Downlink System Design for the STRATHcube Satellite Mission

28 March 2025

Supervisor: Louise Crockett
Department of Electronic and Electrical Engineering
University of Strathclyde, Glasgow

Daniel Stebbings
reg. 202118874

I hereby declare that this work has not been submitted for any other degree/course at this University or any other institution and that, except where reference is made to the work of other authors, the material presented is original and entirely the result of my own work at the University of Strathclyde under the supervision of Louise Crockett.

Abstract

Contents

List of Figures

Definitions

STAC:	Spacecraft Tracking & Command Station
VHF:	Very High Frequency
UHF:	Ultra High Frequency
FE:	Front End
LVDS:	Low Voltage Differential Signalling
DVB-S2:	Digital Video Broadcasting - Satellite - Second Generation
ACM:	Adaptive Coding and Modulation
TS:	Transport Stream
XTCE:	XML Telemetric and Command Exchange
SDR:	Software Defined Radio
UPL:	User Packet Length
DFL:	Data Field Length
BBFRAME:	Baseband Frame
IQ:	In-phase and Quadrature
SPI:	Serial Peripheral Interface
PBR:	Passive Bistatic Radar
ISS:	International Space Station
COTS:	Commercial Off-The-Shelf
BCH:	Bose-Chaudhuri-Hocquenghem
LDPC:	Low-Density Parity-Check
FECFRAME:	Forward Error Correction Frame
PLFRAME:	Physical Layer Frame
FEC:	Forward Error Correction
SNR:	Signal to Noise Ratio
CNR:	Carrier to Noise Ratio
ITU:	International Telecommunication Union
PS:	Processing System
PL:	Programmable Logic
CCSDS:	Consultative Committee for Space Data Systems
ESA:	European Space Agency
FYS:	Fly Your Satellite
RF:	Radio Frequency
CCDD:	Core Flight System (CFS) Command and Data Dictionary
IPC:	Inter-Process Communication
SoC:	System on Chip
CRC-8:	8 bit Cyclic Redundancy Check
GSE:	Generic Stream Encapsulation
FIFO:	First In First Out
I2C:	Inter-Integrated Circuit
CAN:	Controller Area Network
IP:	Internet Protocol
PDR:	Preliminary Design Review
BER:	Bit Error Rate
FPGA:	Field Programmable Gate Array
ADC:	Analog to Digital Converter
DAC:	Digital to Analog Converter
ETSI:	European Telecommunications Standards Institute
VCM:	Variable Coding and Modulation
VL-SNR:	Very Low Signal-to-Noise Ratio
BPSK:	Binary Phase Shift Keying
PDU:	Protocol Data Unit
AWGN:	Additive White Gaussian Noise
RTL:	Register Transfer Level

1 Introduction

The objectives for this project were as follows

1. Reliability
2. Datarate
3.
4. Fit within resources available
5.

2 Literature Review

2.1 STRATHcube

Sporadic work has been completed for the downlink communications system in the previous years of the project. In TODO: a tradeoff study was conducted of the communications system. It identified the UHF amateur allocation in 435 - 438 MHz as suitable for uplink and downlink. A preliminary link budget was conducted using information about the STAC ground station and a radio module was selected.

The first radio selected was the GAUS Low Power UHF Radio which can use various frequency shift keying modes and convolutional codes for error correction. This has a stated max capacity of 250kbps, but per the datasheet this rating is not currently supported leaving the actual maximum rate of 100kbps. Additionally, the datasheet also states that Reed Solomon coding is supported, whilst also stating that it is not *currently* supported in a footnote. Additionally, the coding rates for which the datarate values are calculated are not available.

In TODO: another tradeoff study was conducted for the primary payload system, ultimately selecting the TOTEM SDR from Alen Space. Alen Space also manufacture a UHF Front End (FE) compatible with the TOTEM SDR, for this reason it was decided to consolidate both the primary telecommunications and primary payload onto the TOTEM SDR in order to reduce component count and project cost. The full specification and operation of the TOTEM SDR is defined in Section 2.2.

UHF communications will be transmitted using the ISIS deployable antenna system configured with a single deployable dipole antenna. The exact specifications are selectable by the user, being rated for 10 MHz of usable bandwidth at design frequency and a VSWR < 1.9:1.

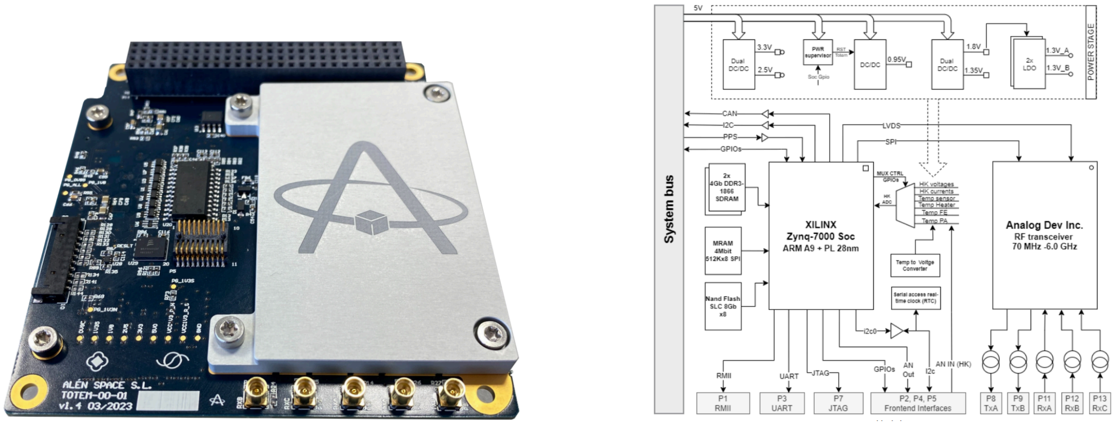
A member of the team completed a research internship analysing the downlink in summer 2024. This analysis compared multiple types of modulation and Forward Error Correction (FEC), ultimately recommending Digital Video Broadcasting - Satellite - Second Generation (DVB-S2) for the final system. It also analysed the maximum bandwidth for the link to close, i.e. to have a positive link margin, arriving at a figure of 158.5 kHz. The resulting link budget is shown in Table 1. With the ground station undefined, many of the performance figures were based on the link budget created by AcubeSAT, [1] an open source satellite mission

Table 1: Summer 2024 Link Budget

Spacecraft		
Transmit Power	1.76	dBW
Transmitter Gain	0	dBi
Transmitter Line Losses	−1.93	dB
Transmitter Antenna Pointing Loss	−3	dB
EIRP	−3.17	dBW
Link		
Frequency	435	MHz
Bandwidth (Max Achievable)	158.5	kHz
Path Length (409 km Altitude, 15° Elevation)	1196.622	km
Free Space Path Loss	−146.777	dB
Other Losses (Atmospheric, Polarisation, …)	−4.6	dB
Ground Station		
Received Incident Power	−154.61	dBW
Receiver Gain	12	dB
Receiver Line Losses	−2.4	dB
Receiver System Noise Temperature	249.3	K
Receiver Sensitivity	−11.97	dB-K
Implementation Loss	−2	dB
Received CN0R	62.03	dB
Received CNR	12.025	dB
Required CNR	−10	dB
Link Margin	2.025	dB

2.2 TOTEM SDR

The TOTEM SDR consists of an AMD Zynq 7020 System on Chip (SoC) Field Programmable Gate Array (FPGA) connected to an AD9364 RF Transceiver via Low Voltage Differential Signalling (LVDS), as shown in Figure 1b. Compatible frontend modules can be mounted on the motherboard using the connector in the center of the board, which can be seen in Figure 1a.



(a) Motherboard (b) Block Diagram

Figure 1: TOTEM SDR

The Zynq 7020 has dual ARM Cortex-A9 processor cores that form the Processing System (PS) and FPGA fabric that forms the Programmable Logic (PL). This allows improved performance, as serial operations such as network interfacing can be accomplished on the PS and highly parallel operations such as signal processing can be accomplished on the PL. The Zynq

The AD9364 is a high performance RF transceiver with separate ports for receive and transmit. It can operate from 70 MHz to 6 GHz and has a bandwidth of up to 56 MHz with a 12 bit Analog to Digital Converter (ADC) and Digital to Analog Converter (DAC). A Serial Peripheral Interface (SPI) bus is used for control signals and a high speed LVDS interface for In-phase and Quadrature (IQ) data. This device is part of the larger family of AD936x transceivers form Analog Devices. The chips in this family differ in port count, bandwidth, and operating frequency, however the control interfaces are very similar across devices. For this reason, many software drivers and FPGA IPs work with multiple devices in the family.

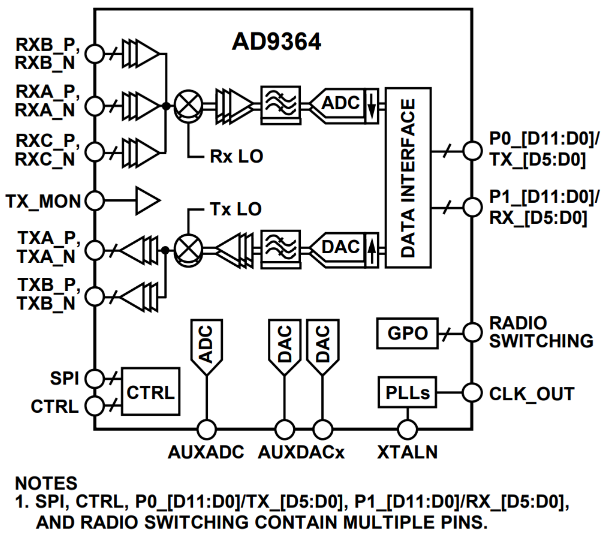
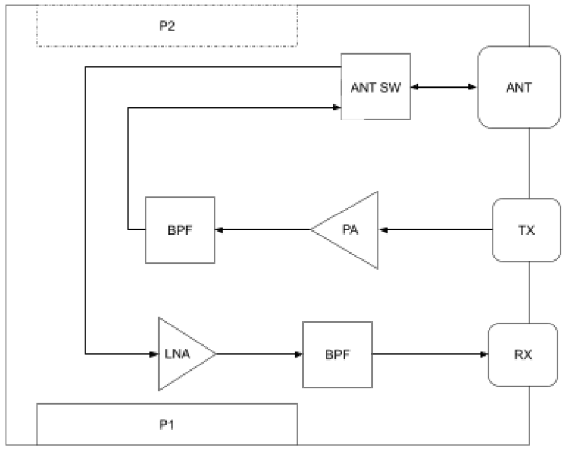


Figure 2: AD9364 Functional Block Diagram

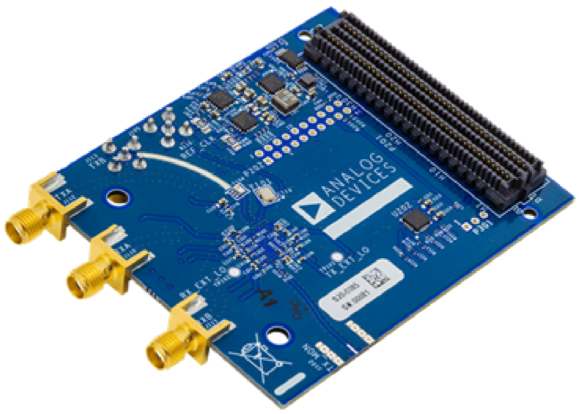
The frontend module is called FrontendUHF, and includes a transmit / receive switch, bandpass filtering and amplification for both transmit and recieve. It has a frequency range of 430 to 440 MHz and a typical power output of 30dBm. Figure 3 depicts the module and a block diagram of its operation.

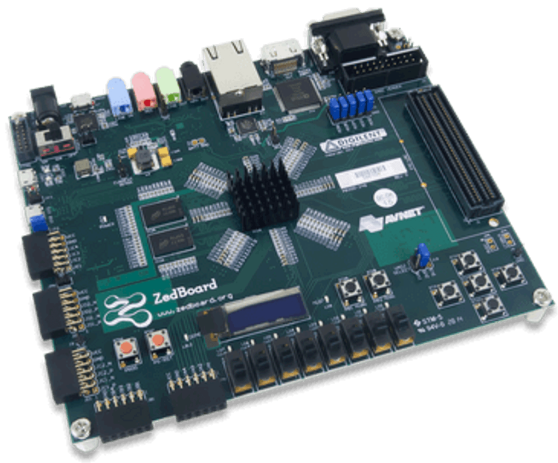


(a) FrontendUHF module (b) FrontendUHF Block Diagram

Figure 3: FrontendUHF

As the TOTEM SDR could not be purchased in time for the project, implementation was targeted towards development boards. The Digilent Zedboard is a Zynq 7020 development board with much less external RAM than the TOTEM, however it has the same FPGA resources. The Zedboard also includes an FPC connector, allowing the connection of high speed peripherals. This can be used to connect an FMCOMMS development board from Analog Devices, one of which is available for the AD9364 used in the TOTEM. As the control interfaces are the same, another FMCOMMS board from the AD936x family can be used for functional testing without changing the design.





(a) FMCOMMS4 (b) Zedboard

Figure 4: Development Boards

2.3 STAC Ground Station

The Spacecraft Tracking & Command Station (STAC) ground station was first created in 2008 and resides on the roof of the James Weir building at the University of Strathlycde. After a fire in the building, the project was abandoned in 2012. In 2015/2016, a master's group renovated the STAC and were successful in receiving telemetry from the Strand-1 CubeSat. The station has since been out of use and has not been maintained, as such, the current status of the components is unknown.

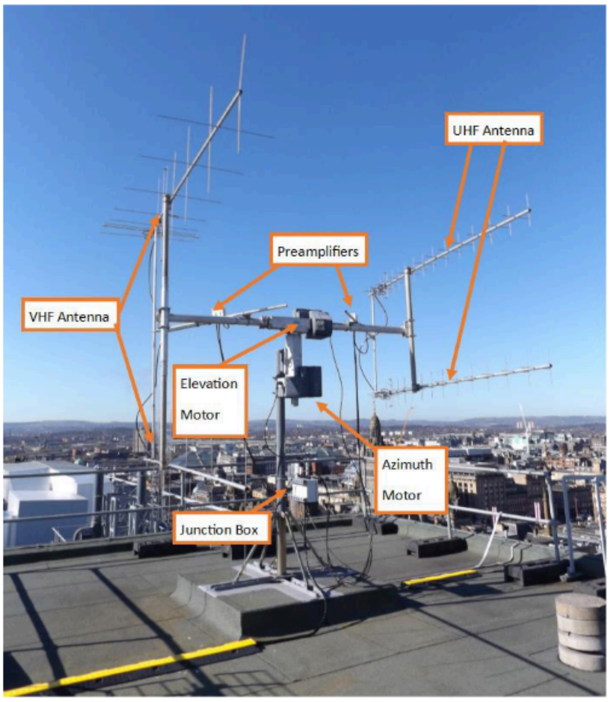


Figure 5: STAC After 2016 Renovation

The STAC has dual Very High Frequency (VHF) and Ultra High Frequency (UHF) antennas and includes pre-amplifiers suitable for both receive and transmit. The UHF antennas are the 436CP30 from M2 Antenna Systems and the UHF pre-amplifier is the SP-7000 from SSB. The details of which are shown in Table 2 and Table 3 respectively.

Table 2: SP7000 Specification

Frequency Range	430-440 MHz
Noise Figure	0.9 dB
Maximum Gain	20 dB

Table 3: 436CP0 Antenna Specification

Frequency Range	432-440 MHz
Gain	15.50 dBic
Beamwidth	30 $^{\circ}$
Max VSWR	1.6:1

As part of the 2015/2016 renovation, a link budget was created for reception of communications from the Strand-1 satellite. Table 4 shows the original numbers, with the “Unit” column subsequently added for context.

Table 4: STAC Strand-1 UHF Downlink Link Budget

Parameter	20 Degrees	90 Degrees	Unit
Frequency	4.40E+08	4.40E+08	Hz
Speed	3.00E+08	3.00E+08	m/s
Wavelength	2.06	2.06	m
Transmitted Power	0.5	0.5	W
Transmitter Gain	1	1	dB
Line Loss	−3	−3	dB
EIRP	−1.5	−1.5	dBW
Path Length	3253000	811000	m
Space Loss	−136.5	−123.5	dB
Antenna Pointing Loss	−0.7	−0.7	dB
Polarization Loss	−0.3	−0.3	dB
Receiver Gain	10.2	10.2	dB
System Noise Temperature	19.03089987	19.03089987	K
Data Rate	9600	9600	bps
Boltzmann's Constant	228.6	228.6	dB
Bit Energy to Noise Ratio	16.88	28.95	dB
Miscellaneous	−25	−25	dB
Required Energy to Noise Ratio	10	10	dB
Margin	6.88	18.95	dB

2.4 Standards

2.4.1 DVB-S2 Overview

DVB-S2 utilises two stages of FEC, the first code is Bose-Chaudhuri-Hocquenghem (BCH) followed by Low-Density Parity-Check (LDPC). This combination results in extremely strong error correction performance, allowing near Shannon limit performance.

ETSI released an extension to the original DVB-S2 standard called DVB-S2X, this included several features to improve efficiency for high throughput satellites, such as bonding multiple transponders, beam hopping, and high order modulations up to 256APSK. Particularly relevant, are the new features for Very Low Signal-to-Noise Ratio (VL-SNR), which include new Physical Layer Frame (PLFRAME) structures, Binary Phase Shift Keying (BPSK) modulation, and lower coding rates down to 1/5. Features were also added to improve the efficiency of Generic Stream Encapsulation (GSE) packet transmission.

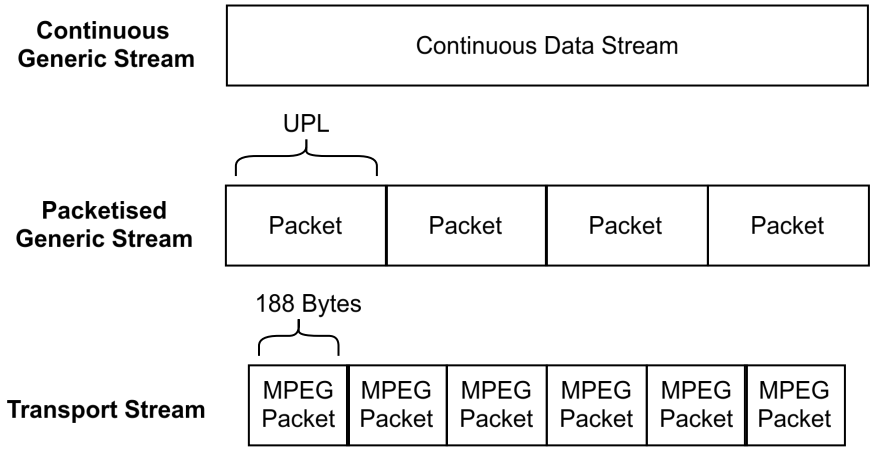
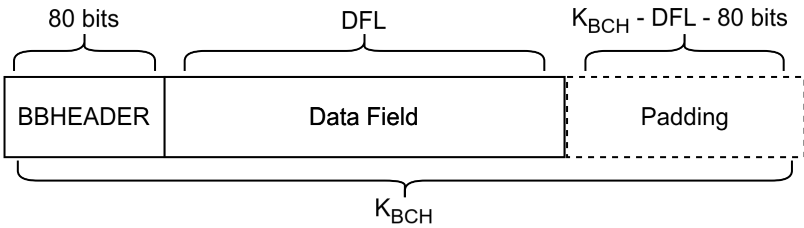
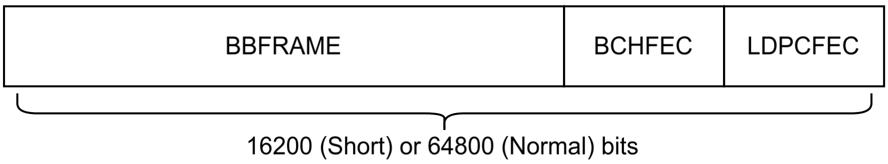


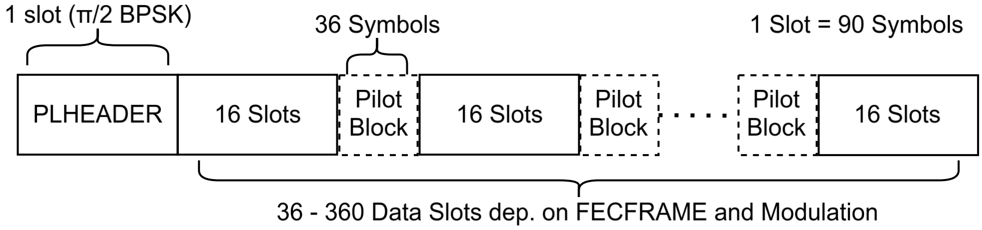
Figure 6: DVB-S2 Input Stream Types



(a) BBFRAME



(b) FECFRAME



(c) PLFRAME

Figure 7: DVB-S2 Frame Structures

2.4.2 CCSDS

2.5 Interference

Interference is particularly prevalent in the UHF amateur band. In [2]

In [3] the effect of narrowband continuous wave interference was investigated for DVB-S2 QPSK communications and an adaptive notch filter designed. Figure 10 [3, Fig. 27] shows the effect on BER of a Jamming to Signal Ratio (JSR) of just −6dB. Without filtering, and at low Eb/N0 values, the recovery is significantly degraded however the filter is able to improve performance to close to that of the theoretical peak. The paper also notes that the filter could reduce performance in certain scenarios.

3 ACM Analysis

The link budget was then reassessed and updated to identify varying parameters and to reflect the impact of ACM. It has also been updated to reflect the information obtained regarding the STAC ground station [4]. The current operation of the STAC is unknown, as such component values and performance figures are to be confirmed.

3.1 System Definitions

Table 5: Static Parameters

Name	Value	Source
System		
Frequency (f)	437 MHz	Centre of UHF Amateur Satellite Service Allocation
Bandwidth (B)	150 kHz	
STRATHCube		
Transmit Power (P_{Tx})	1W	TOTEM UHF FE Limit, [5]
Cable Losses (L_{Cable})	0.116 dB	20cm RG-188/AU, AcubeSAT
VSWR	1.9 : 1	ISIS Antenna Datasheet [6]
Antenna Reflection Loss ($L_{\text{Reflection}}$)	0.44 dB	Equation 1, AcubeSAT
Connector Losses ($L_{\text{Connector}}$)	0.2 dB	4 Connectors @ 0.05dB, AcubeSAT
Switch Losses (L_{Switch})	0.5 dB	AcubeSAT, included specutalively
Total Line Losses (L_{Line})	1.26 dB	Equation 2
Transmit Antenna Gain (G_{Tx})	0 dBi	ISIS Antenna Datasheet [6]
EIRP	**0.50 dBW**	Equation 3
Ground Station		
Receive Antenna Gain (G_{Rx})	**14.15 dBi**	STAC UHF Antenna [4]
LNA Gain (G_{LNA})	20 dB	SP-7000 Datasheet, STAC [7]
Line Losses	2.39 dB	AcubeSAT
Ground Station Noise Temperature		
Reference (T_{Ref})	290K	Standard Value, [8, Sec. 5.5.2]
Antenna / Sky (T_{Ant})	154K	AcubeSAT
Feedline (T_{Feed})	290K	AcubeSAT
LNA Noise Figure (N_{LNA})	0.9 dB	SP-7000 Datasheet [7], STAC
LNA (T_{LNA})	66.8K	Equation 5
Frontend Noise Figure	8 dB	USRP B210 Maximum [9]
Frontend (T_{FE})	1539.8K	Equation 5
Cable Loss (L_{Cable})	1.023 dB	AcubeSAT

Name	Value	Source
Transmission Line Coefficient (α)	0.6331	AcubeSAT
Receiver Noise Temperature (T_{Rx})	**282.7K**	Equation 4
Atmospheric Path Losses		
Scintillation ($L_{\text{Scint,dB}}$)	0.16 dB	AcubeSAT
Rain Fade ($L_{\text{Rain,dB}}$)	0 dB	Assumed as negligible in UHF
Ionospheric ($L_{\text{Ion,dB}}$)	0.4 dB	AcubeSAT
Polarisation ($L_{\text{Pol,dB}}$)	3 dB	
AEL	**3.56 dB**	Equation 6

Table 6: Dynamic Parameters

Name	Adverse	Nominal	Favourable	Source(s)
Elevation	10°	20°	40°	Section 3.2.3
Atmospheric Absorption (L_{Atm})	2.1 dB	1.1 dB	0.4 dB	AcubeSAT
Slant Range	Calculated / Scenario			Equation 7
FSPL	Calculated / Scenario			Equation 9
CNR	Calculated / Scenario			Equation 10
CNR Margin	Calculated / Scenario			Equation 11

3.2 Methodology

3.2.1 Link Budget

Reflection loss can be calculated as follows: [1]

$$\begin{aligned} L_{\text{Reflection,W}} &= P_{\text{Tx,W}} \times \frac{(\text{VSWR}-1)^2}{(\text{VSWR}+1)^2}[\text{W}] \\ L_{\text{Reflection,dB}} &= 10 \times \log_{10}\left(\frac{P_{\text{Tx,W}} - L_{\text{Reflection,W}}}{P_{\text{Tx,W}}}\right)[\text{dB}] \end{aligned} \quad (1)$$

The Transmitter total line losses are calculated as follows:

$$L_{\text{Line,dB}} = L_{\text{Cable,dB}} + L_{\text{Reflection,dB}} + L_{\text{Connectors,dB}} + L_{\text{Switch,dB}}[\text{dB}] \quad (2)$$

EIRP:

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

Receiver noise temperature: [1]

$$T_{\text{Rx}} = \alpha \times T_{\text{Ant}} + (1-\alpha) \times T_{\text{Feed}} + \frac{T_{\text{FE}} \times L_{\text{Cable}}}{G_{\text{LNA}}}[K] \quad (4)$$

Noise figure can be converted to noise temperature as follows: [8, eq. 5.28]

$$T = T_{\mathrm{Ref}}\left(10^{\frac{F_{\mathrm{dB}}}{10}} - 1\right) \tag{5}$$

Atmospheric Effect Loss and Atmospheric Path Loss:

$$\mathrm{AEL}_{\mathrm{dB}} = L_{\mathrm{Scint,dB}} + L_{\mathrm{Rain,dB}} + L_{\mathrm{Ion,dB}} + L_{\mathrm{Pol,dB}}[\mathrm{dB}] \tag{6}$$

$$\mathrm{APL}_{\mathrm{dB}} = \mathrm{AEL}_{\mathrm{dB}} + L_{\mathrm{Atm,dB}}[\mathrm{dB}] \tag{7}$$

Slant Range: [10]

$$\begin{gathered} \mathrm{SR} = \sqrt{R^2 + (R+H)^2 - 2 \times R \times (R+H) \times \cos(\theta)} \\ \text{Where :} \\ R = \text{Earth Radius} + \text{Ground Station Altitude} \\ H = \text{Satellite Altitude} - \text{Ground Station Altitude} \\ \alpha = \text{Satellite Elevation Angle} \\ \theta = \arccos\left(\frac{R - R\sin^2(\alpha) + \sin(\alpha)\sqrt{(R\sin(\alpha))^2 + H^2 + 2RH}}{R+H}\right) \end{gathered} \tag{8}$$

Free Space Path Loss: [8, eq. 5.10]

$$\mathrm{FSPL} = 20\log_{10}\left(\frac{4\pi d f}{c}\right)[\mathrm{dB}] \tag{9}$$

Received CNR:

$$\mathrm{CNR}_{\mathrm{Rx}} = \mathrm{EIRP} - \mathrm{FSPL} - \mathrm{APL} + G_{\mathrm{Rx}} + 228.6 - 10\log_{10}(T_{\mathrm{Rx}}) - 10\log_{10}(B)[\mathrm{dB}] \tag{10}$$

Link Margin:

$$\mathrm{Margin} = \mathrm{CNR}_{\mathrm{Rx}} - \mathrm{CNR}_{\mathrm{Required}}[\mathrm{dB}] \tag{11}$$

3.2.2 Required CNR by Modulation and Coding Rate

Values for spectral efficiency and minimum $\frac{E_s}{N_0}$ are provided in [11, Tab. 13]. Those values are derived from simulation of a DVB-S2 system with 50 LDPC decoding iterations, 64,800 bit FECFRAME, no pilots, perfect carrier and synchronization recovery, no phase noise and an AWGN channel. The system shall include pilots to improve decoding performance, the spectral efficiency of which was obtained from [12, Tab. 3-1]. As such, the actual minimum $\frac{E_s}{N_0}$ will be lower, adding further margin under AWGN conditions.

Interference, demodulation and phase noise effects are still to be analysed, which will reduce the calculated link margin. For this reason a margin target of 10dB was selected.

Additionally, it was assumed that perfect filtering is in place and thus that the total system spectral efficiency is equal to that of the theoretical value for the modulation and coding rate. With that assumption, Equation 12 and Equation 13 were used to create Table 7.

$$\frac{E_s}{N_0} = \frac{C}{N}[\text{dB}] \tag{12}$$

$$\text{Capacity} = \eta \times B[\text{bps}] \tag{13}$$

Table 7: DVB-S2 Modulation and Coding Rate Requirements, 150kHz Bandwidth,

Bits / Symbol	**Modulation**	**Coding Rate**	**Spectral Efficiency (bps/Hz)**	**Data Rate (bps)**	**Minimum CNR (dB)**	**Minimum CNR w. 10dB Margin (dB)**
4	QPSK	1/4	0.4786	75860	-2.35	7.65
4	QPSK	1/3	0.6408	101600	-1.24	8.76
4	QPSK	2/5	0.7706	122100	-0.3	9.7
4	QPSK	1/2	0.9653	153000	1	11
4	QPSK	3/5	1.16	183900	2.23	12.23
4	QPSK	2/3	1.291	204600	3.1	13.1
4	QPSK	3/4	1.452	230200	4.03	14.03
4	QPSK	4/5	1.549	245600	4.68	14.68
4	QPSK	5/6	1.615	256000	5.18	15.18
4	QPSK	8/9	1.724	273300	6.2	16.2
4	QPSK	9/10	1.746	276700	6.42	16.42
8	8PSK	3/5	1.74	275700	5.5	15.5
8	8PSK	2/3	1.936	306800	6.62	16.62
8	8PSK	3/4	2.178	345100	7.91	17.91
8	8PSK	5/6	2.422	383900	9.35	19.35
8	8PSK	8/9	2.586	409900	10.69	20.69
8	8PSK	9/10	2.618	415000	10.98	20.98
16	16APSK	2/3	2.575	408100	8.97	18.97
16	16APSK	3/4	2.896	459100	10.21	20.21
16	16APSK	4/5	3.091	489800	11.03	21.03
16	16APSK	5/6	3.222	510700	11.61	21.61
16	16APSK	8/9	3.44	545200	12.89	22.89
16	16APSK	9/10	3.483	552000	13.13	23.13
32	32APSK	3/4	3.623	574300	12.73	22.73
32	32APSK	4/5	3.866	612800	13.64	23.64
32	32APSK	5/6	4.031	638900	14.28	24.28
32	32APSK	8/9	4.303	682000	15.69	25.69
32	32APSK	9/10	4.357	690600	16.05	26.05

3.2.3 Adaptive Coding and Modulation Analysis

An initial proof of concept investigation was conducted to determine if implementation of ACM is worth the increased complexity. This investigation assumed a fixed orbit altitude of 409km and used ISS TLE data to propagate this for the full mission length of 180 days. Orbit propagation was conducted using the MATLAB Satellite Communications Toolbox [13] Satellite Scenario and Access objects.

Using the system parameters defined in Section 3.1, the equations defined in Section 3.2.1, and the required CNR values defined in Table 7, the max achievable data rate was precomputed for each elevation value from 0 to 90° in 5° increments for both 170km and 409km altitude orbits, the resulting rates shown are in Figure 8.

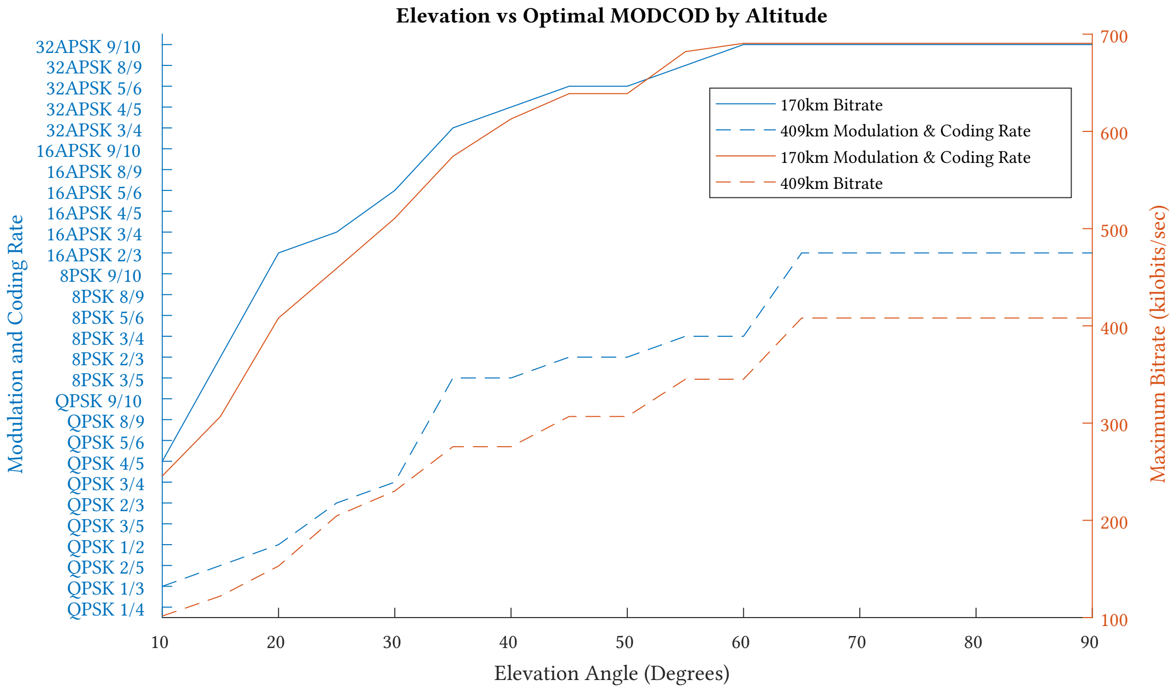


Figure 8: Elevation vs Throughput

To improve performance, the simulation is run with two timesteps. First, a coarse search is run with a timestep of 100 seconds and the accessIntervals() function used to find the starting time of each ground station pass. Then, a fine search using a timestep of 1 second is used to find the elevation of the satellite over time during each pass.

The simulated elevation angles were then binned with values rounded down to the nearest multiple of 5. A histogram of the binned elevation angles versus the time spent within each elevation bin was then created. This was then multipled by the corresponding values in Figure 8 to obtain an estimate of the total data downlinked over the course of the mission using ACM. For CCM it was assumed that the capacity value corresponding to 10° elevation was used for the entire mission. The resulting plots are shown in Figure 9.

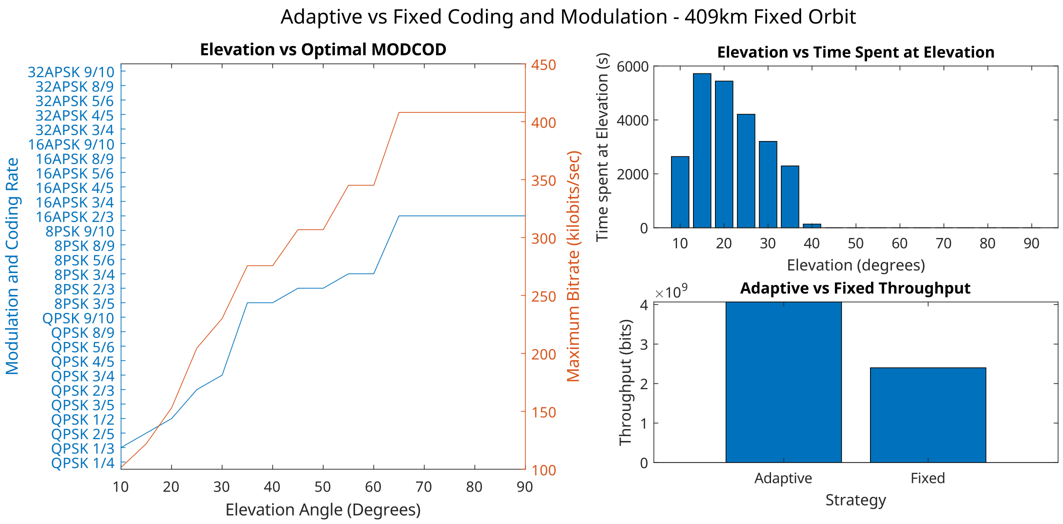


Figure 9: ACM Performance Analysis

3.3 Scenarios

Current analysis has been restricted to link budgets based on elevation relative to ground station and satellite altitude as the impact of FSPL is dominant over most other factors. Additionally, the impact of component degradation is yet to be investigated and is to be determined. The scenarios were selected such that they represent the best and worst case for FSPL using the STAC ground station over the expected lifetime, with orbital parameters

3.3.1 Commisioning Phase

STRATHcube shortly after deployment from the international space station.

Table 8: STRATHcube Commissioning Phase Budget

Name	Adverse	Nominal	Favourable
Altitude	409km		
Slant Range	1463km	1001km	611km
FSPL	148.5 dB	145.2 dB	140.9 dB
CNR	10.9 dB	14.1 dB	19.1 dB
Highest Achievable MODCOD w. 10dB Margin	QPSK 2/5	8PSK 3/5	16PSK 3/4
CNR Required	−0.3 dB	4.0 dB	9.0 dB
Bitrate	115.6 kbps	217.8 kbps	386.2 kbps

3.3.2 Transition Phase

STRATHcube at end of primary phase.

Table 9: STRATHcube Transition Phase Budget

Name	Adverse	Nominal	Favourable
Altitude	170km		
Slant Range	743km	456km	260km
FSPL	142.7 dB	138.4 dB	133.5 dB
CNR	16.1 dB	20.4 dB	26.0 dB
Highest Achievable MODCOD w. 10dB Margin	8PSK 2/3	16APSK 3/4	32APSK 9/10
CNR Required	6.62 dB	10.21 dB	16.05 dB
Bitrate	290.4 kbps	434.5 kbps	653.5 kbps

3.4 Areas for Further Investigation

Thusfar the downlink link budget has been concerned with proving viability and performance limits for development of the transmitter system. As such, there has been comparatively less investigation of the receiver system and there has been a large reliance on numbers derived from the AcubeSAT link budget. There are multiple key challenges for implementing a DVB-S2 receiver, the largest issue being interference, which can be prevalent on the planned UHF band [2], another being carrier synchronisation and phase correction.

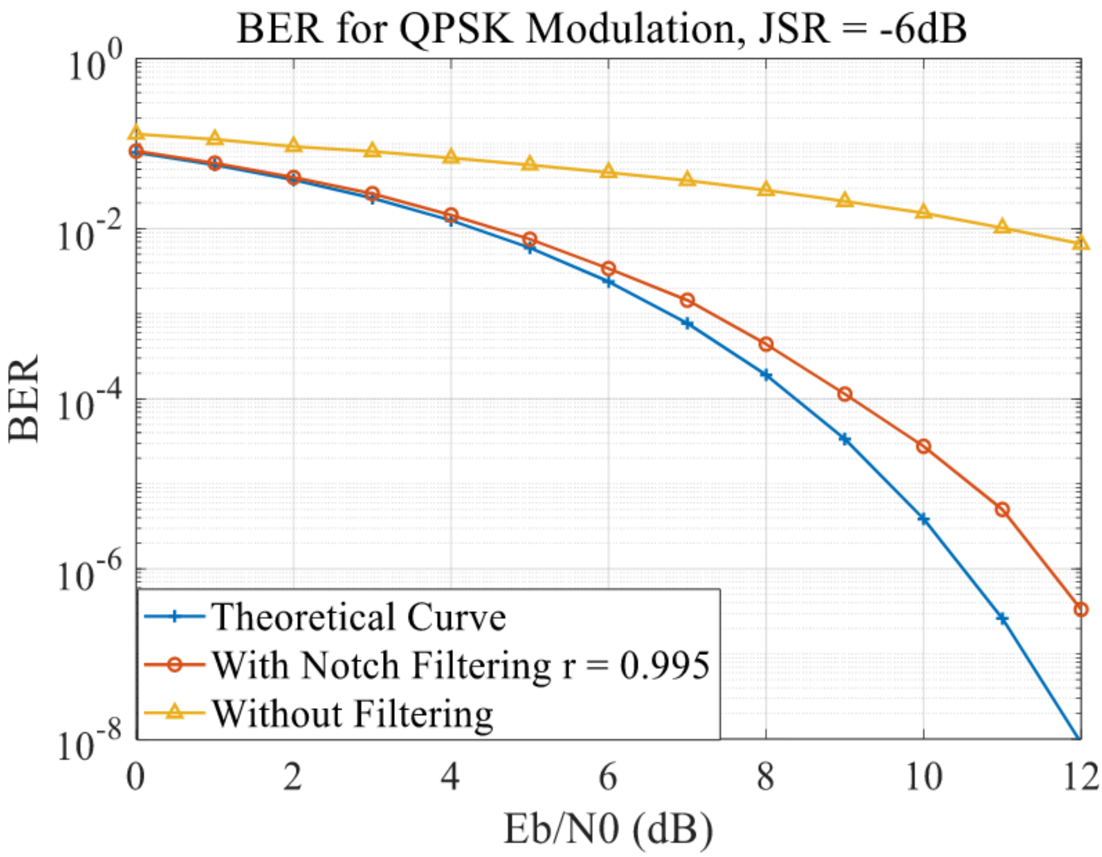


Figure 10: Impact of interference on DVB-S2 QPSK signal reception.

4 System Design

4.1 Systems Engineering

4.2 Transmitter

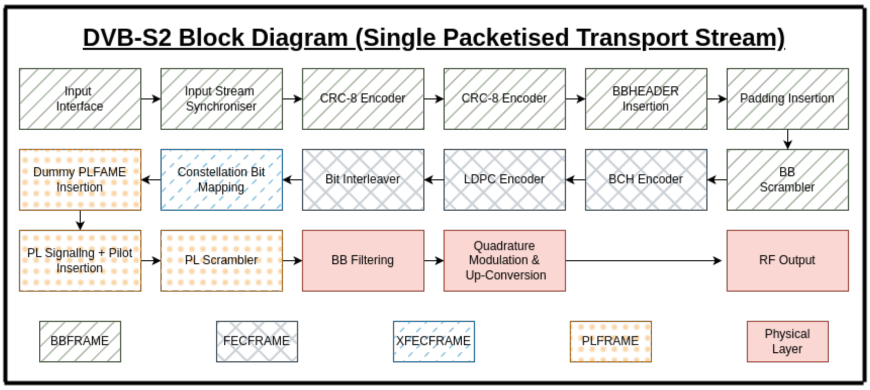


Figure 11: Transmitter Block Diagram

4.3 Packet Handling

4.4 Full System

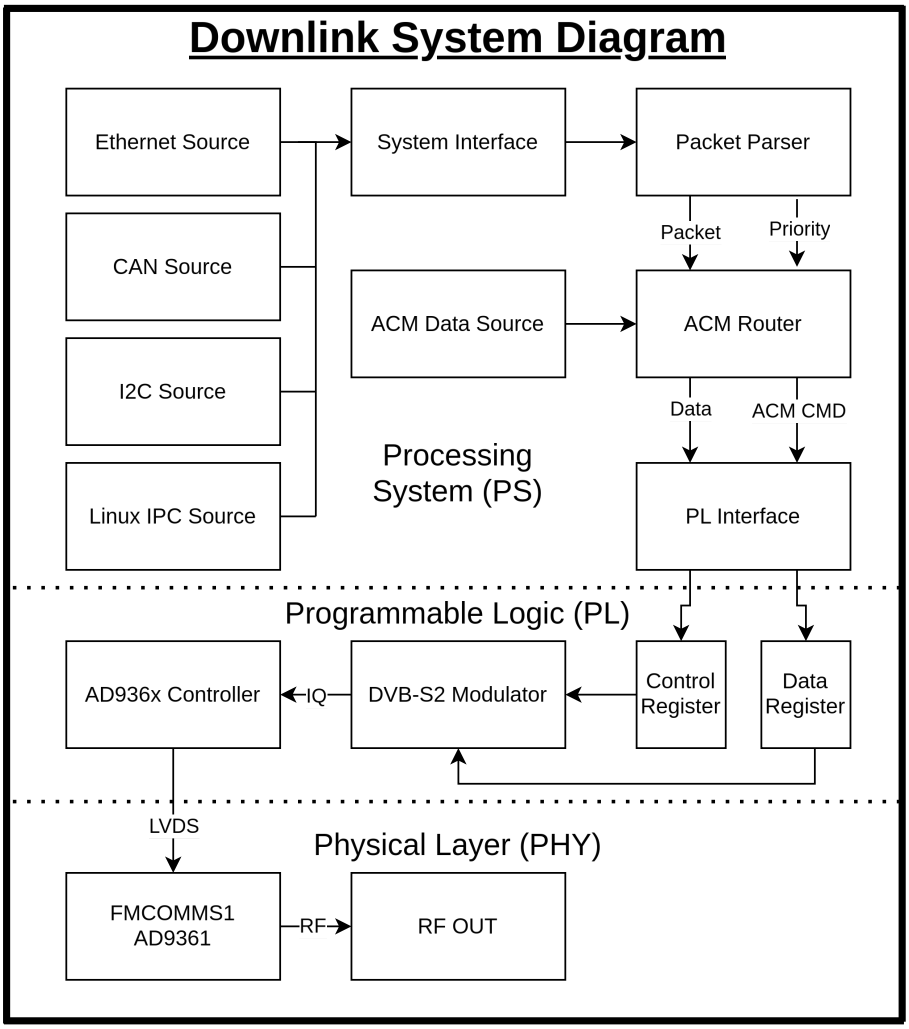


Figure 12: System Diagram

5 Implementation

5.1 Transmitter

5.1.1 Tool Selection

There were multiple options for implementation of the DVB-S2 subsytem.

Table 10: Implementation Tool Tradeoff

Method	Advantage	Disadvantage
GNU Radio software implementation	Simplicity of implementation	Processing speed
COTS IP Core	Reliability	Expensive
Vitis Model Composer	Simplicity of implementation	
MATLAB HDL Coder	Specific Support from Analog Devices	Resource efficiency

1.
2. Scratch implementation in Register Transfer Level (RTL) code.
3. Use of off-the-shelf DVB-S2 IP core
4. MATLAB HDL Coder
5. Vitis Model Composer or System Generator

5.1.2 DVB-S2 Modulation

The core of the design is built upon a DVB-S2 HDL coder example created by Mathworks.

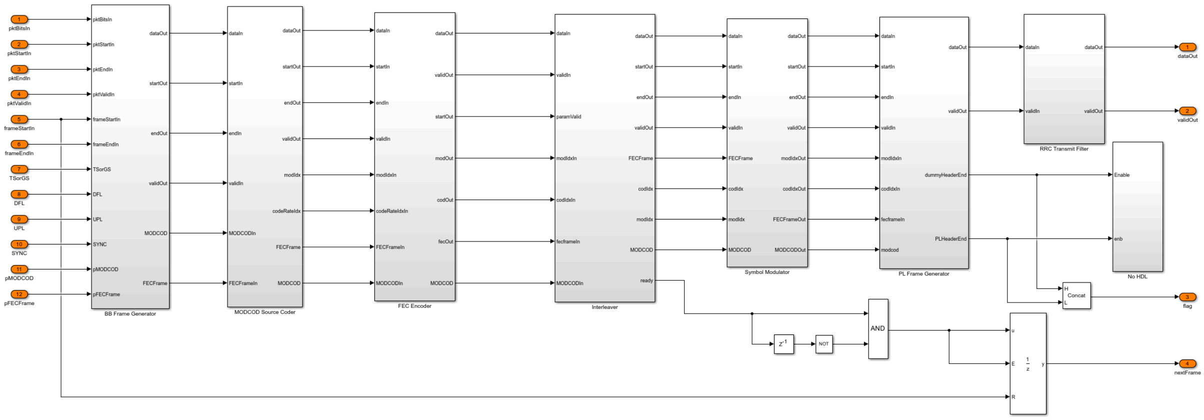


Figure 13: DVB-S2 HDL Transmitter MATLAB Example Design

Table 11: AXI-Stream Minimal Signals

Port	Type	Purpose
pktBitsIn	Boolean Stream	
pktStartIn	Boolean	
pktEndIn	Boolean	
pktValidIn	Boolean	
frameStartIn	Boolean	
frameEndIn	Boolean	
TSorGS	ufix2	
DFL	uint16	
UPL	uint16	
SYNC	uint8	
pMODCOD	ufix5	
pFECFRAME	boolean	

5.1.3 Transceiver Integration

This then needed to interface with the rest of the system. It was decided to use the HW/SW Codesign features of HDL Coder to generate IIO bindings for the software to hook into. Support for Zedboard and FMCOMMS is provided by a support package. A MATLAB Example provided the interface that was then used to implement the final design.

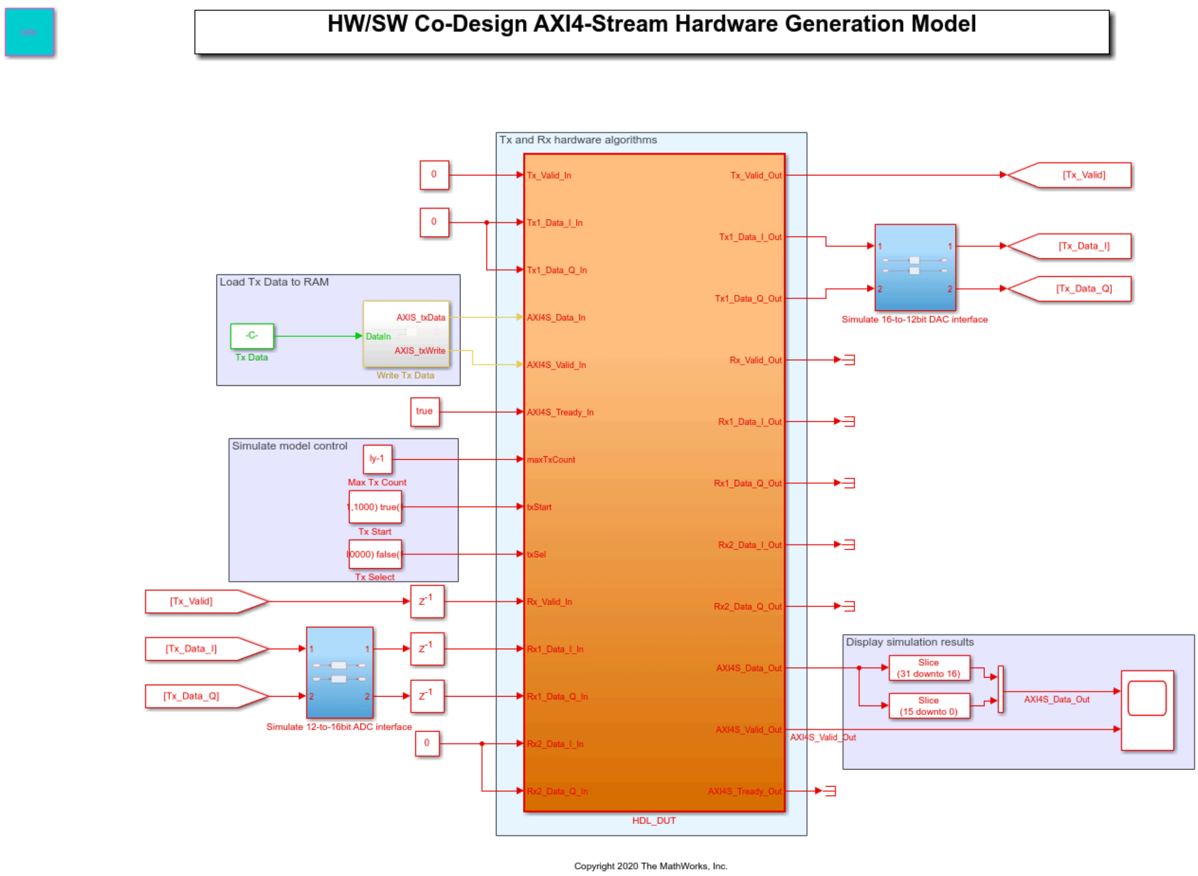


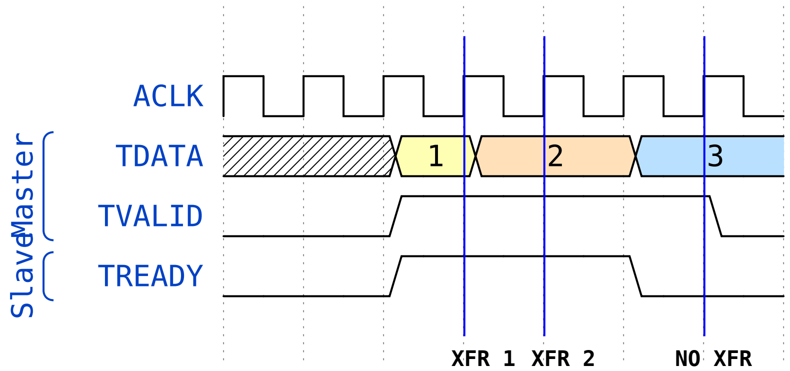
Figure 14: HW/SW Codesign Chirp Example

The provided example supports both the transmit and receive paths for the AD936x transceiver. This offers the possibility of implementing both the PBR processing and downlink communications using the same block design.

Data is transferred from the PS via one of two methods. AXI-lite interfaces are used for control signals, as they have lower throughput, this was used for all control signals, such as Data Field Length (DFL), User Packet Length (UPL), etc. An AXI-Stream was used to transfer packet data, as it has a much higher throughput.

Table 12: AXI-Stream Minimal Signals

Signal	Type	Purpose
TData	uint32	Data to be transferred from master to slave
TValid	boolean	Indication from master to slave that data is valid and can be read
TReady	boolean	Indication from slave to master that it is ready for new data
TLast	boolean	Indication from master to slave that the current packet is the last in the current stream



Listing 1: AXI-Stream Timing

The DVB-S2 design used requires sideband signals to indicate the start and end of a frame or packet. Additionally, due to the use of HDL Coder, the implementation of TUser sidebands was deemed to be infeasible. Unlike the other control signals, these require a high level of synchronisation with the data stream, necessitating their inclusion within the 32 bit TData.

The remaining 28 bits could then be used to carry the packet data. No DFL size was evenly divisible by 28, giving two avenues for implementation. The first option was to implement a signalling system within the TDATA field allowing for a variable amount of packet bits within each TDATA field. The second was to find the largest number that factored all possible DFL sizes and accept the lower performance.

All DFL sizes were factorised, giving a maximum size of 8 bits. AXI-Streams can transfer data much faster than the resultant symbols could be transmitted, so it was decided to accept the performance loss of using a subset of the TDATA field.

Table 13: Possible DFL Sizes (bits)

Normal FECFRAME	15928, 21328, 25648, 32128, 38608, 42960, 48328, 51568, 53760, 57392, 58112
Short FECFRAME	2992, 5152, 6232, 6952, 9472, 10552, 11632, 12352, 13072, 14152

Bits	0	1	2	3	4:31
Signal	Packet Start	Packet End	Frame Start	Frame End	Data

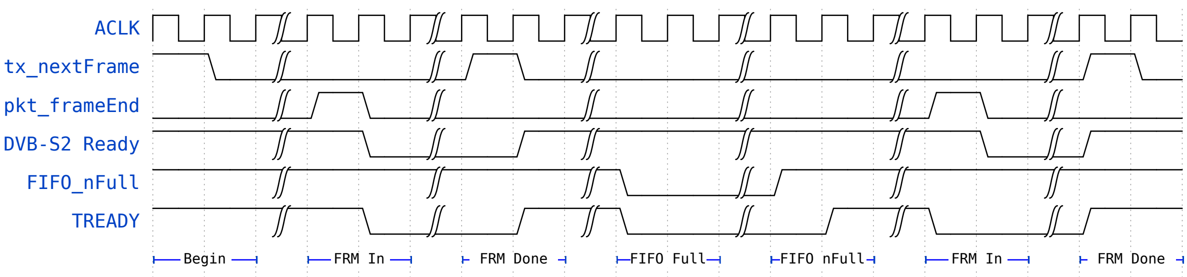
(a) AXI Packet With Sidebands

Bits	0	1	2	3	4:11	12:31
Signal	Packet Start	Packet End	Frame Start	Frame End	Data	Unused

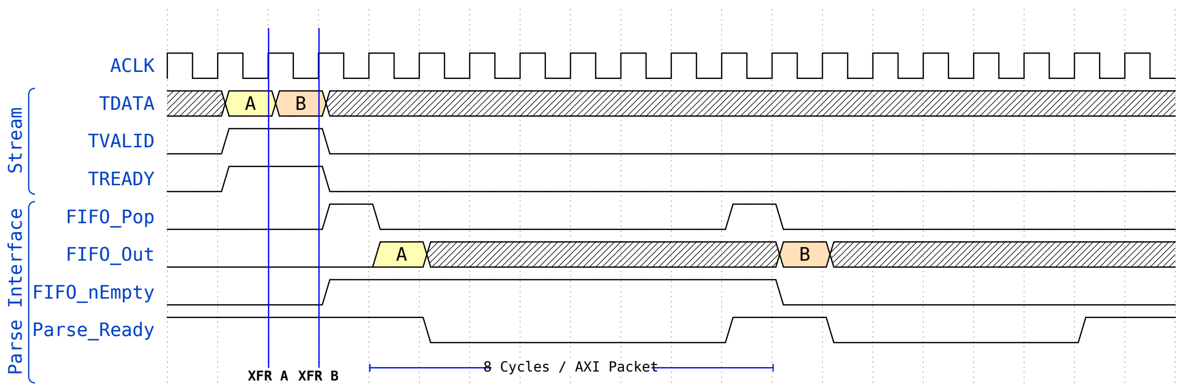
(b) AXI Packet Final Structure

Figure 15: AXI Packet Structure

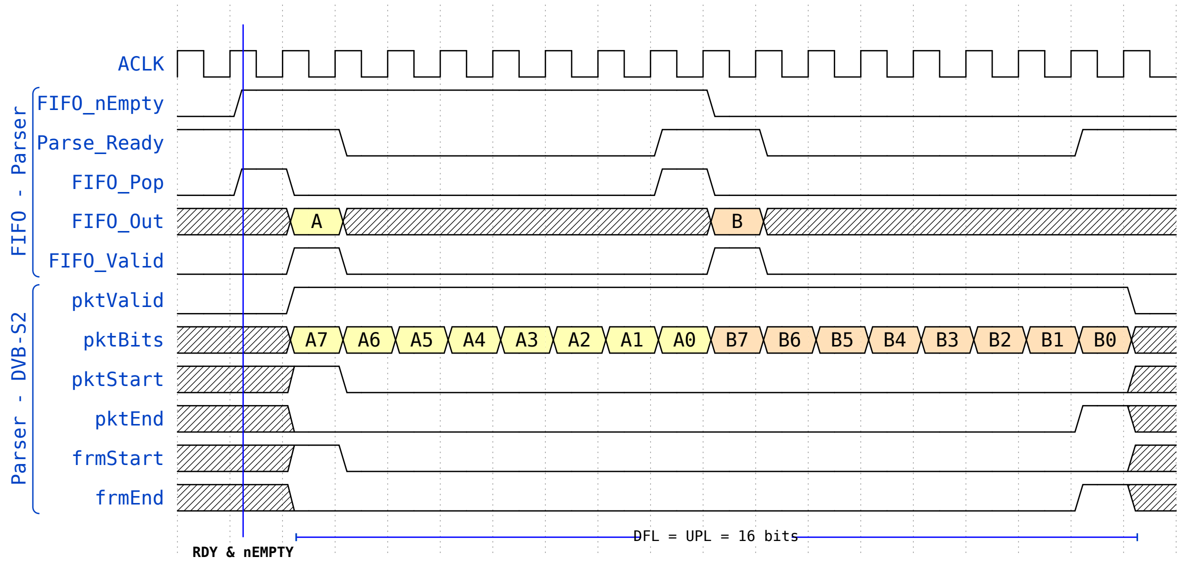
The AXI packets contain the start and end signals, as well as a byte of packet data in a parallel format. This must be serialised into a bitstream to interface with the DVB-S2 modulation block.



Listing 2: AXI-Stream TReady Timing



Listing 3: FIFO Timing

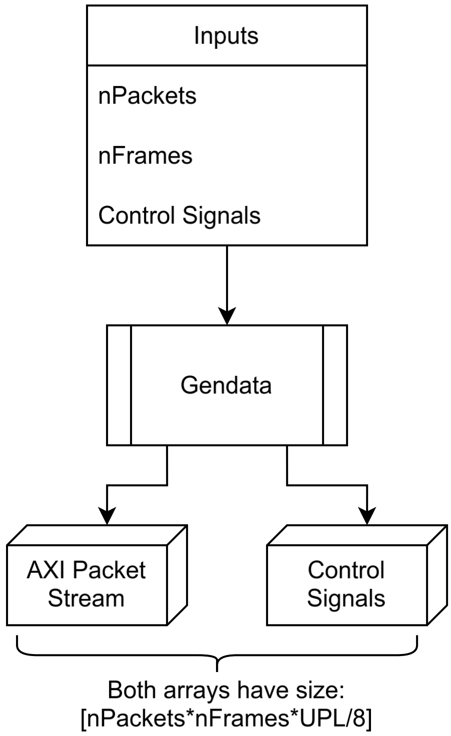


Listing 4: Parser Timing

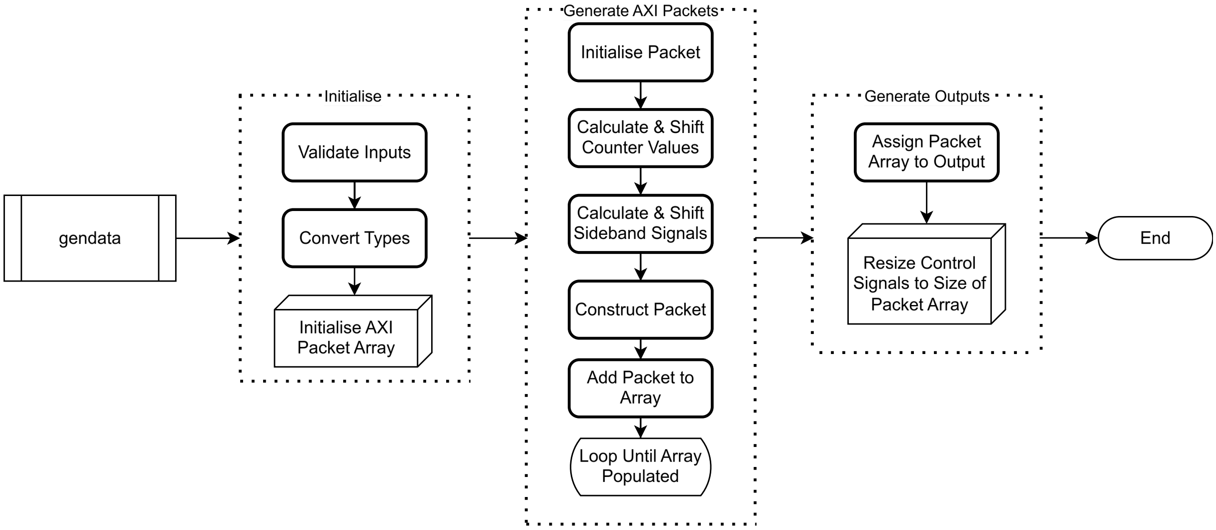
5.2 Packet Handling

5.2.1 Test Data Generation

To verify the proper functioning of the transceiver, synthetic packet data was required. Additionally, all sideband signals and control signals would need to be generated appropriately to ensure all inputs were valid.



(a) High Level Flow



(b) Low Level Flow

Figure 16: Data Generation Function Structure

5.2.2 GSE

6 Results

6.1 Transmitter

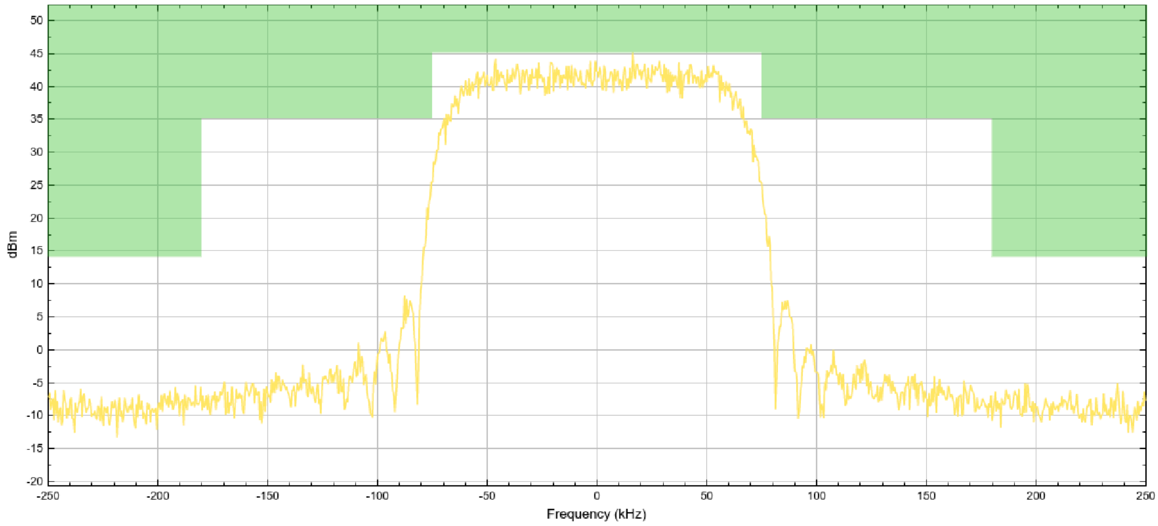


Figure 17: Spectrum at Output to DAC

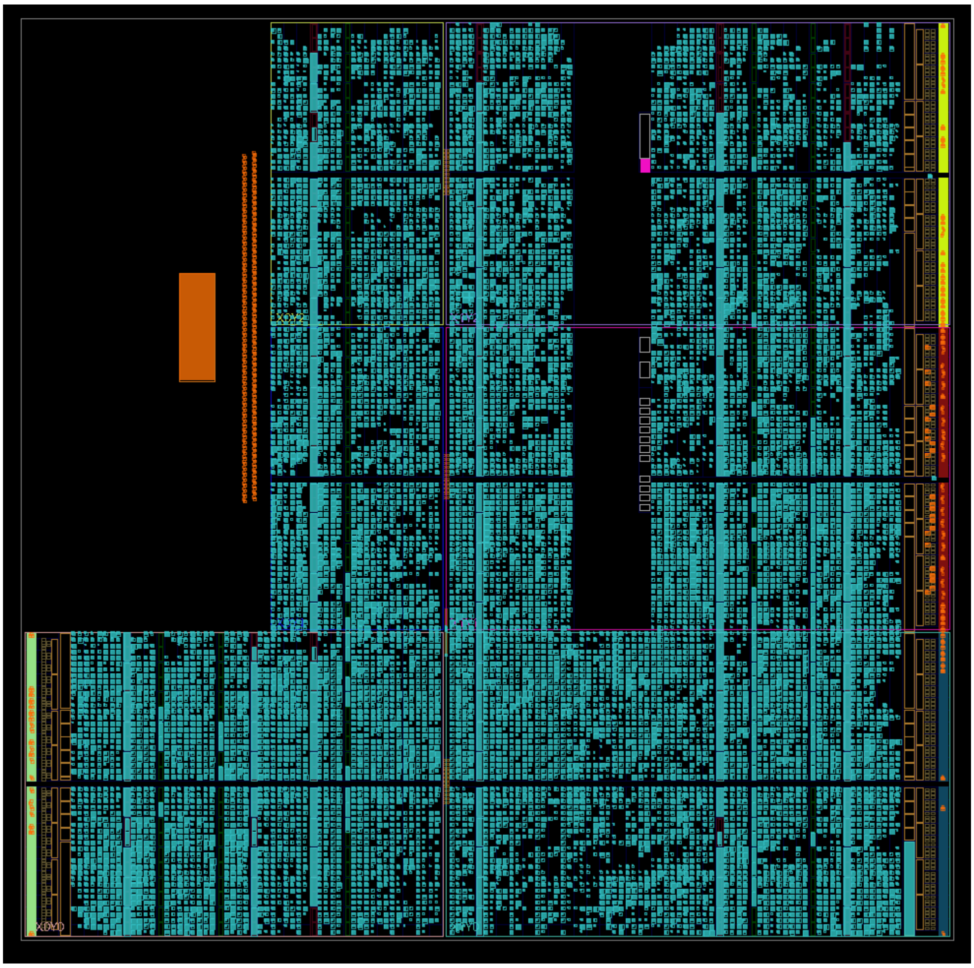


Figure 18: Implemented Design on Zynq 7020 FPGA

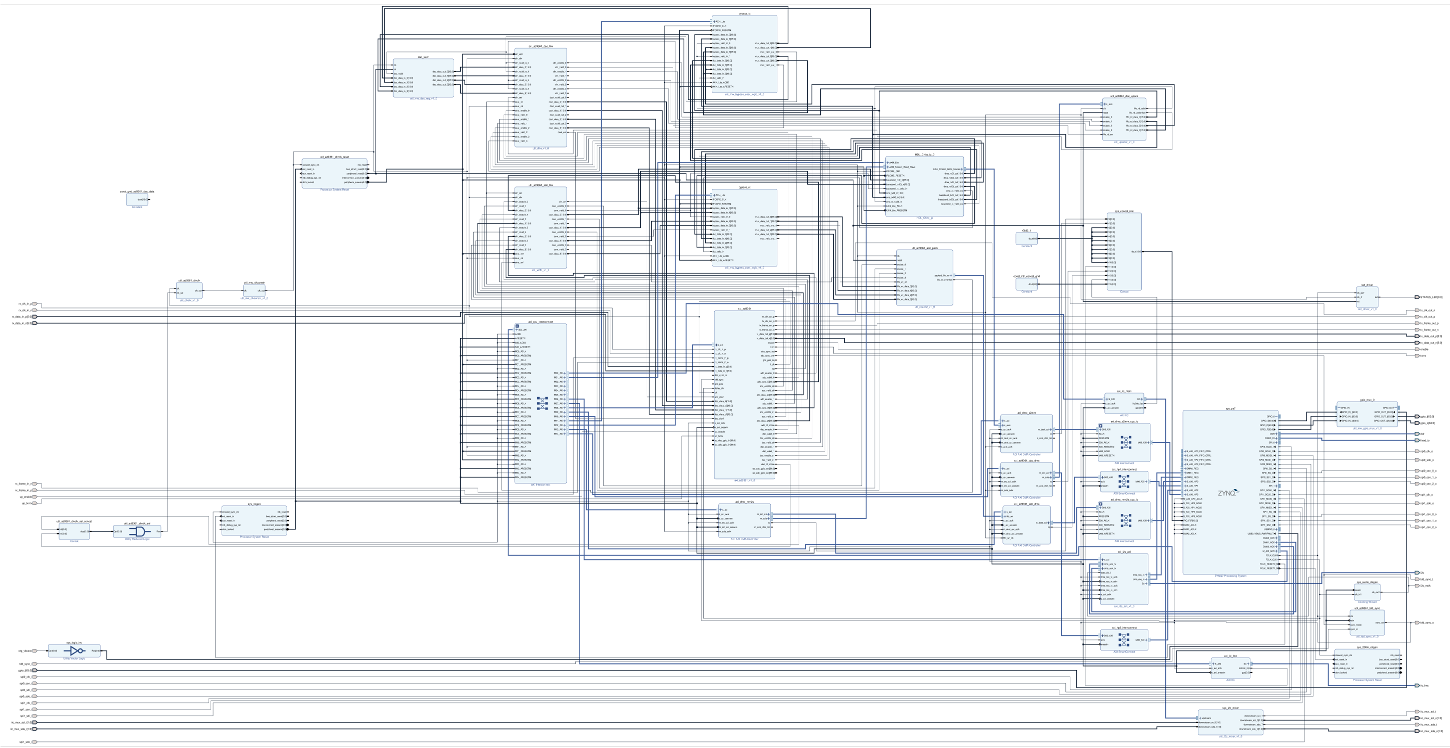


Figure 19: Generated Vivado Block Diagram

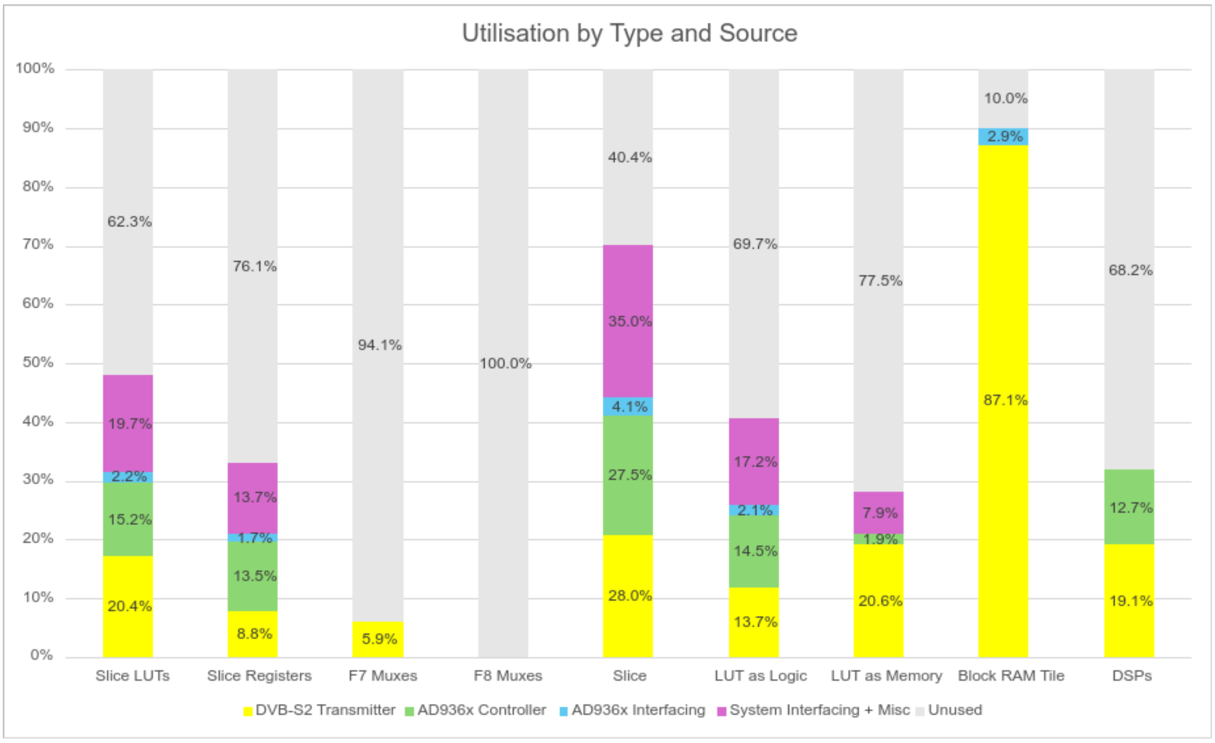


Figure 20: Utilisation of Implemented Design by Subsystem

7 Discussion

8 Conclusion

8.1 Further Work

9 Bibliography

[1] E. Amarantidou, "AcubeSAT UHF Link Budget Analysis." Accessed: March 12, 2025. [Online]. Available at: https://gitlab.com/acubesat/comms/budgets/link-budget-analysis/-/blob/master/CDR%20budgets/UHF_link.xlsx?ref_type=heads

[2] G. Quintana-Diaz, D. Nodar-López, A. González Muíño, F. Aguado Agelet, C. Cappelletti, and T. Ekman, "Detection of radio interference in the UHF amateur radio band with the Serpens satellite," *Advances in Space Research*, vol. 69, no. 2, pp. 1159–1169, Jan. 2022, doi: 10.1016/j.asr.2021.10.017.

[3] M. H. Same, G. Gandubert, P. Ivanov, R. Landry, and G. Gleeton, "Effects of Interference and Mitigation Using Notch Filter for the DVB-S2 Standard," *Telecom*, vol. 1, no. 3, pp. 242–265, Dec. 2020, doi: 10.3390/telecom1030017.

[4] Calum Clarke, Daniel Aitken, Craig Sutherland, and Hannah Wright, "Group H EM501 Final Report: Strathclyde Spacecraft Tracking & Command Station." 2016.

[5] Alén Space, "FrontendUHF Datasheet." Alén Space, April 2021.

[6] ISISPACE, "CubeSat Antenna System for 1U/3U - ISISPACE." Accessed: February 28, 2025. [Online]. Available at: https://www.isispace.nl/product/cubesat-antenna-system-1u-3u/

[7] SSB, "SP-7000 Datasheet." Accessed: March 14, 2025. [Online]. Available at: https://www.ssb.de/shop/download/EN-1050_SP-7000.pdf

[8] B. Sklar, *Digital communications: fundamentals and applications*, 2. ed., 17. print. Upper Saddle River, NJ: Prentice Hall PTR, 2009.

[9] Ettus Research, "B210 Spec Sheet." Accessed: March 14, 2025. [Online]. Available at: https://www.ettus.com/wp-content/uploads/2019/01/b200-b210_spec_sheet.pdf

[10] MathWorks, "MATLAB slantRangeCircularOrbit Documentation." Accessed: March 14, 2025. [Online]. Available at: https://uk.mathworks.com/help/satcom/ref/slantrangecircularorbit.html

[11] 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." July 2014.

[12] CCSDS, "CCSDS Protocols over DVB-S2—Summary of Definition, Implementation, and Performance." June 2023.

[13] MathWorks, "Satellite Communications Toolbox." Accessed: December 13, 2024. [Online]. Available at: https://uk.mathworks.com/products/satellite-communications.html