Analysis and Implementation of DVB-S2 in the UHF Band for STRATHcube Downlink Communications

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Aim

Design of the downlink communications system for the STRATHcube satellite and creation of an engineering model using development boards.

Background - STRATHcube

- Student Led 2U CubeSat Project
- Part of European Space Agency (ESA) Fly Your Satellite! and Design Booster programs
- Primary payload implementing Passive Bistatic Radar (PBR) for in-orbit debris detection

Primary Communications

- Space rated module from Alén Space to be used for both communications and PBR
- Zynq 7020 FPGA w. Analog Devices AD9364 transceiver.
- 435-440MHz Amateur space band

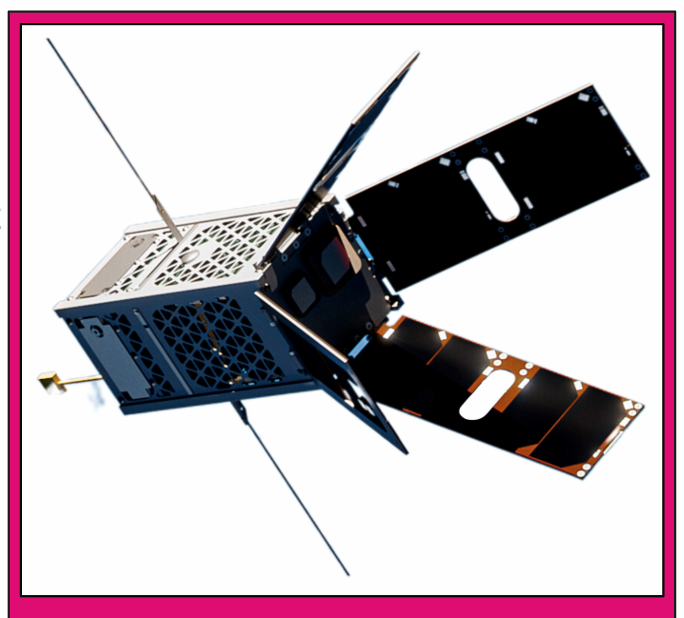

Figure 1: STRATHcube Render

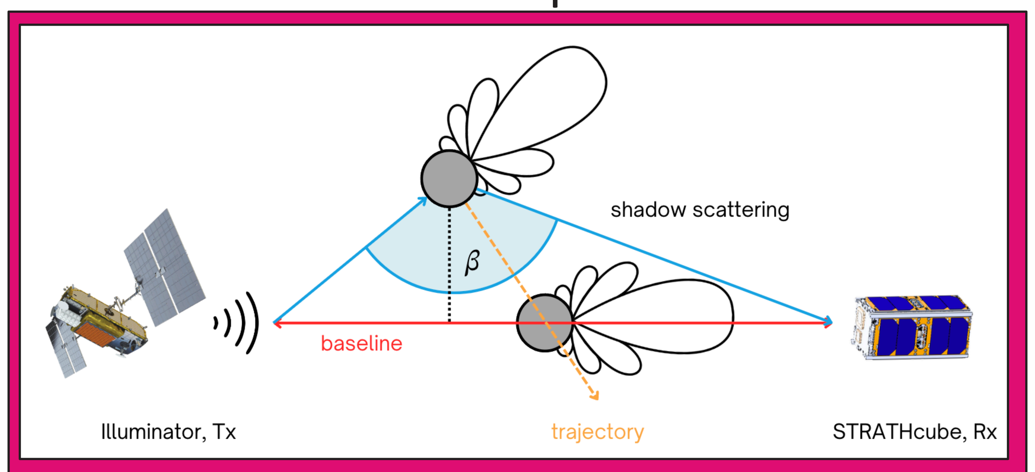

Figure 2: Passive Bistatic Radar

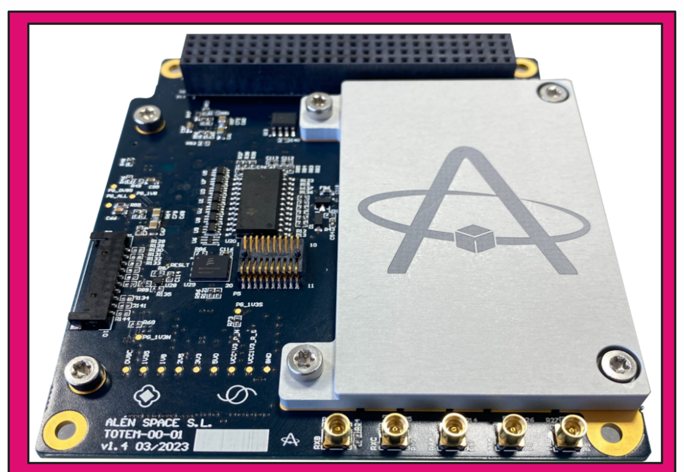

Figure 3: TOTEM SDR [1]

Background - DVB-S2

- Digital Video Broadcasting - Satellite Second Generation (DVB-S2) is a standard for efficient and reliable satellite data transmission
- Modular structure to allow adaptation to application
- Features for Adaptive Coding and Modulation (ACM); changing of modulation and coding rate based on channel conditions allowing higher throughput, at the cost of increased complexity.
- Near Shannon Limit performance [2] due to concatenated codes: Bose-Chaudhuri-Hocquenghem (BCH) & Low Density Parity Check (LDPC)
- Modulated with 4 - 32 position Amplitude & Phase Shift Keying (APSK)
- Coding Rates from 1/4 to 9/10
- Both can be varied frame to frame for ACM

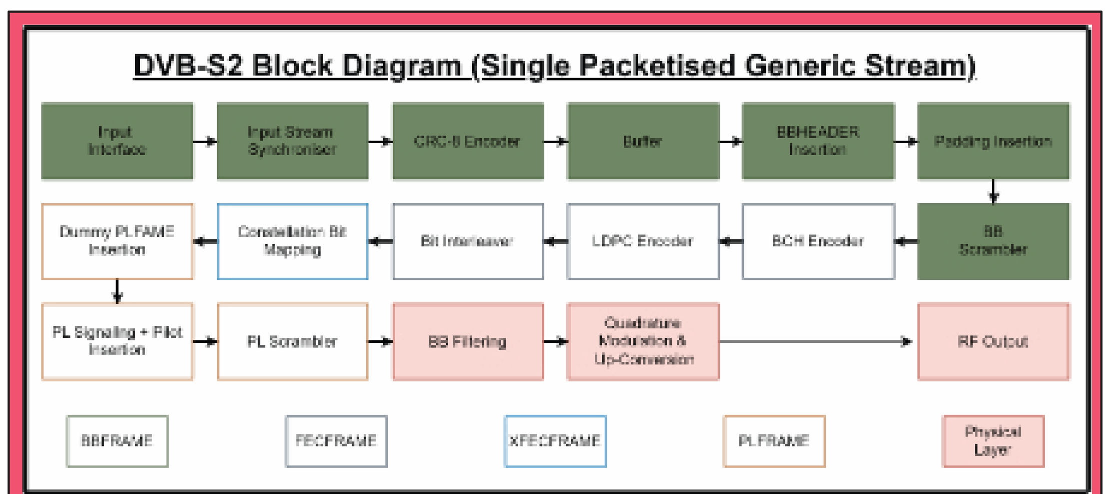

Figure 4: DVB-S2 Block Diagram [3]

Link Analysis - Link Budget

- Analysis of Link budget to identify static and dynamic parameters
- Manufacturer values, ITU atmospheric models and estimation for link parameters.
- Further investigation of noise power and interference at ground station site required
- Required SNR from [4] for each DVB-S2 modulation and coding.
- Final system may include pilot signals to improve recovery

TABLE II
DYNAMIC LINK PARAMETERS

Name	Values	Source
Elevation	10° to 40°	10° threshold to be counted as pass, 40° max elevation found through simulation
Altitude	170 km to 425 km	Deployment altitude from ISS to transition altitude trigger
Slant Range (SR)	260 km (40° @ 170km) to 1505 km (10° @ 425km)	MATLAB function [8]
Free Space Path Loss (FSPL)	133.5 dB (260km) to 148.8 dB (1550km)	(5)
Atmospheric Losses (AL)	0.074 dB (40°) to 0.318 dB (10°)	Includes gaseous, scintillation, cloud and rain losses. Calculated using atmospheric models with ITU-Rpy [9]

TABLE III
LINK BUDGET

Parameter	Adverse	Favourable
Elevation	10°	40°
Altitude	425 km	170 km
Noise Power	−125.1 dBW	
Signal Power	−123.2 dBW	−107.7 dBW
SNR	1.9 dB	17.4 dB
Optimal Modulation and Coding Rate	QPSK $\frac{1}{3}$	32APSK $\frac{5}{6}$
Required SNR	−1.24 dB	14.28 dB
Margin	3.14 dB	3.12 dB
Spectral Efficiency	0.6408	4.0306
Data Rate	16.020 kb/s	100.76 kb/s

$$\Gamma = \frac{\mathrm{VSWR}-1}{\mathrm{VSWR}+1} \quad (1)$$

$$L_{\mathrm{Matching,dB}} = 10\log_{10}(1-\Gamma^2)[\mathrm{dB}] \quad (2)$$

$$\mathrm{EIRP}_{\mathrm{dB}} = 10\log_{10}(P_{\mathrm{Tx,W}}) - L_{\mathrm{Line,dB}} - L_{\mathrm{Switch,dB}} - L_{\mathrm{Match,dB}} + G_{\mathrm{Tx,dB}}[\mathrm{dBW}] \quad (3)$$

$$\mathrm{P}_{\mathrm{T,dB}} = F_{\mathrm{T}} + 10\log_{10}(kT_0B) \quad (4)$$

Free Space Path Loss: [10, eq. 5.10]

$$\mathrm{FSPL} = 20\log_{10}\left(\frac{4\pi d f}{c}\right)[\mathrm{dB}] \quad (5)$$

TABLE I
STATIC LINK PARAMETERS

Name	Value	Source
System		
Frequency (f)	437 MHz	Centre of UHF Amateur Satellite Service Allocation
Bandwidth (B)	25 kHz	Commonly allocated bandwidth
Target Margin	3 dB	Standard margin target
STRATHCube		
Transmit Power (P_{Tx})	1W (0 dBW)	TOTEM UHF FE Limit, [3]
Cable Losses (L_{Cable})	0.116 dB	20cm RG-188/AU
Antenna VSWR	1.9 : 1	ISIS Antenna Datasheet [4]
Antenna Matching Loss (L_{Matching})	0.44 dB	(2)
Connector Losses ($L_{\mathrm{Connector}}$)	0.2 dB	4 Connectors @ 0.05dB, Estimation
Switch Losses (L_{Switch})	0.5 dB	Estimation
Transmit Antenna Gain (G_{Tx})	0 dBi	ISIS Antenna Datasheet [4]
Effective Isotropic Radiated Power (EIRP)	**−1.26 dBW**	(3)
Ground Station		
Receive Antenna Gain (G_{Rx})	15.5 dBic	STAC UHF Antenna [2]
Polarisation Loss (L_{Pol})	3 dB	Linear to circular
Pointing Loss (L_{Point})	1 dB	Estimation
Preamplifier Gain (G_{Preamp})	20 dB	SP-7000 Datasheet [5]
Preamplifier Noise Figure (F_{Preamp})	0.9 dB	SP-7000 Datasheet [5]
Line Losses	5.47 dB	36m of RG213
Receive SDR Noise Figure (F_{SDR})	8 dB	Ettus Research B210 Datasheet [6]
Terrestrial Noise Figure (F_{T})	6 dB rel. kT_0B	Outdoor manmade noise in city at 425 MHz [7, Tab. 3]
Terrestrial Noise Power (P_{T})	−154.0 dBW	(4)

Link Analysis - Orbital Simulation

- Analysing ACM performance for STRATHcube mission
- Orbital simulation for duration of mission comparing fixed and adaptive DVB-S2 system.
- ACM downlinked 6.01Gb
- Constant QPSK 1/3 downlinked 1.88Gb

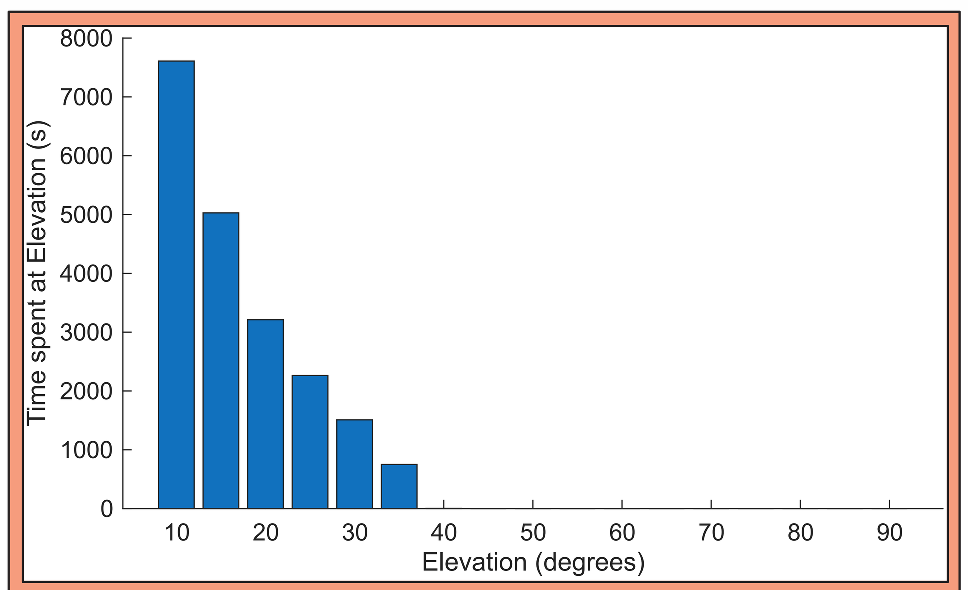

Figure 5: Elevation Time Over Ground Station

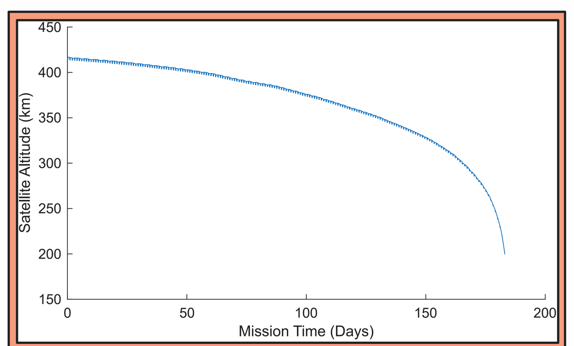

Figure 6: Satellite Altitude Over Mission

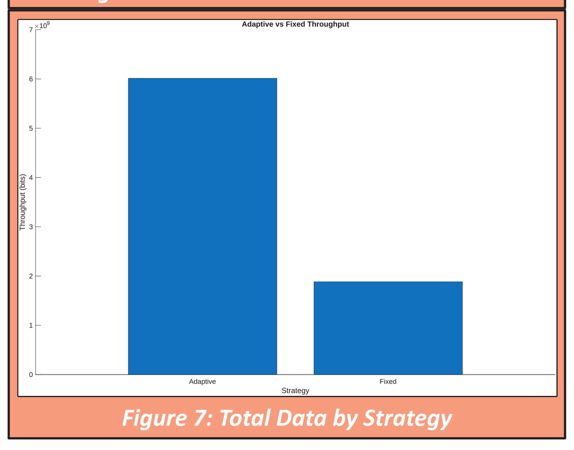

Figure 7: Total Data by Strategy

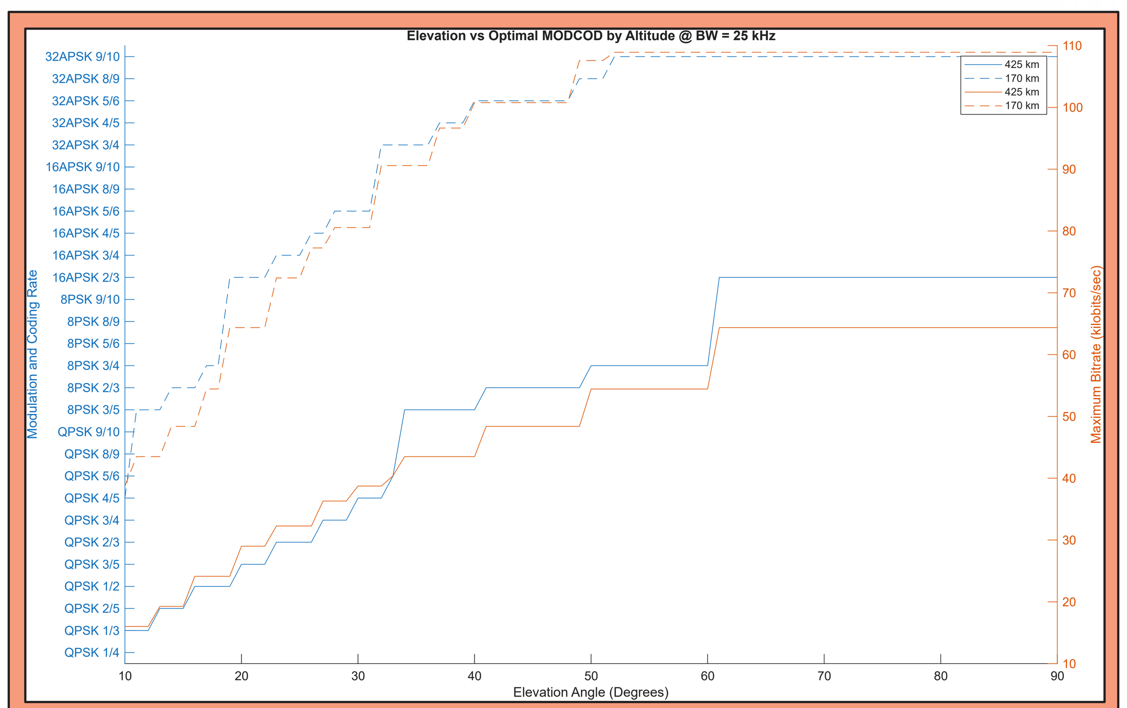

Figure 8: Elevation vs Optimal MODCOD and Throughput

System Design

- Packets received through multiple interfaces then parsed and grouped by priority
- ACM Router assigns by channel state and reliability needs
- Generic Stream Encapsulation (GSE) protocol [5] used to handle variable frame sizes
- PL-PS Interface using Libiio library [6]
- Transceiver controller block to handle chip interface
- Engineering model designed for FPGA and Transceiver development boards for verification.

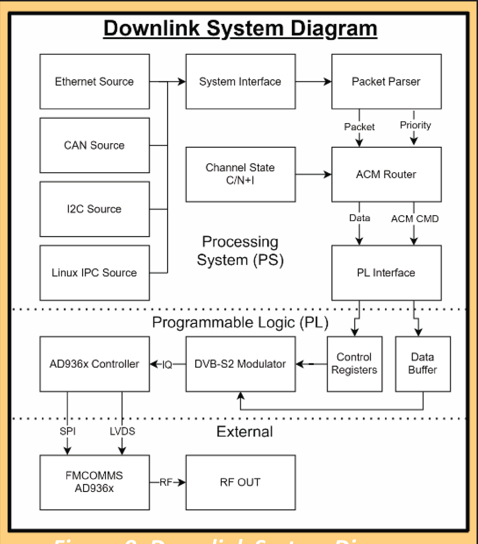

Figure 9: Downlink System Diagram

Implementation

- Hardware design using MathWorks HDL Coder [7] to reduce development time.
- Built on MathWorks Reference DVB-S2 implementation [8] to reduce technical risk
- Added PS interface logic and integrated with target transceiver

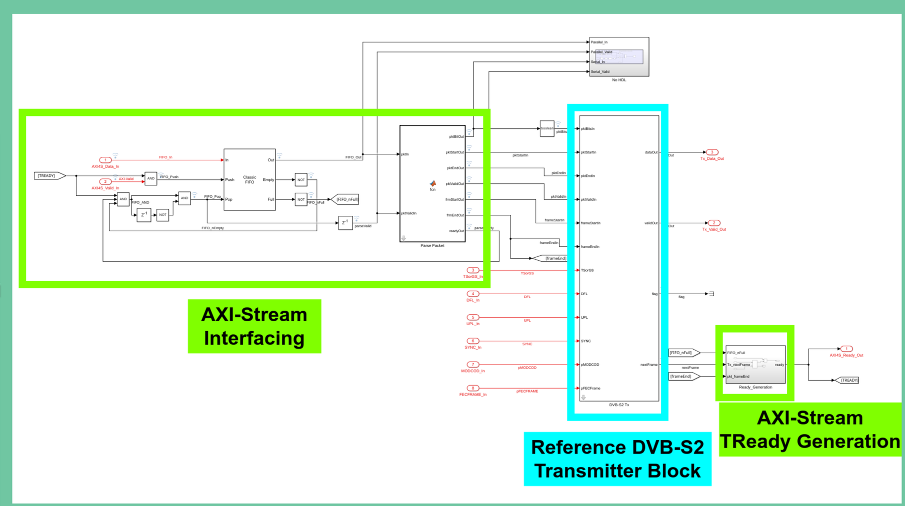

Figure 10: MathWorks HDL Coder Implementation

Results

- Output spectrum simulated using Simulink and tested against ITU spectrum mask for the amateur space service [9] and found to be passing
- Design successfully exported, synthesised using Vivado, and found to meet timing requirements at 61.44 MHz
- Resource usage analysed and found to meet limitations present on chip. Usage of most resource types below 50%, although the Block RAM (BRAM) usage was found to be high.
- Vivado Power Analysis showed estimated power consumption between 3.286 W and 4.009 W

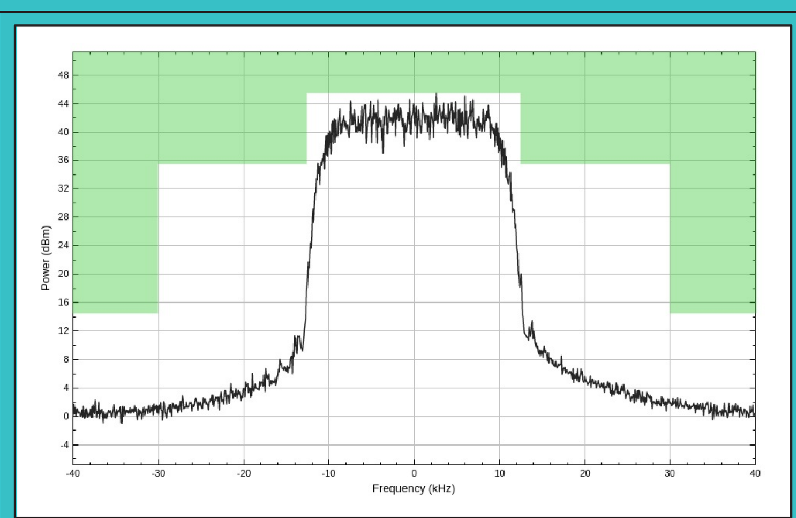

Figure 11: Output Spectrogram with ITU mask

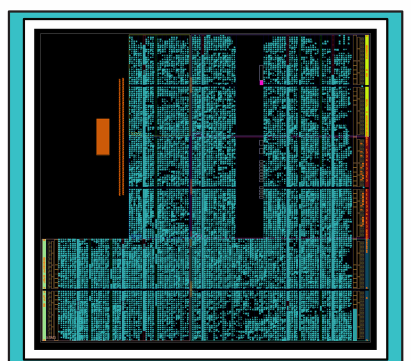

Figure 12: Design Implementation on Chip

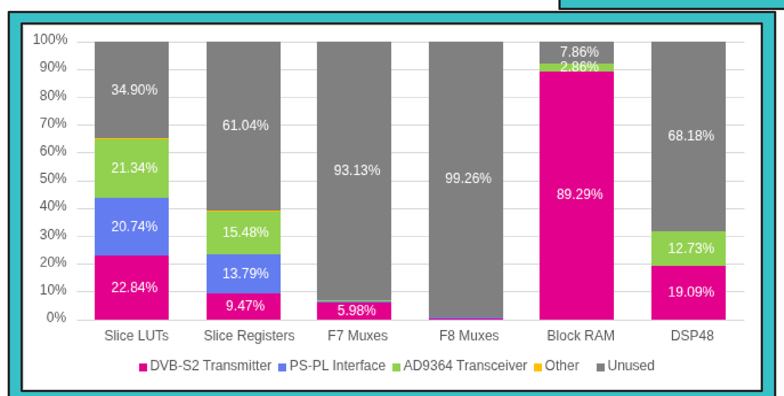

Figure 13: FPGA Resource Usage by Source

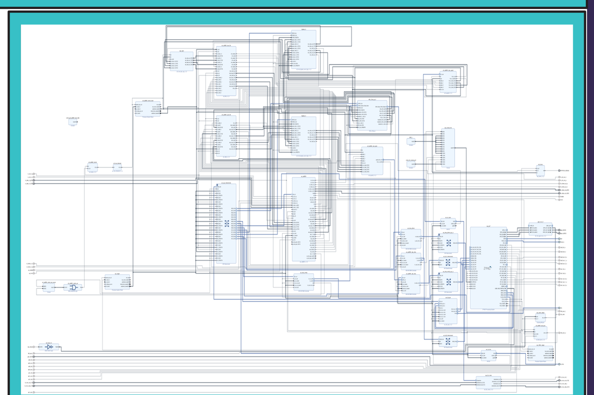

Figure 14: Vivado Block Diagram

Summary

1. Analysed performance of ACM for STRATHcube mission and found significant performance benefits
2. Implemented design using MathWorks HDL Coder, building off a reference DVB-S2 transmitter implementation
3. Design found to be implementable in hardware, however requiring resource and power optimisation.

References

[1] Alén Space, 'TOTEM Motherboard Datasheet'. Alén Space, Apr. 01, 2024.

[2] M. Eroz, F.-W. Sun, and L.-N. Lee, 'DVB-S2 low density parity check codes with near Shannon limit performance', International Journal of Satellite Communications and Networking, vol. 22, no. 3, pp. 269–279, 2004, doi: 10.1002/sat.787.

[3] ETSI TR 102 376-1, Nov. 2015.

[4] ETSI, "EN 302 307-1 - V1.4.1 - Digital Video Broadcasting (DVB); Second generation framing structure, channel coding and modulation systems for Broadcasting, Interactive Services, News Gathering and other broadband satellite applications; Part 1: DVB-S2." Jul. 2014.

[5] ETSI, TS 102 606-1 - V1.2.1, Jul. 2014.

[6] Analog Devices, analogdevicesinc/libiio. (Dec. 09, 2024). C. Analog Devices, Inc. Accessed: Dec. 13, 2024. [Online]. Available: https://github.com/analogdevicesinc/libiio

[7] The MathWorks Inc, HDL Coder (R2024b). (2024). The MathWorks Inc., Natick, Massachusetts, United States. [Online]. Available: https://www.mathworks.com

[8] MathWorks, DVB-S2 HDL Transmitter. (2024). MATLAB. MathWorks. Accessed: Dec. 11, 2024. [Online].

[9] Unwanted emissions in the out-of-band domain, ITU, SM SM.1541-7, Sep. 2024.