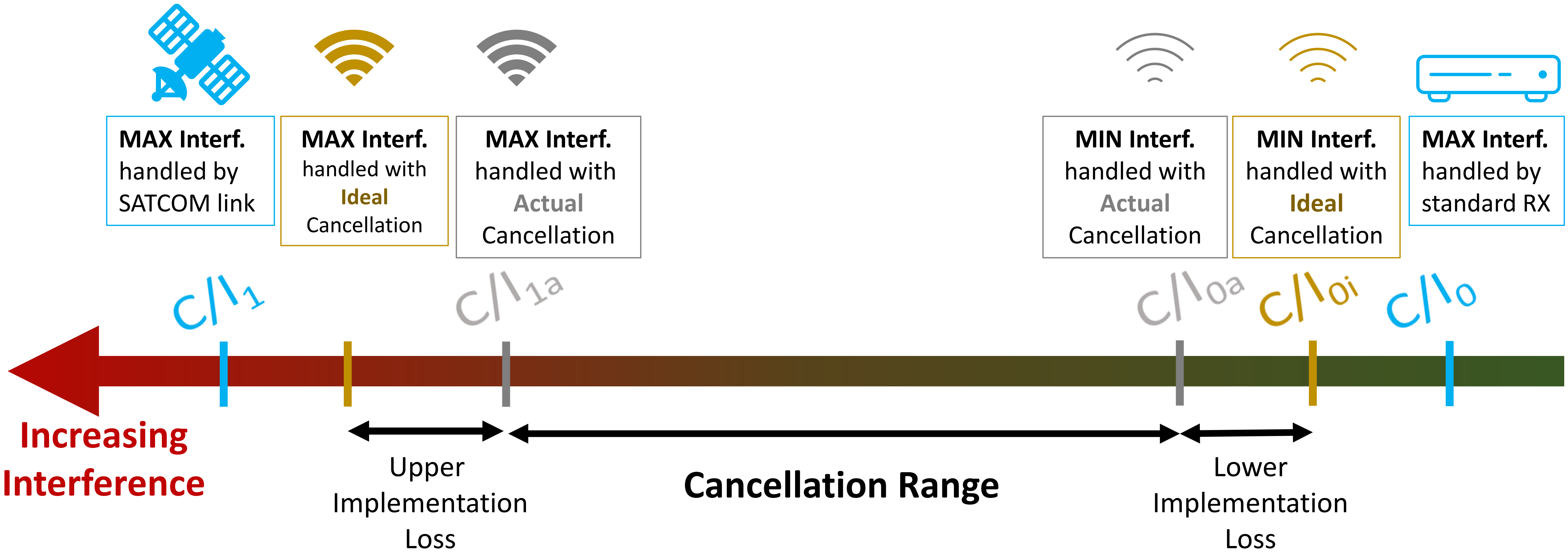
Business plans 2022-2023

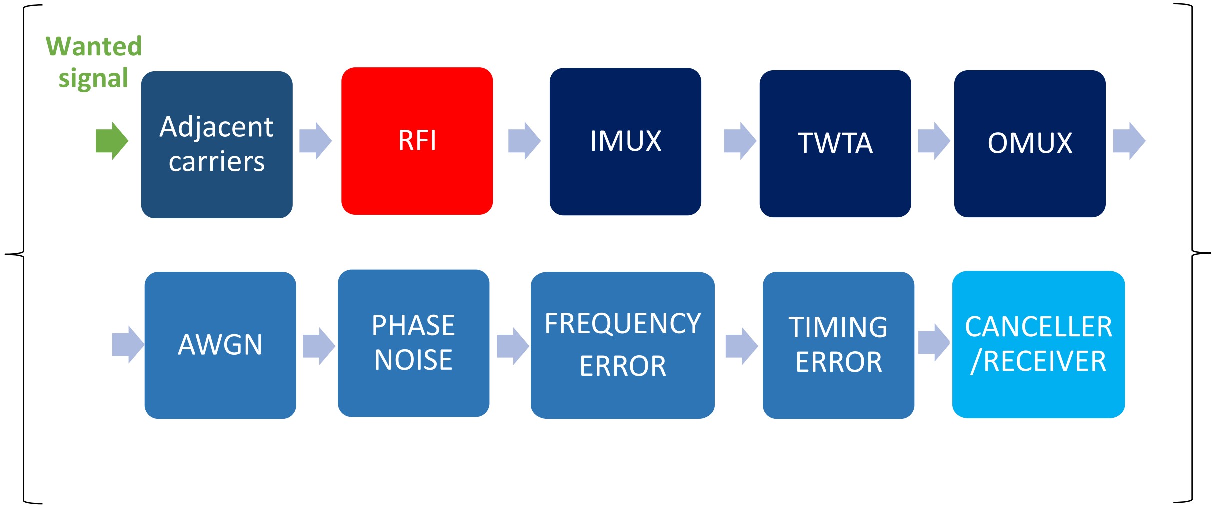
- Implementation migration plan from TRL6 to TRL9 for CASE1 and CASE2 until Q2 2023
- Facilitate stand-alone demo systems to early adopters and work with them in product qualification/refinement
- Define requirements for IP license integration and start project with interested early adopters
- Find/design the proper HW platform for the standalone product with a proper cost/capabilities balance

Definitions



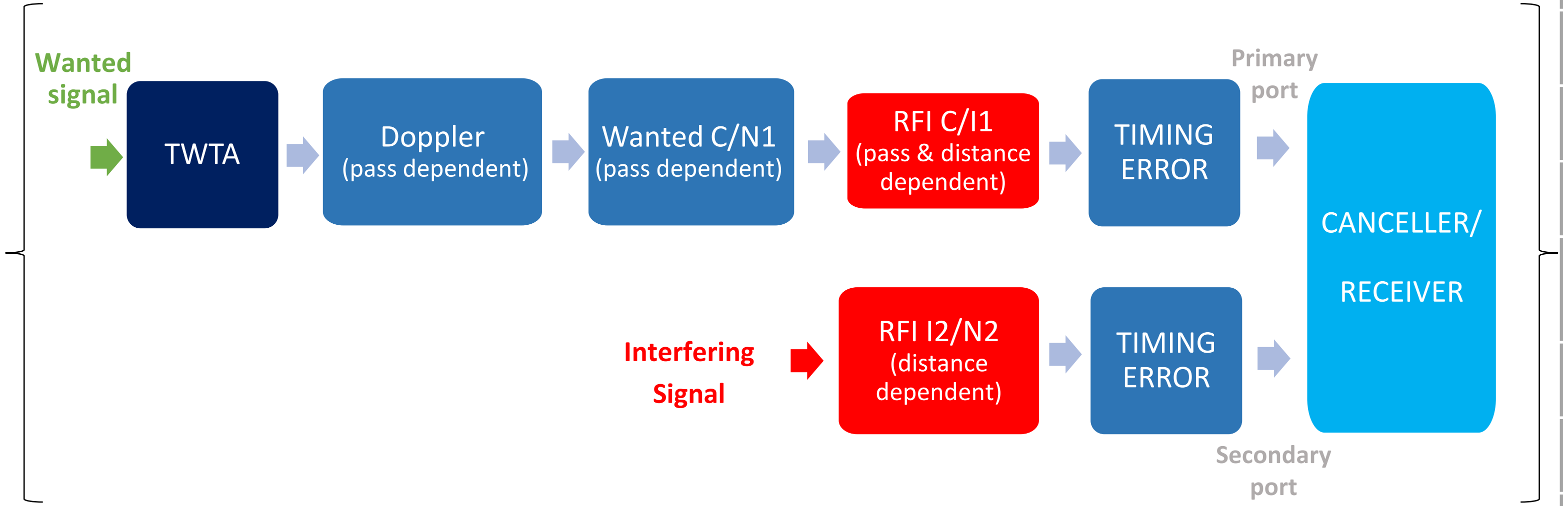
Channel models

CASE1
CASE2



TWTA/IMUX/ OMUX	DVB-S2X channel model Linearized TWTA Ka-band 236MHz TXP bandwidth
Carrier frequencies	Wanted at left edge and two adjacent with 1.15 separation
Phase noise	Professional Ka-band LNB
Freq offset	10% of symbol rate
Timing offset	25ppm

CASE3



Satellite	Deimos-2 (620km orbit height)
TWTA	Needed for 2db margin at 5º elevation
Primary antenna	4m dish size, noise according to ITU-R P.372-8 @2250MHz
Primary frontend	LNA with 27.25K noise temperature and 58dB gain, SDR port with 8dB noise figure
Interferer station	EIRP 6-24dBW, 10km maximum distance from GS, 25m antenna height, point-to-point propagation channel
secondary antenna	Hemispheric antena with 2dBi gain and noise temperatura of 270K
Freq offset	Max 85Khz (max Doppler 75Khz)
Timing offset	3ppm

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Signal models

CASE1/2 wanted and CASE2 RFI (DVB-S2)	
Symbol rate	30 Mbaud (Wanted) 15/6 Mbaud (RFI)
Bandwidth	36 MHz (Wanted) 18/7.2 MHz (RFI)
Sampling Rate	60 Msamples/s
Samples per symbol	2 (Wanted), 4/10 (RFI)
Frame type	Normal
Pilots	ON
MODCODs	QPSK ¾ and 8PSK ¾ with BCH+LDPC Coding
Reception band	950-1950 MHz
RRC filter roll-off	20%
Link Margin	3-12 dB
Wanted to RFI bandwidth factor	2 and 5

CASE1 RFI (CW)	
Parameter	Value
Signal to Interference ratio (C/I)	Configurable value in dB
CW#1 Frequency shift	Configurable value in MHz (1 MHz default value)
CW#2 Frequency shift	Configurable value in MHz (3 MHz default value)
Dynamic CW frequency sweeping rate	Configurable value in KHz
Dynamic CW amplitude rate	Configurable value in KHz

CASE3 wanted (CCSDS telemetry)	
Symbol rate	6 Mbaud
Bandwidth	8.1 MHz
Sampling Rate	12 Msamples/s
Samples per symbol	2 (Wanted)
Frame type	CADU framing
MODCODs	QPSK, concatenated RS+Viterbi code
Reception band	2200-2290 MHz
Root Raised Cosine (RRC) transmission filter roll-off	35%
Link Margin	3-6 dB

CASE3 RFI (PMP Fixed Link)	
Symbol rate	6, 3 and 2 Mbaud
Bandwidth	8.1, 4.05 and 2.70 MHz
Sampling Rate	12 Msamples/s
Samples per symbol	2, 4 and 6
MODCODs	QPSK
RRC filter roll-off	35%

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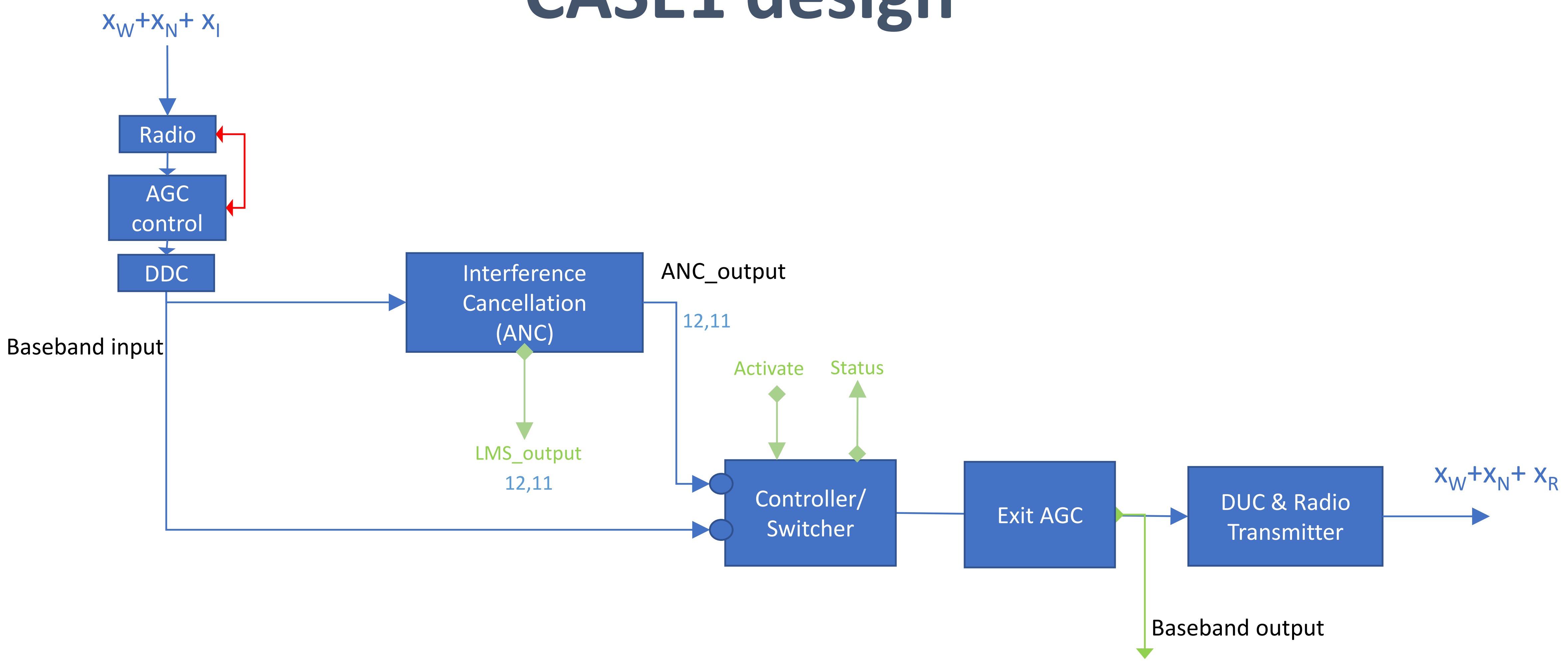
Cancellers design approach

- Leading product requirements
  - Single (wanted service) antenna
  - No time-frequency-bandwidth-level coordination between wanted and interfering signal
- Many potential RFI algorithms examined at proposal time
  - MUD joint demod/decod (linear, MLSE, SIC/PIC etc.), BSS, transform-based, ML-based
  - NOMA, PLNC, PCMA, self-interference cancellation
  - Most of them require some coordination, are not mature enough or are too complex
- Focus on well-known, complexity-controlled techniques that maximize validity in the operating scenario
  - Adaptive filtering for CASE1
  - Soft RFI cancellation for CASE2
  - Hard RF cancellation plus adaptive filtering for CASE3

CASE1 design



ANC: Adaptive Noise Canceller

Signal path

External Monitoring & Control data

Internal data exchange

x_W Wanted signal

x_I Interference signal

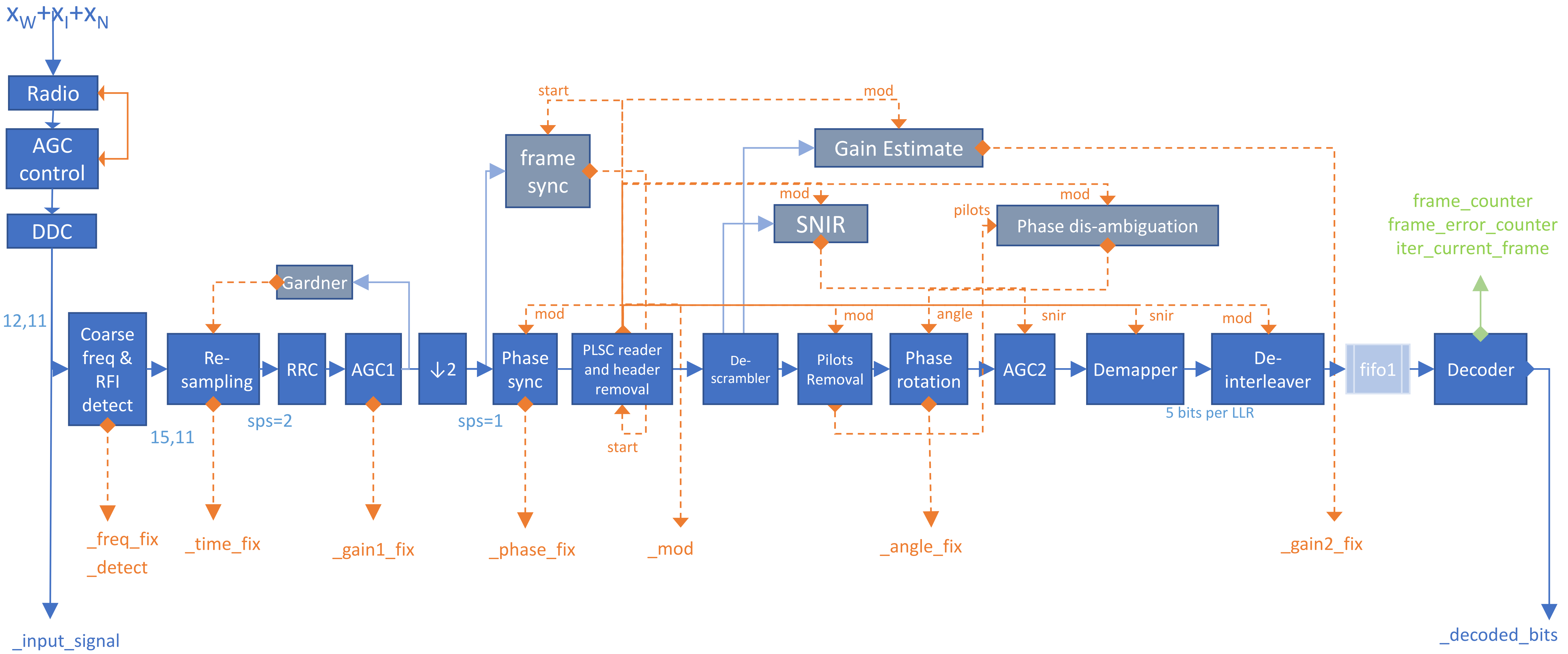
x_N Noise signal

x_R Residual interference

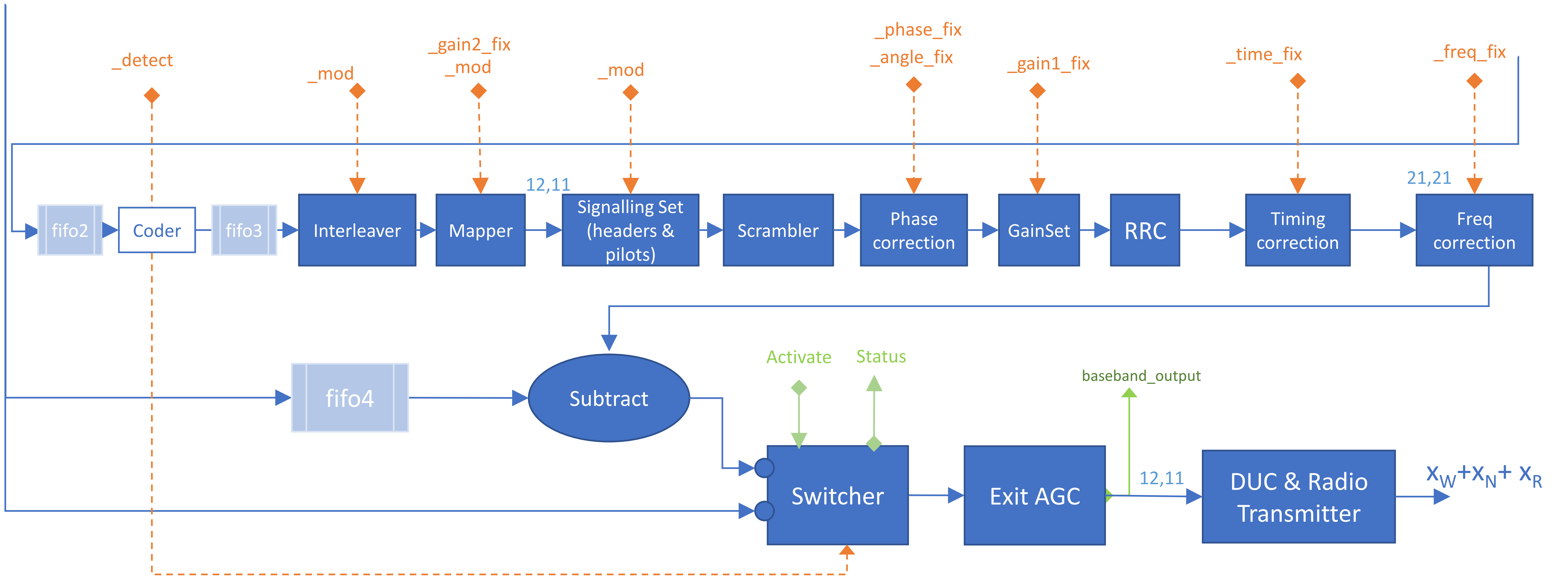
CASE1 design notes

- Canceller blind to protected waveform
- Spectral interference separation thanks to the wanted vs RFI bandwidth difference
- Performance depends mainly on ANC filter choice and adaptation step
  - The filter must isolate the CWs avoiding excessive noise injection
  - Performances bounded by saturation in the complete RF chain
- Simulations data show cancellation ranges exceeding 30dBs with no gap in the low-RFI side of the range
- Better range with QPSK and larger link margins
- Good tracking performance
- No need for RFI detection as SNR loss is negligible when active and no RFI is present

CASE2 design (1/2)



CASE2 design (2/2)



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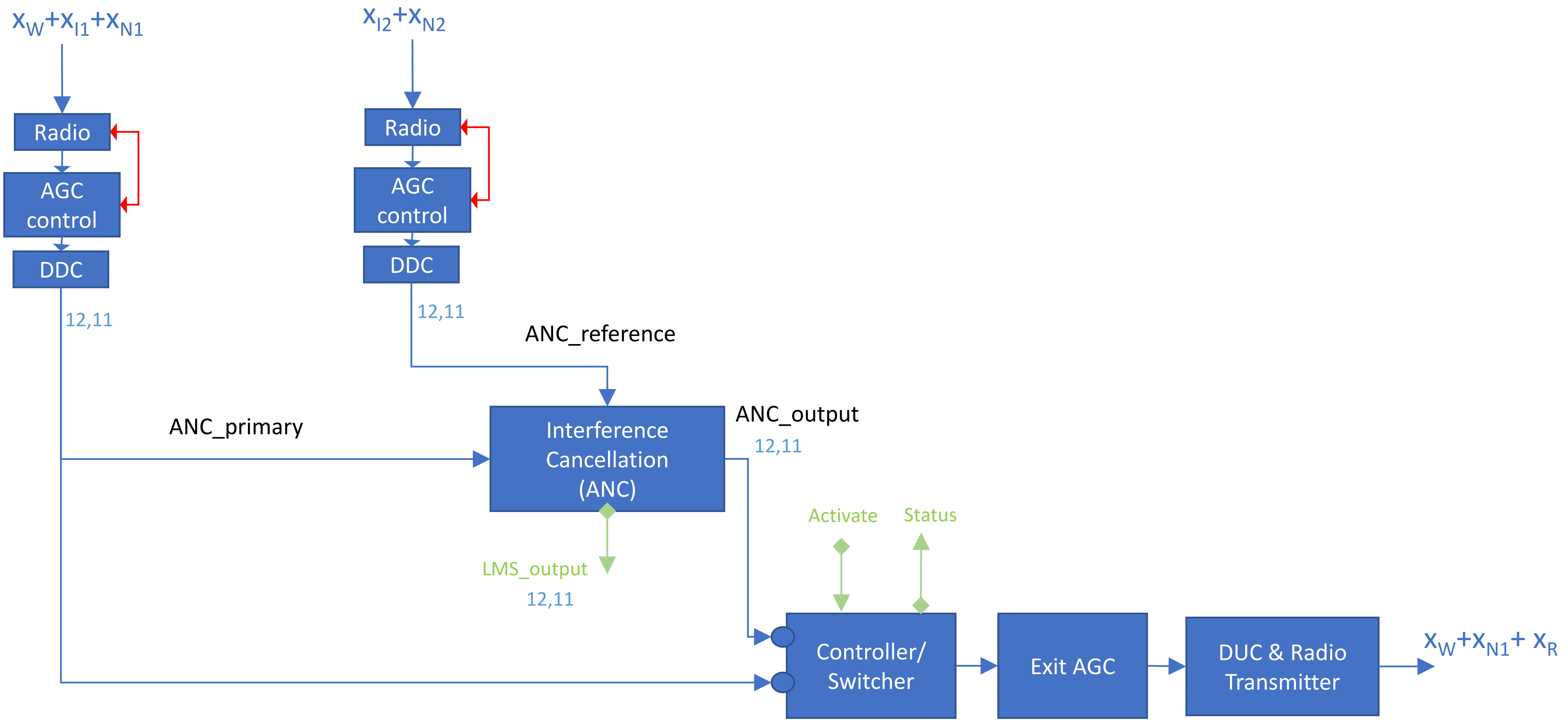
CASE2 design notes

- Canceller blind to protected waveform
- RFI separation thanks to the RFI demodulation/decoding
- Performance depends mainly on demodulation/decoding quality and the ability to reconstruct synchronizers-estimators corrections (phase, timing, gain) and is bounded by saturation in the complete RF chain
- Simulations data show cancellation ranges exceeding 30dBs with a certain gap in the low-RFI side of the range
- Performance (cancellation range and low-RFI gap) varies with the wanted/RFI MODCOD combination, wanted/WFI bandwith ratio and service link margin
  - Best with strong MODCODs and high bandwith ratios and link margins
- Tracking performance (RFI MODCOD and amplitude) depends on estimator quality
- RFI detection/estimation needed to tune to RFI frequency and bandwith

CASE3 design

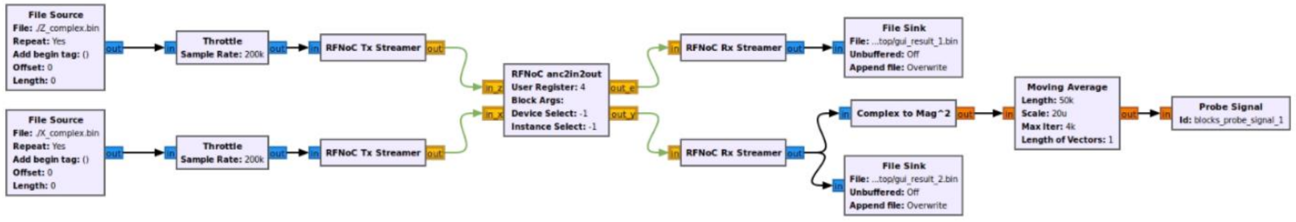


CASE3 design notes

- Canceller blind to protected waveform
- Interference separation thanks to a RFI replica received with aux antenna
- Performance depends on ANC filter choice, adaptation step and notably on the interference to noise ratio of the secondary antenna
  - The in-band secondary noise cannot be rejected by the ANC
  - Need for close interferer distances or directional antenna
  - Performances bounded by saturation in the complete RF chain
- Simulations data show a cancellation range exceeding 30dBs with no gap in the low-RFI side of the range
- Good tracking performance
- No need for RFI detection as SNR loss is negligible when active and no RFI is present

Implementation Approach

- COTS SDR equipment (USRPs) with mixed FPGA/CPU processing
  - high-quality clock, low noise figure
  - AGC and IQ/DC offset corrections
  - ADC/DAC 12-16 bits
  - Sampling rates 60-160MHz
- VHDL development with Vivado
- C++ for M&C console development
- GNURadio+RFNOC framework for flexible CPU-FPGA processing chains with radio+file+network I/O
  - High expertise needed in practise



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Implementation notes

- Selected Matlab fixed-point models
- Own fixed-point conversions library (Matlab and VHDL) developed
- Paired Matlab-VHDL developers for algorithm logic implementation
- Optimization of bitwidths, division operations and pipelining
- Stick to native FPGA clock
- Split-design for CASE2 due to 3rd party LDPC decoder integration issues
- Large work to automate Matlab-Vivado-GNUradio testing

Site Type	Used	Available	Util%
Slice LUTs	135377	218600	61.93
Slice Registers (FF)	191272	437200	43.75
Block RAM	329.5	545	60.46
DSP	822	900	91.33

CASE1 FPGA resources

Site Type	Used	Available	Util%
Slice LUTs	184410	218600	84.36
Slice Registers (FF)	126425	437200	28.92
Block RAM	206.5	545	37.89
DSP	536	900	59.56

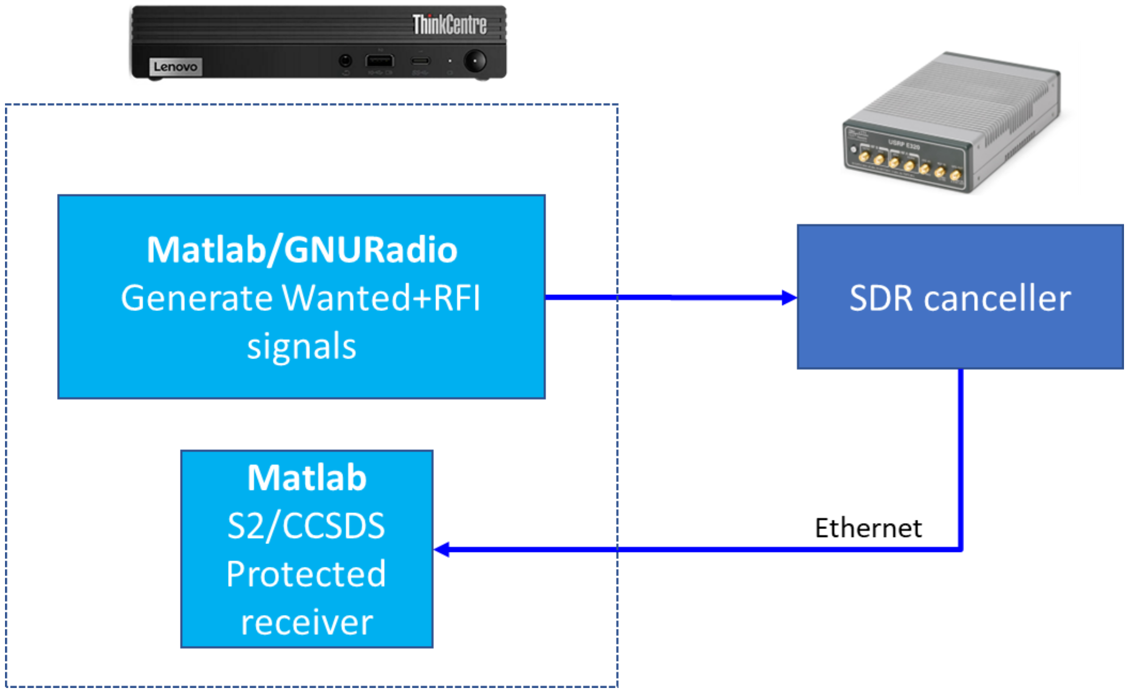
Site Type	Used	Available	Util%
Slice LUTs	99328	218600	45.44
Slice Registers (FF)	168280	437200	38.39
Block RAM	398.5	545	73.12
DSP	248	900	27.56

CASE2 FPGA resources

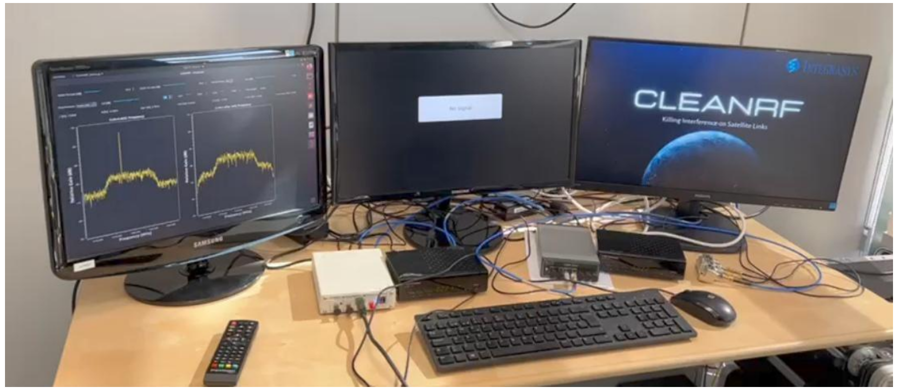
Site Type	Used	Available	Util%
Slice LUTs	130647	218600	59.77
Slice Registers (FF)	191463	437200	43.79
Block RAM	399.5	545	73.30
DSP	690	900	76.67

CASE3 FPGA resources

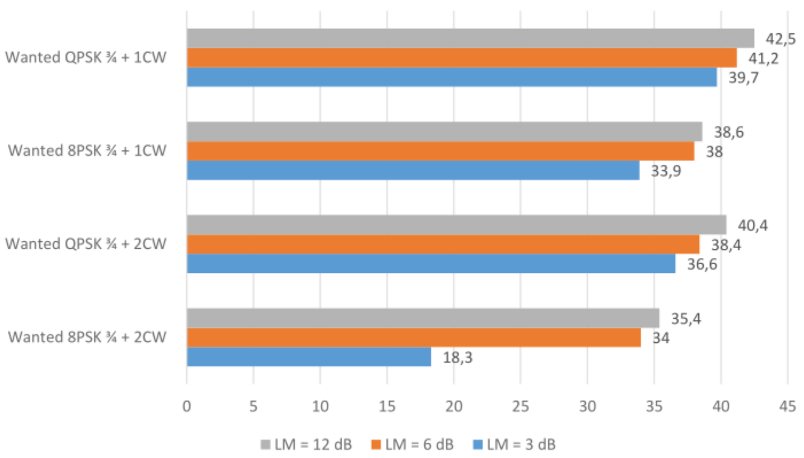
FAT tests



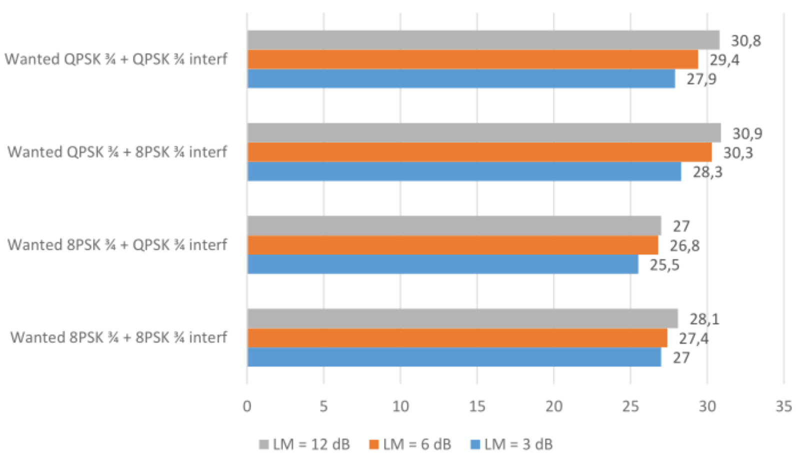
CASE1	Cancellation ranges under static conditions, sweeping CW and C/I ramps Canceller latency
CASE2	Cancellation ranges under static conditions, C/I ramps and ACM changes Canceller latency
CASE3	Cancellation ranges under static conditions and realistic C/I C/N profiles Caneller latency



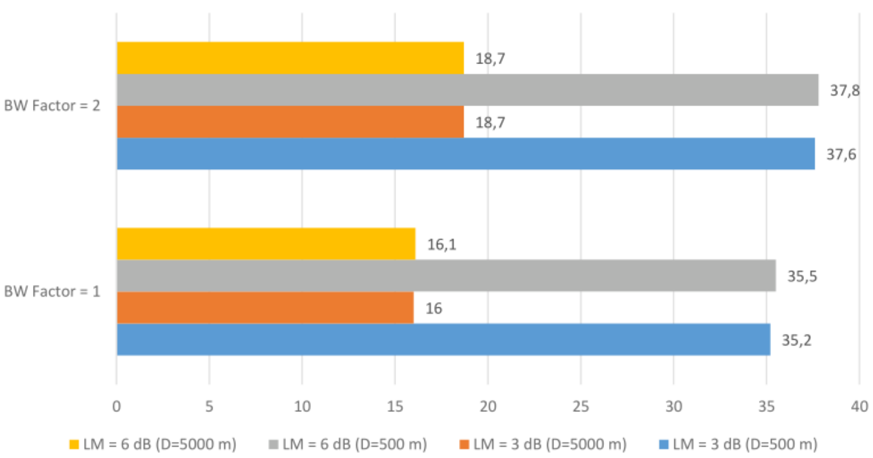
FAT TESTS results



CASE1 cancellation ranges



CASE2 cancellation ranges (bw ratio=5)



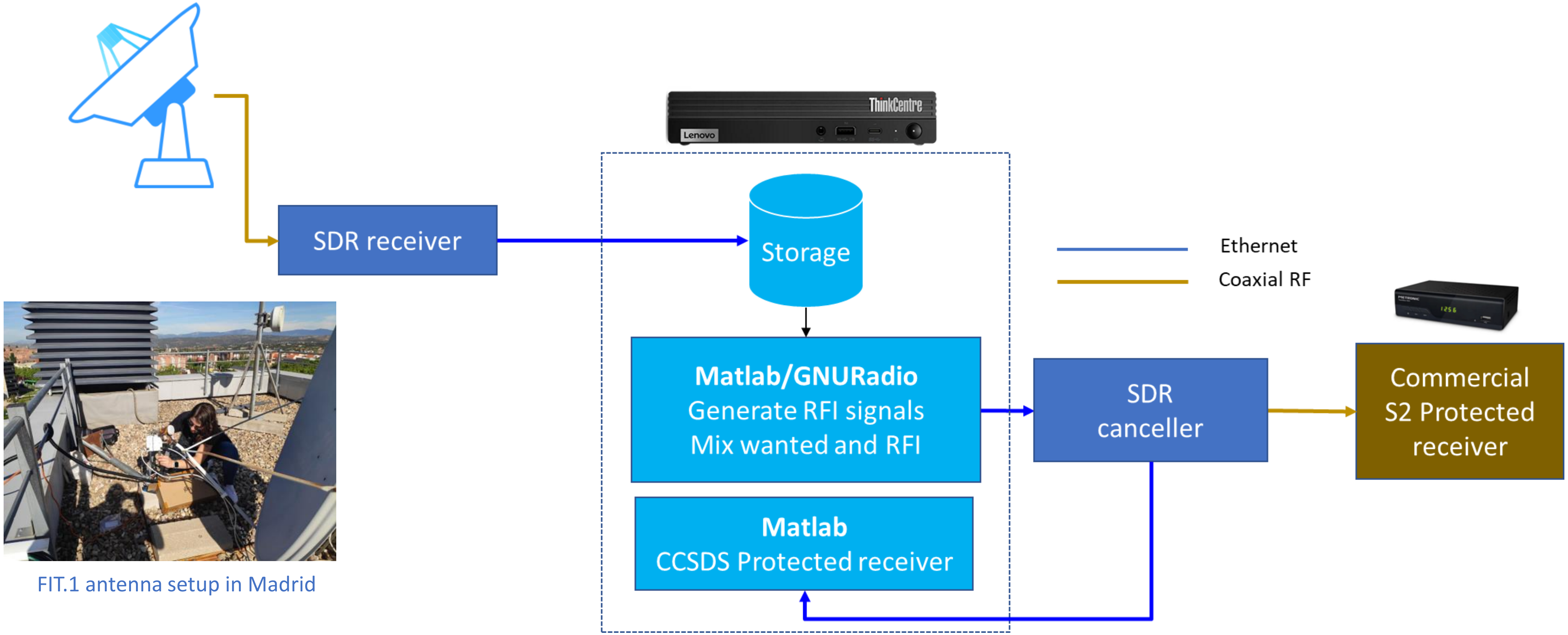
CASE3 cancellation ranges

- Overall loss (in C/I1a) under 2dBs
- 8PSK with low margin and 2CWs the only with significant loss
- Same good tracking performance (exceeding 20Hz over the band)
- Latency of 7 microseconds

- Overall C/Io loss around 1dB and overall C/I1a loss under 1dB
- No loss under C/I ramps
- 1 frame loss during ACM changes
- Latency of 0.5 milliseconds

- Overall loss (in C/I1a) under 2dBs
- Good tracking performance adapting to C/I profiles of realistic passes
- Latency of 7.6 microseconds

FIT.1 tests



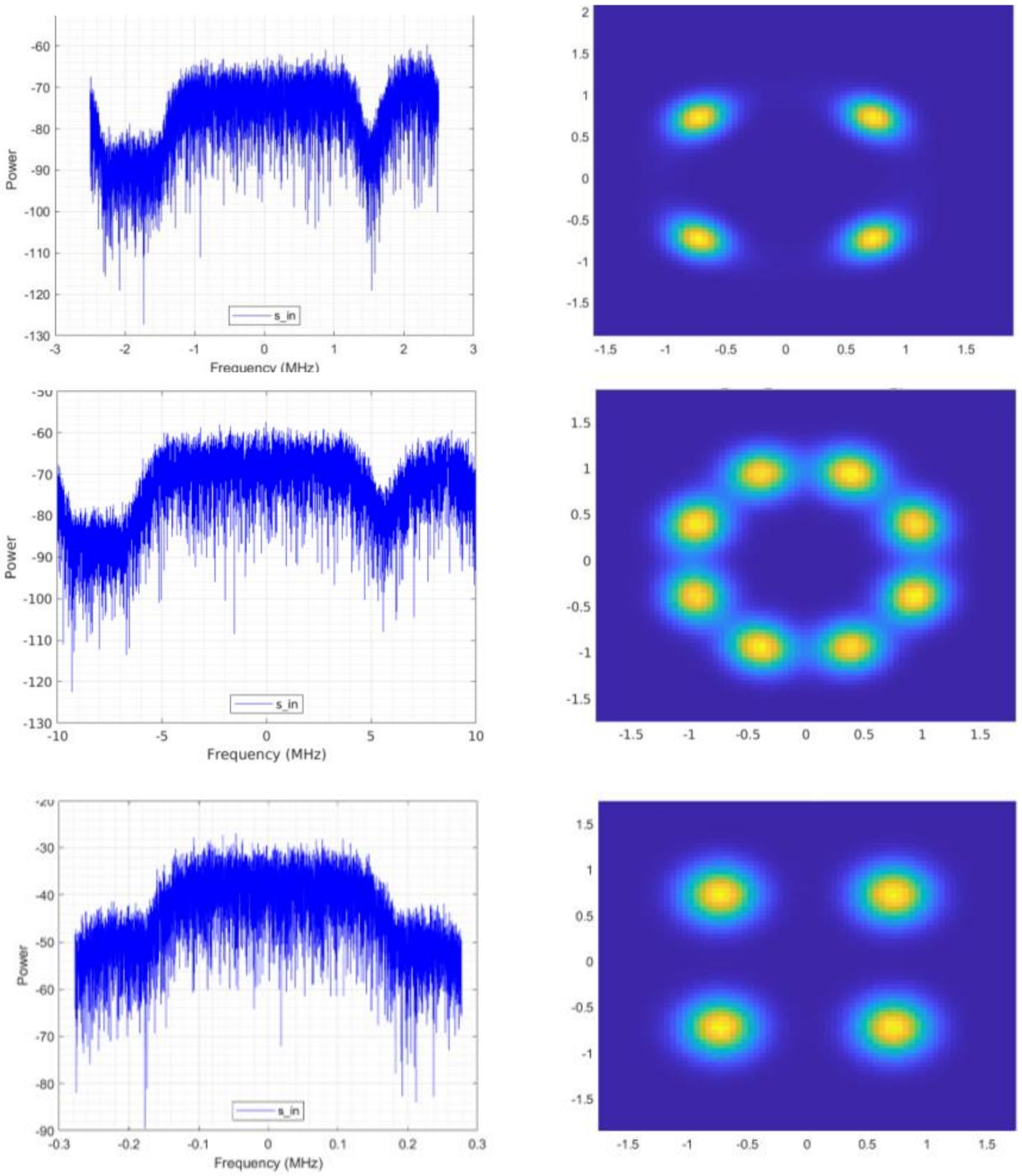
FIT.1 antenna setup in Madrid

CASE1	Cancellation ranges under static conditions and sweeping CW for 8PSK and QPSK recorded signals
CASE2	Cancellation ranges under static conditions for 8PSK and QPSK recorded signals
CASE3	Cancellation ranges under static conditions

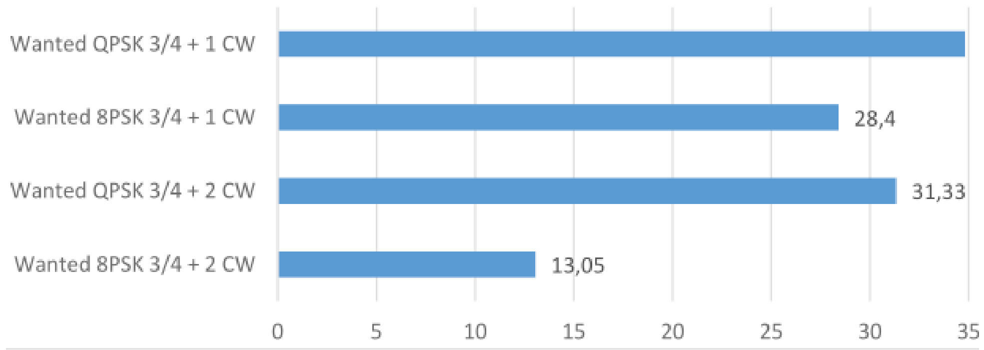
FIT.1 tests signals

Modcod	Standard	Symbol Rate	Satellite	Band	Center Freq (Ku)	Center Freq (IFL)	Pol	TV Channel	SNR (est.)
QPSK ¾	DVB-S2	2.5 Mbaud	Hispasat 30W	Ku	10914 MHz	1164 MHz	H	BOM Cine	14.54dB
8PSK ¾	DVB-S2 (multi-stream)	9.14 Mbaud	Hispasat 30W	Ku	11330 MHz	1580 MHz	H	Aragon TV	12.4dB

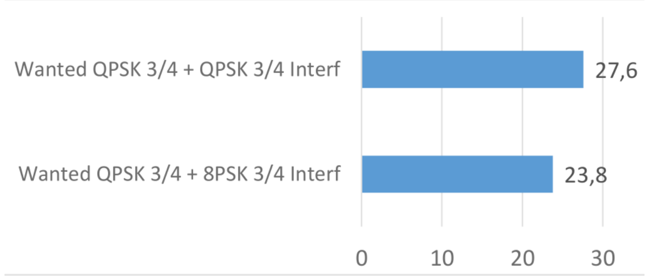
Modcod	Standard	Symbol Rate	Satellite	Band	Center Freq	SNR (est.)
QPSK 1/2	CCSDS		Echostar XXI	S		11.6dB



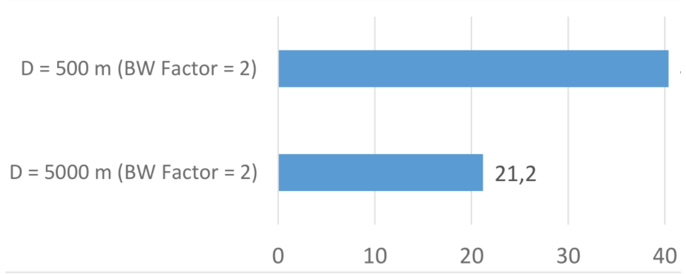
FIT.1 tests results



CASE1 cancellation ranges



CASE2 cancellation ranges



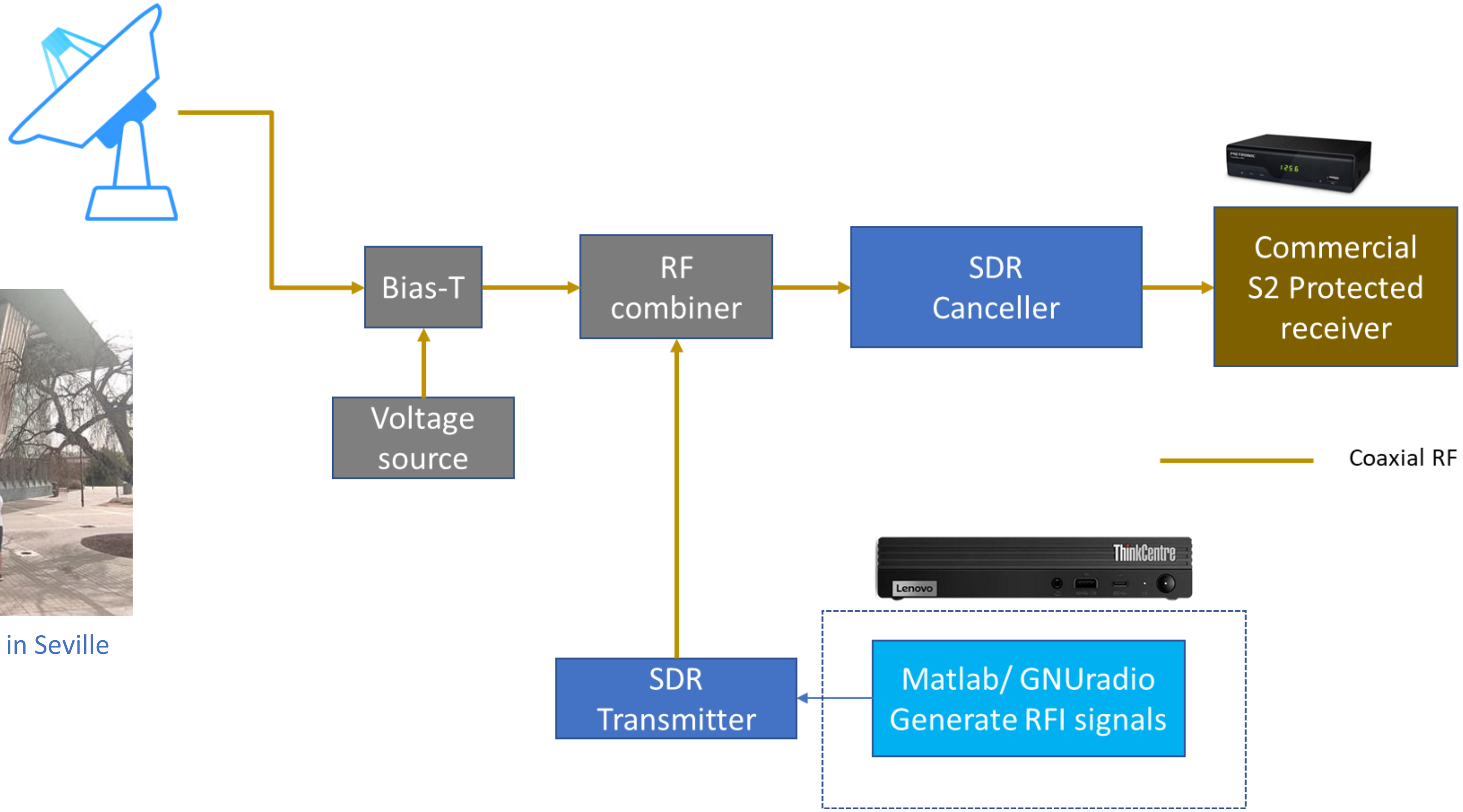
CASE3 cancellation ranges

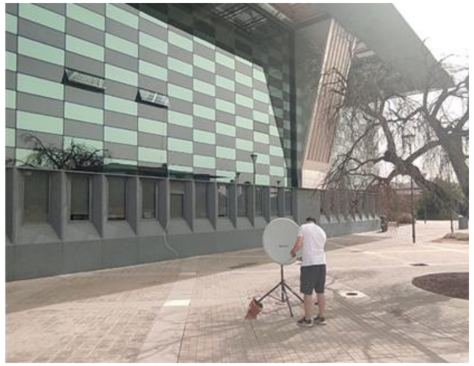
- Loss of 4-5dbs against FAT tests (correcting for link margins)
- Different wanted receiver and QEF criterion
- Possible influence of the radio output LO which is visible in the spectrum.
- Possible increased injected noise due to adjacent carriers

- Minimal loss against FAT tests (correcting for link margins)
- The RFI is synthetically recreated and channel conditions are fairly good
- The wanted signal represents just noise for the interference one.

- Minimal loss against FAT tests (correcting for link margins)
- Excellent channel conditions

FIT.2 tests



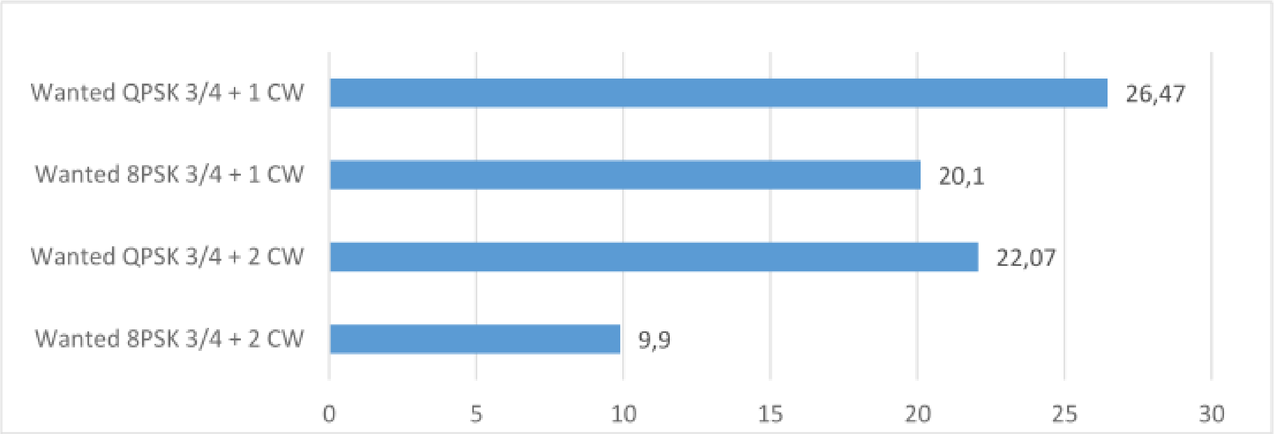


FIT.2 antenna setup in Seville

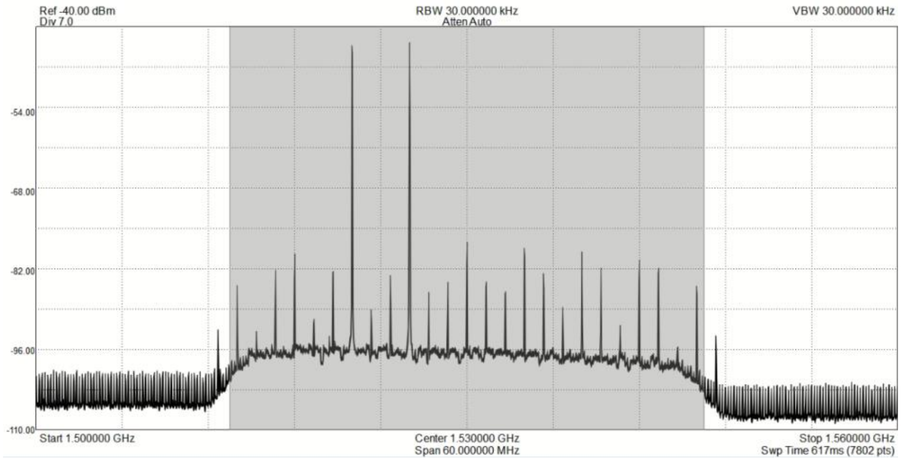
CASE1	Cancellation ranges under static conditions for QPSK and 8PSK live signals

Modcod	Standard	Symbol Rate	Satellite	Band	Center Freq (Ku)	Center Freq (L)	Pol	TV Channel	SNR (est.)
QPSK ¾	DVB-S	27.5 MHz	Hispasat 30W	Ku	10890 MHz	1140 MHz	V	Canal Parlamentario	12.2
8PSK ¾	DVB-S2	27.5 MHz	Hispasat 30W	Ku	12130 MHz	1530 MHz	H	Record TV Europa	12.1

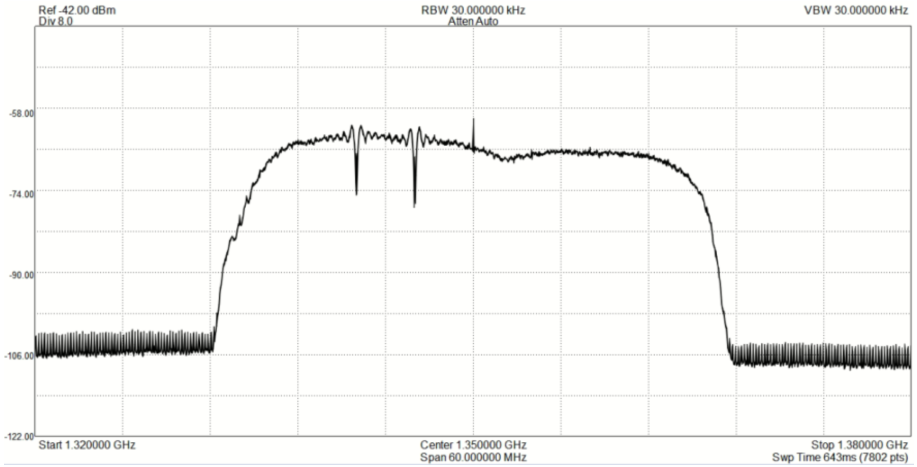
FIT.2 tests results



- Loss of 5-8dBs against FIT.1 tests (correcting for link margins)
- Results are limited by the lack of dynamic range in the SDR transmitter that generates significant nolinear distortion (which cannot be cancelled)
- Nonlinear distortion affects more to higher interference values (higher losses in QPSK than in 8PSK)
- This case represents a terrerial CW interference
- Verified full-radio behaviour at high rates



FIT.2 generated high-power 2CW



FIT.2 canelled spectrum for 8PSK 2CW

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Summing up

- Sound RFI cancellation techniques have been studied in depth, simulated and implemented successfully in HW properly identifying its critical features, limitations and demonstrating operation in real-life conditions
- The techniques allow for complete RFI cancellation at the expense of certain reduction in SNR, providing robustness and maximim availability to critical services.
- When used in combination with techniques such that trade throughput for resilience (e.g. ACM) CLEANRF is expected to maximize throughput in addition to adding robustness
- CLEANRF techniques are fully complementary to other anti-RFI techniques (e.g. freq-based and code-based spread spectrum)
- Open design for cooperation with existing services when interference appears to optimize cancellation performance

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Future work

- Overall consolidation of implementations from TRL6 to TRL9
- Testing in real systems, checking for non-wanted interactions (e.g. adaptive power/ACM)
- Extending supported bandwiths
- Integrating different cases at convenience with proper switching mechanism
- CASE1
  - Improve 8PSK with multiple CW by using CW estimation and synthesis, which is much less noisy than current method but also not that fast for moving CWs
- CASE2
  - Finalize LDPC decoder integration
  - Extension to more interference waveforms and consideration of ways of reducing the cancellation gap in the low-interference zone and dependence on interference waveforms
- CASE3
  - Possible migration to cancel terrestrial mobile interference

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Lessos learnt

- Largest team project at Integrasys
  - Distributed in Seville, Madrid, Alicante
  - Large number of dependencies due to the ambitious goals and time plan
- Large technology advance
  - Rather little heritage to build upon
  - Signal processing, SDRs, VHDL
- Some lessons from project management
  - Have good theoric model of how things should wor, sSound papers with repeatable results
  - Assume the overhead of double-triple check everything
  - Plans A, B and C with varying accuracy and time-to-result
  - Large number of tools used (Teams, Trello, Excel, Word)….but hard to beat Powerpoint, (physical) whiteboards and most personal interactions

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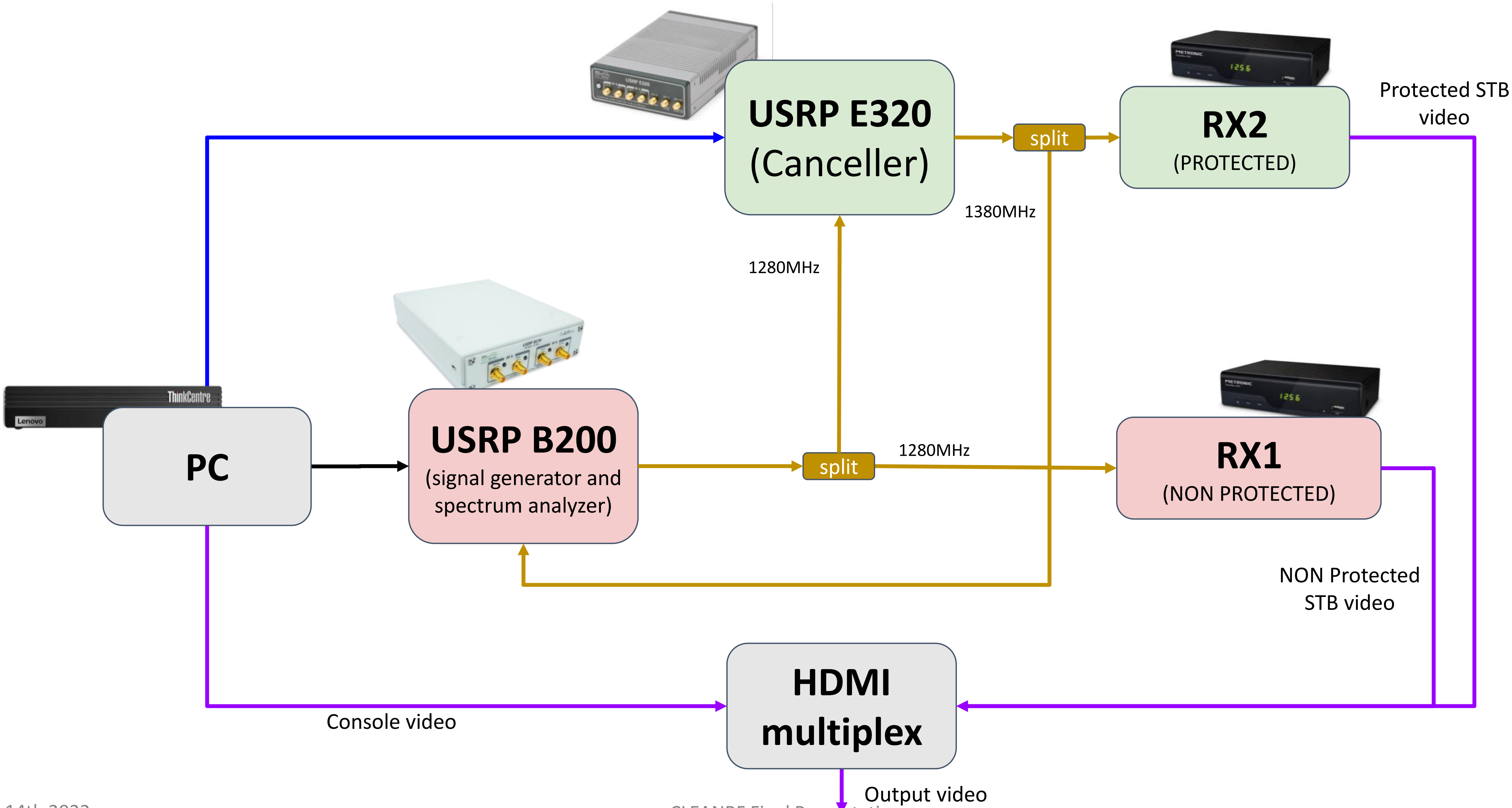
The CLEANRF TEAM

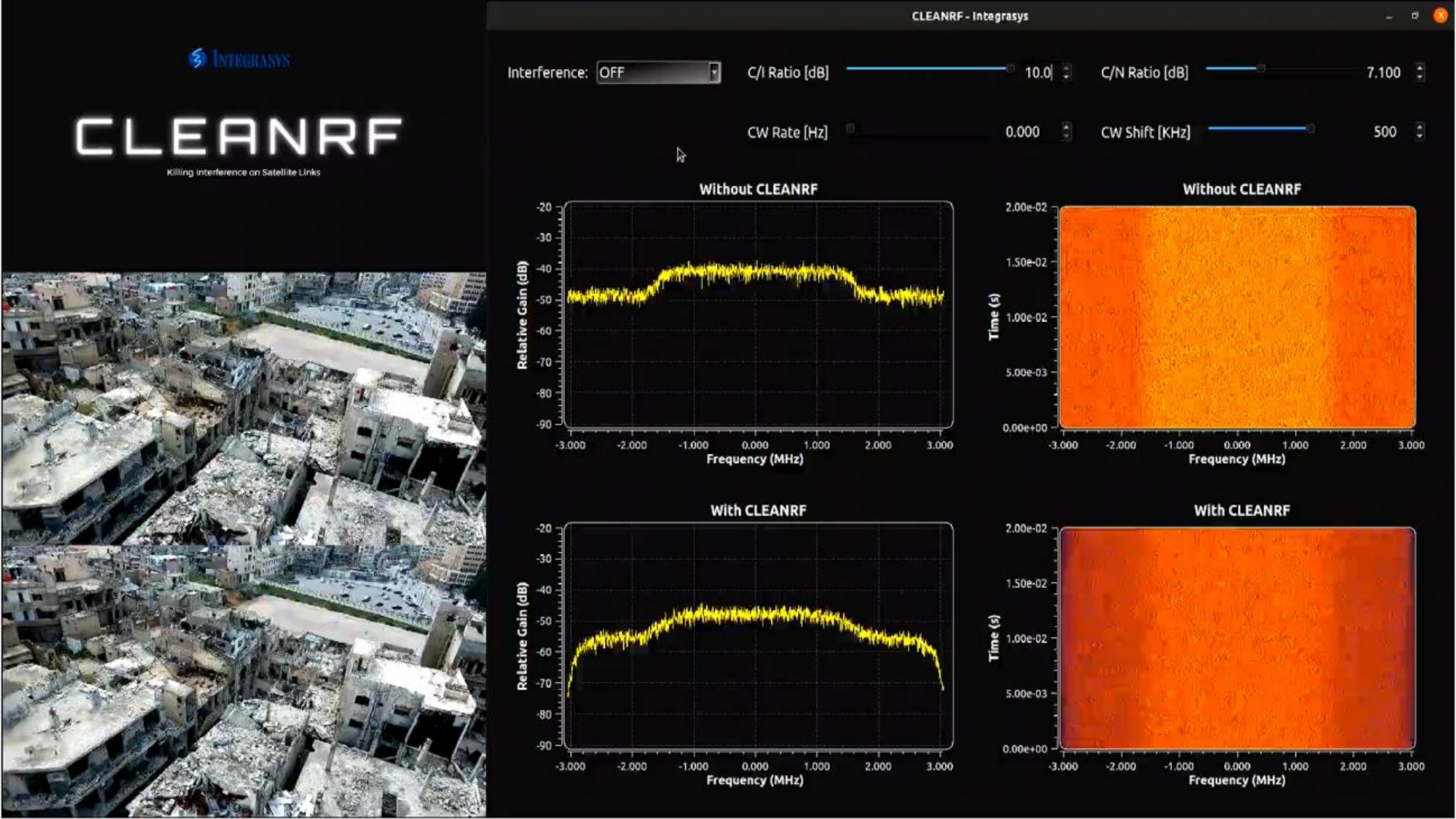
- María Muñoz (Sevilla)
- Javier Valera (Sevilla)
- Pablo del Campo (Sevilla)
- Adrián Campos (Sevilla)
- Jose Cordero (Sevilla)
- Pedro Ruiz (Sevilla)
- Jose Sanchez (Sevilla)

- Margarita Martinez (Madrid)
- Sara Torres (Madrid)
- Juan Manuel Martinez (Madrid)
- David Lopez (Madrid)
- Lucas Garcia (Madrid)
- Cristina Lopez (Madrid)
- Alvaro Sanchez (Madrid)

- Nader Alagha (ESTEC)
- Nikolaos Toptsidis (ESTEC)
- Frank Zeppenfeldt (ESTEC)

Demostration




CLEANRF - Integrasys
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CLEANRF
Killing interference on Satellite Links
Interference: OFF
C/I Ratio [dB] 10.0
C/N Ratio [dB] 7.100
CW Rate [Hz] 0.000
CW Shift [KHz] 500
Without CLEANRF
Relative Gain (dB)
Frequency (MHz)
Without CLEANRF
Time (s)
Frequency (MHz)
With CLEANRF
Relative Gain (dB)
Frequency (MHz)
With CLEANRF
Time (s)
Frequency (MHz)

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