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

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***Abstract*—This paper outlines the downlink system design for STRATHcube. Performance and link analyses were conducted, analysing communication windows over the course of the mission and expected theoretical performance. The design was implemented in hardware using MathWorks HDL Coder and initial code developed for packet handling in software.**

Initial performance analysis was conducted in comparison to a reference implementation which uses Constant Coding and Modulation (CCM) and optimises for maximum availability. It showed a significant uplift in data throughput over the course of the mission. Additionally, resource analysis of the target FPGA SoC and the implemented design, as well as timing analysis show that the system will be implementable in hardware.

***Index Terms*—CubeSat, Communications, DVB-S2, Software Defined Radio**

I. Introduction

A. CubeSat Communications

Efficient downlink of data is a critical challenge in CubeSat missions, as they are highly constrained in power, bandwidth, and by the dynamic channel conditions imposed during a ground station pass. These issues are further exacerbated in the commonly used Ultra High Frequency (UHF) amateur allocation due to in band interference and further bandwidth constraints.

There are several dynamic factors inherit in satellite to ground communications, including pointing losses, total slant range and scintillation effects. Some of these factors can be known in advance, however others such as interference, are difficult to predict and have an outsized impact on error rates. For this reason systems with Adaptive Coding and Modulation (ACM) can improve link availability and spectral efficiency compared to Constant Coding and Modulation (CCM) or those that change based on predicted values but without real time adaptation, Variable Coding and Modulation (VCM), however this does come at the cost of increased complexity.

Digital Video Broadcasting - Satellite - Second Generation (DVB-S2) is one such ACM system, with near Shannon limit performance and a modular standard allowing it to be matched to the usecase. Despite this, it has not seen common use in the UHF band for CubeSats as it typically requires complex and expensive Software Defined Radio (SDR) based hardware with higher power draw. However, STRATHcube will already include such hardware for its primary payload, presenting an opportunity for increased downlink capability for minimal added cost.

A similar system is described in [1], which details a Zynq 7020 Field Programmable Gate Array (FPGA) System on Chip (SoC) SDR-based communication platform operating in the 915 MHz UHF band and utilising ACM. The system used similar modulation to DVB-S2 but with a different coding method. Their analysis showed an almost doubling in throughput compared to CCM. This proved that ACM systems for CubeSats are feasible and could offer large performance benefits. The presented system is found to have a notably high power consumption during transmission, however it is argued that this is offset by the short length of ground station passes.

B. The STRATHcube Mission

STRATHcube is a 2U CubeSat in development at the University of Strathclyde and part of the *ESA Fly Your Satellite! Design Booster* program. It has two payloads, each targeting a key area of space sustainability.

The primary payload is a technology demonstrator of a Passive Bistatic Radar (PBR) for the detection of space debris using an SDR. The satellite will record IQ data for analysis on the ground, although compressed, this will be a considerable data volume therefore the downlink datarate will be one of the primary bottlenecks for its operation. Consequently, there will already be a powerful Field Programmable Gate Array (FPGA) based SDR included on the mission, the Alén Space TOTEM SDR, which would allow a DVB-S2 transmitter to be implemented as a "piggy-back" on the primary payload using spare resources.

The secondary payload aims to measure the aerothermal effects leading to solar panel fragmentation by recording and transmitting sensor data during the moments up to re-entry. This is unlikely to occur near a ground station and instead a secondary transceiver is to be used that communicates via the Iridium network.

The Spacecraft Tracking & Command Station (STAC) based at the University of Strathclyde is the current planned ground station for the mission. It is equipped with two circularly polarised UHF antennas from M² Antenna Systems Inc [2], an SP-7000 pre-amplifier from SSB Electronic and an Ettus Research B210 SDR for reception. The station has been out of use for some time, so rated performance values may not match the current state of the hardware.

C. Mission Phases

The mission shall be split into four distinct operational phases starting with deployement from the International Space Station (ISS) and ending with the demise of the satellite.

1) Early Operations and Commissioning (~10 days): Deployment from the ISS and system activation.
2) Primary Operations (~170 days): Alternating PBR measurements and data downlink during ground station windows until altitude trigger (~170km).
3) Transition Phase: Reconfiguration for re-entry. Involves transition to communications primarily via Iridium network.
4) Secondary Phase: Re-entry data collection and downlink until demise.

The UHF downlink communications will occur during the first three phases, driving subsequent analysis.

D. Objectives

This work focused on the development of STRATHcube's downlink communications system design, with objectives to:

1) Develop detailed downlink system design
2) Develop an engineering model targeting development boards

The scope was limited to exclude the uplink design, with deployment onto hardware as an optional goal. Due to this, the system was designed to be modular to facilitate future development.

II. Adaptive Coding and Modulation Analysis

A. Link Budget Analysis

A new link budget was created to identify the received Signal to Noise Ratio (SNR) at each time step during the pass. Parameters were divided into static, those that would not change during a pass, and dynamic, those that would, as shown by Table I and Table II.

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 ($L_{\text{Connector}}$)	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)

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]

$$\Gamma = \frac{\text{VSWR} - 1}{\text{VSWR} + 1} \tag{1}$$

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

$$\begin{aligned}\text{EIRP}_{\text{dB}} = 10\log_{10}(P_{\text{Tx,W}}) - L_{\text{Line,dB}} - L_{\text{Switch,dB}} \\ -L_{\text{Matching,dB}} + G_{\text{Tx,dB}}[\text{dBW}]\end{aligned} \tag{3}$$

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

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

$$\text{FSPL} = 20\log_{10}\left(\frac{4\pi df}{c}\right)[\text{dB}] \tag{5}$$

Where $k = 1.38 \times 10^{-23}$ J/K is the Boltzmann constant and $T_0 = 290$K is the reference temperature.

The final received signal power can be calculated the EIRP less all losses and the received noise power as the terrestrial noise power with amplification from the preamp and including the noise figure of each element of the receive chain.

$$\begin{aligned}P_{\text{Rx,dB}} = \text{EIRP}_{\text{dB}} - \text{FSPL}_{\text{dB}} - \text{AL}_{\text{dB}} - L_{\text{Pol,dB}} \\ -L_{\text{Point,dB}} + G_{\text{Rx,dB}} + G_{\text{Preamp,dB}} \\ -L_{\text{Line,dB}}[\text{dBW}]\end{aligned} \tag{6}$$

$$\begin{aligned}P_{\text{N,dB}} = P_{\text{T,dB}} + G_{\text{Preamp,dB}} + F_{\text{Preamp,dB}} \\ +F_{\text{SDR,dB}}[\text{dBW}]\end{aligned} \tag{7}$$

Therefore the SNR of the received signal is simply:

$$\text{SNR} = P_{\text{Rx,dB}} - P_{\text{N,dB}}[\text{dB}] \tag{8}$$

DVB-S2 uses Amplitude and Phase Shift Keying (APSK) modulation, from QPSK to 32APSK and coding rates from 1/4 to 9/10. Further modulation and coding options were added with DVB-S2X to support an even wider SNR range, although these were not considered during this investigation. Additionally, there are two options for the frame length, Normal and short, and pilots can be optionally inserted to improve receiver performance.

The minimum SNR required was taken from [11, Tab. 13] which assumed a normal frame length, no pilots, 50 Low-Density Parity-Check (LDPC) decoding iterations, perfect carrier and synchronisation recovery, no phase noise, and an Additive White Gaussian Noise (AWGN).

Interference is likely to be present in this band due to amateur radio users, spurious emissions and other sources. Further, phase noise will likely be induced due to multipath and atmospheric effects. The calculated margin will therefore be optimistic compared to the practical system. To offset this, when calculating data rate the spectral efficiency for a system with pilots was used from [12].

The link budget and margin for an adverse and a favourable scenario is shown in Table III with the optimal modulation and coding rate selected to meet the 3dB margin requirement. The data rate was calculated directly from the spectral efficiency and bandwidth using (9).

$$\text{Data Rate} = \eta \times B[\text{bps}] \tag{9}$$

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

B. *Adaptive vs Constant*

Proof-of-concept analysis was conducted to assess if the performance gains offered by ACM justify the increased complexity. A simulation of the orbit was used to identify the elevation angle and satellite altitude during pass opportunities over the STAC for the full duration of the mission.

Due to the location of the ground station, the observed elevations did not rise above 40°, as shown in Fig. 2. The majority of passes occured in the range of 10° to 20°. The corresponding optimal modulation and coding rates and datarates are shown in Fig. 3.

For reference, the data rate for a CCM DVB-S2 system was used that maximised availability, in this case using QPSK 1/3 for the duration of the mission. The ACM system was assumed to take the optimal setting for each 10 second timestep of the simulation.

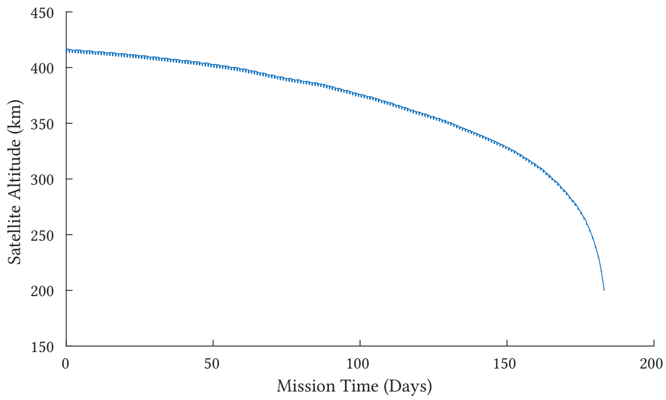

Fig. 1. STRATHcube altitude from deployment to mode transition

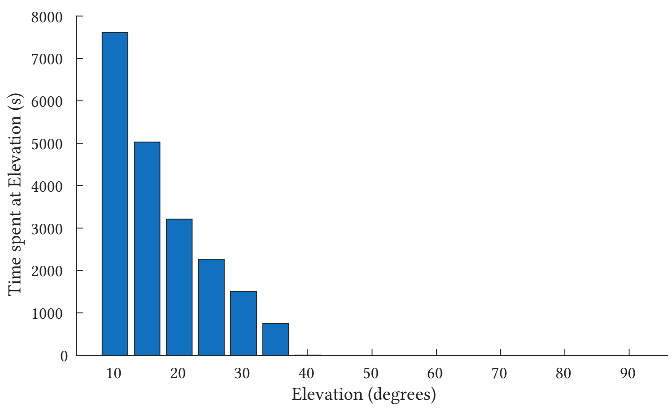

Fig. 2. STRATHcube time spent at elevation over STAC

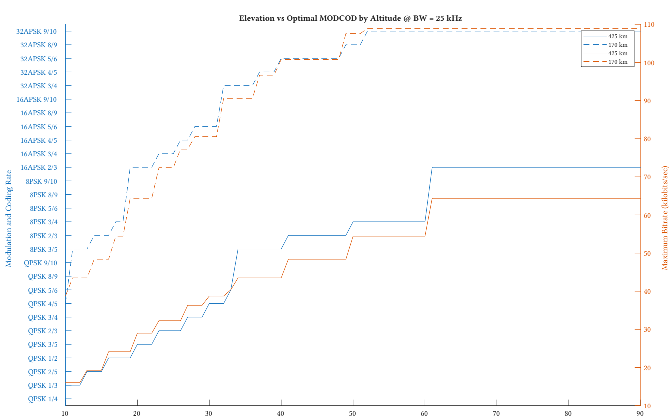

Fig. 3. Optimal MODulation and CODing (MODCOD) rate by elevation and altitude.

Table IV shows the total data downlinked by each strategy. The adaptive system was able 3.19× the amount of data versus the constant system, indicating that the increased system complexity is outweighed by the improved performance.

TABLE IV
Total Data Downlinked by Strategy

Strategy	Total Data Downlinked (Gb)
Constant	1.88
Adaptive	6.01

C. *Areas for Further Investigation*

The link budget presented was developed to show viability of an adaptive DVB-S2 system, as such there was comparatively less investigation of the ground station receiver system. The implementation of the receiver will be challenging, and require further investigation of the in band interference present at the site. Should the margin decrease, the expanded modulation and coding options in DVB-S2X for very low SNR applications could be used. Additionally, the bandwidth calculations did not account for filter roll-off, this is discussed further in Section III.B.

III. Transmitter Design and Implementation;

A. *Design*

Following the ACM analysis, it was decided to implement a DVB-S2 compliant system with ACM capabilities. As flight hardware could not be sourced for this investigation, the target platform was a combination of a Digilent ZedBoard Zynq 7020 development board attached to an Analog Devices AD-FMCOMMS4 AD9364 development board. As the interface of the AD936x series transceivers are the same, the system could be verified with a different transceiver in the same family.

The designed system had a modular structure, allowing unit testing of each component and facilitating changes in the future as the satellite is developed further.

- **Processing System (PS)**:
  - **System Interface**: Aggregate packets from all external input sources.
  - **Packet Parser**: Parse the input packets to determine their priority level.
  - **ACM Router**: Assign packets into buffers according to Quality of Service (QoS) requirements and encapsulation using Generic Stream Encapsulation (GSE) for efficient framing.
  - **PS-PL Interface**: Break up packets for transfer using an Advanced eXtensible Interface (AXI) Stream and manage control signals for the DVB-S2 Transmitter system.
- **Programmable Logic (PL)**:
  - **DVB-S2 Interface**: Manage interface from DVB-S2 transmitter block to PS AXI-Stream interface.
  - **DVB-S2 Transmitter**: Manages framing, coding, modulation and filtering at baseband.
  - **AD936x Controller**: Manages interface with transceiver.
- **External Hardware**:
  - **AD9364 Transceiver**: Upconversion and transmission of signal.

B. Implementation

The FPGA implementation was accomplished using MathWorks HDL Coder [13] due to ease of implementation and ease of testing. Further, using the *Hardware Software Codesign* [14] methodology, both the transceiver interface and PS-PL interface bindings could be automatically generated.

A reference DVB-S2 HDL Coder implementation by MathWorks [15] was selected to reduce technical risk, as it was pretested, allowing faster development of the rest of the system. Further logic was added around this block to manage the AXI-Stream interface and to convert the output for the 12 bit DAC interface. The transmitter portion is shown in Fig. 6. The roll-off factor was selected as 0.25 to balance throughput with filter complexity and resulted in a symbol rate of 20,000 / second.

The implementation of packet handling is yet to be completed, although relevant libraries have been identified and work begun on a C++ implementation of GSE. Further, the packet handling system shall be designed to work with schemas for packet definition to reduce the difficulty of modification as the satellite design is updated.

C. Results & Discussion

MATLAB code was created to generate synthetic AXI packets to test the system in Simulink. The resulting output spectrum was shown to be passing against the International Telecommunication Union (ITU) out of band emissions mask for the amateur and amateur satellite service [16] as shown in Fig. 4.

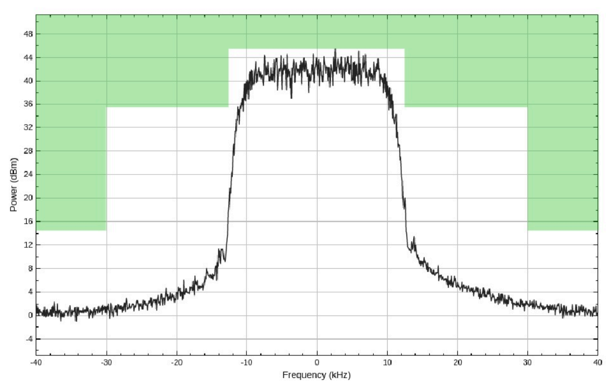

Fig. 4. Power spectrum at transmitter output. Note that the power scale is not representative of the actual peak output power. The shaded area shows the ITU emission mask, where green indicates passing.

The resource of the implemented Vivado design is shown by subsystem and resource type in Fig. 5 and Table VI. This design is intended to be expanded in the future to include the payload signal processing, as well as the receive chain, therefore, excessive resource usage could cause issues.

Overall, the highest resource usage was in the block RAM, where this design used 89% of those available. This was used for three buffers within the design, 24 for the implemented interfacing logic, a further 25 for the frame during error correction, and 75.5 for the physical layer framing. The high usage is primarily due to the entire frame being stored at once at each stage. Large optimisations could be made if the frames were stored and generated in chunks, perhaps at a higher clock speed to ensure that the output does not stall.

The other resource usage rates were deemed acceptable, the multiplexer and DSP48 tile usage was particularly low and should not impact further designs, however, the slice Look Up Table (LUT) usage is quite high overall with only 34.9% free.

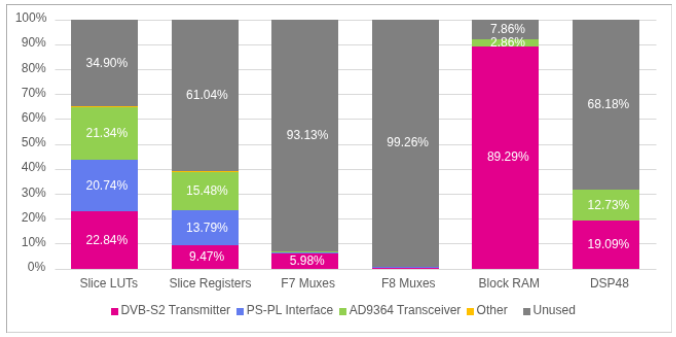

Fig. 5. Percentage utilisation by resource type and subsystem. The DVB-S2 transmitter is shown in pink, the processing system and programmable logic in blue, and the transceiver controller in green.

Following this, a timing report was generated, finding a worst negative slack of 0.126 ns, a worst hold slack of 0.016 ns and a worst pulse width slack of 0.264 ns at 61.44 MHz. Although the design met timing, the large chip area used due to high block RAM utilisation could cause issues if higher clock speeds are required in the future.

A further power report was generated using the Vivado power analysis tool to estimate the efficiency of the final design. The tool was used in maximum usage mode. A range of default toggle rates were used to identify the expected power draw of the design based on its activity level, as shown in Table V. This does not include the expected power required for the transceiver, or power amplifier components. These are early stage measurements and specific power optimisations have not been implemented yet. Further optimisation and measurement of the implemented system on hardware is required.

TABLE V
TRANSMITTER DESIGN POWER CONSUMPTION BY DEFAULT TOGGLE RATE.

Default Toggle Rate (%)	Estimated Power Consumption (W)
12.5	3.286
25	3.398
50	3.614
75	3.823
100	4.009

TABLE VI
FPGA resource utilisation by subsystem and resource type.

Name	AD9364 Transceiver	PS-PL Interface	Other	DVB-S2 Transmitter	Total Used	Available	Usage (%)
Slice LUTs	11353	11032	98	12151	34634	53200	65.10
Slice Registers	16467	14671	244	10074	41456	106400	38.96
F7 Muxes	78	158	0	1591	1827	26600	6.87
F8 Muxes	16	71	0	12	99	13300	0.74
Block RAM	4	0	0	125	129	140	92.14
DSP48	28	0	0	42	70	220	31.82

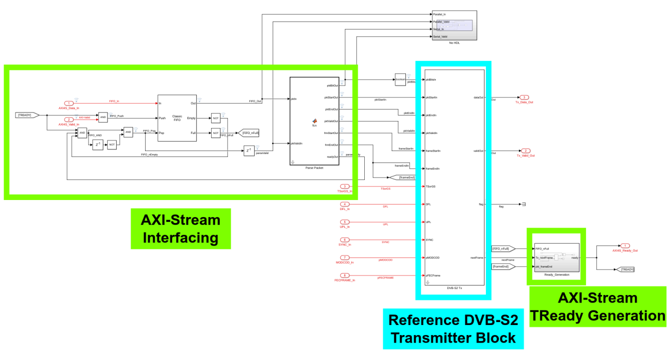

Fig. 6. Block diagram of HDL Coder implementation. Highlighted in cyan is the transmitter block created by MathWorks. Highlighted in green is the implemented blocks for communication with the processing system.

D. Conclusions and Further Work

The performance of a DVB-S2 ACM system was analysed for the STRATHcube mission and found to offer substantial performance benefits, although with a noted added complexity. A transmitter was developed and simulated building upon a MathWorks HDL Coder implementation. This design was then synthesised using Vivado and found to meet timing constraints.

The system is still to be tested in hardware and the packet handling software is still under development. The link calculations were made using several assumptions about the ground station receiver and will be revised when measurements can be made which may impact the transmitter design requirements. Investigation into interference and the development of the receiver is of particular importance.

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