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Design and Development of a High-Speed Communication System for a LEO Nano Satellite

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Abstract

With an increasing number of CubeSats aiming for higher data rates, S-Band has become an emerging standard. However, this goal faces strict design constraints as CubeSats offer a limited power budget and processing capabilities. This paper discusses the design, simulation, and system architecture for the Telemetry and Telecommand (TTC) subsystem of a 3U Nano Satellite equipped with a multispectral imager as its payload. The system implements a Full-Duplex S-Band/UHF architecture, additionally, a backup downlink system is also designed where in the event of a poor link or S-band failure, the system will switch to downlinking in UHF. The paper will present the onboard architecture for the S-band (2.4 GHz) downlink and the UHF (433MHz) uplink/backup downlink system, where various Commercial off-the-shelf (COTS) components are selected according to power constraints and link budget requirements. The communications subsystem is also responsible to carry out packet structuring and Forward Error Correction (FEC) algorithms onboard. This involves implementing CCSDS (TM and TC) frames for the data link layer along with half-rate convolutional code with constraint length 7 concatenated with Reed Solomon (255,223) with an Interleaving Depth of 5. Though adding FEC increases data redundancy, it provides essential coding gain which helps increase data reliability. This paper also discusses the selection procedure of optimal code rate and modulation scheme depending upon the system requirements. Lastly, it will present the dynamic link budget calculation. The paper also discusses the various challenges and limitations faced while implementing high data rates in amateur missions.

Keywords: S-Band, CubeSat, Packets, Link-budget, Convolutional Coding, Reed Solomon Coding

Acronyms/Abbreviations

Consultative Committee for Space Data Systems(CCSDS), Telemetry, Tracking and Commanding (TT&C), Forward Error Correction (FEC), OnBoard Computer (OBC), Electrical Power Subsystem (EPS), Attitude Determination and Control Subsystem (ADCS), Structural and Thermal Subsystem (STS), Bit Error Rate (BER).

1. Introduction

Over the years, CubeSats have become an integral part of space missions. With CubeSat technology, several small startups and academic institutions are planning their own space missions. With ever-increasing technology, the mission payloads have become increasingly complex and thus demand high-speed connectivity with the ground station. Thus, contrary to the traditional use of UHF and VHF bands for amateur missions, more and more CubeSat Teams are slowly shifting to the S-band (2.4 GHz) and higher frequencies. However, this comes at a tradeoff between EPS power supply, OBC processing power, ADCS pointing accuracy, and physical constraints. All these options need to be perfectly balanced for maximum use of available resources.

This paper details the work done by students of Birla Institute of Technology and Science, Pilani, India. This work was done towards the development of a 3U CubeSat by Team Anant under the Student Satellite Program of the Indian Space Research Organization (ISRO). The primary payload of the mission is a multispectral imager.

This paper primarily focuses on the S-Band communication system architecture of the satellite. It starts by talking about the onboard design followed by the antenna placement options. The paper then discusses the selection procedures of various components and the various communication protocols used. Lastly, the paper concludes by discussing the link budget and the future goals of the team.

2. Onboard S-Band Architecture

The OBC chosen is a Zynq 7000 SoC which comprises a dual-core ARM Cortex A9-based processing system. A Linux-based OS, Petalinux has been chosen for the OBC.

2.1 EPS-OBC Interface

The EPS performs significant tasks on the satellite, which are briefly covered in the sub-sections below.

2.1.1 OBC Boot Up Sequence

The EPS boots up the OBC using a NOR flash memory. Redundancy is implemented by having two memories for booting, where the EPS determines which memory to boot from via a GPIO pin.

2.1.2 External Watchdog

The EPS acts as an external watchdog to the OBC; The OBC sends periodic signals to the EPS. If the EPS does not receive a signal in a particular time period, it will attempt to reboot the OBC.

2.1.3 Simple Beacon

A UHF OOK (On-Off Keying) modulated beacon is transmitted by the EPS which contains the satellite callsign and mission-critical data collected by the EPS.

2.1.4 SPI Interface

The EPS acts as the slave while the OBC acts as the master. The EPS provides Housekeeping data to the OBC, which is necessary for OBC mode determination and switching. Based on the mode to be implemented, OBC will send EPS data on which components/subsystems to switch on/off [1].

2.2 OBC Functions

The OBC is dual-core, and certain functions are performed on different cores to balance the load and maintain synchronization. The procedures are elaborated on below.

2.2.1 OBC Core 0

This core will be in charge of the control of various ADCS sensors (magnetometer, GPS, etc., and for control, reaction wheels, and magnetometers) and other housekeeping sensors. It also requests certain housekeeping data from the EPS MCU. Data from these sensors and the ADCS orbit propagator determine the mode of operation of the satellite (Image mode, sun pointing, downlink, etc.) and it will provide relevant information to the EPS for subsystem on/off switching.

2.2.2 OBC Core 1

This Core will control the payload during the image-taking mode and will be in charge of the S-Band transmitter as well as the UHF uplink during the downlinking mode. This is done so as to reduce the burden on Core 0.

2.3 Backup Downlink System

In the unlikely event of a failure of the S-Band downlink, the ground station will ascertain if communications can no longer continue in that band and then order the satellite to shift to UHF half-duplex mode. As given in Fig 6, RF switches are used to switch between the UHF uplink and backup downlink, and also between either of those and the OOK beacon.

3. Component Selection

The S-Band Patch Antenna and Transmitter were the two major components present in the S-band architecture which required careful deliberation.

3.1 Antenna:

For the S-band downlinking system, a patch antenna was the preferred choice of antenna owing to its relatively lower volume occupancy and weight constraints. A list of the requirements considered in candidate antennas is elaborated below with brief quantification wherever possible.

1. Tried and tested space heritage.
2. Relatively narrow HPBW (around 60 degrees).
3. Minimal thickness of around 4.1 mm (specified by the STS team).
4. Minimal mass < 50 g (including the connector).
5. Gain > 6dBi over the concerned frequency band.

3.2 Transceiver:

The mission objective of downlinking the multispectral payload data requires effective modulation schemes, high data rates, and resilient error correction (while ensuring a high throughput). Additionally, all these requirements must be met with minimal power consumption. During the search for S-band transceivers, the Clyde Space STXC transceiver seemed highly conducive to this mission due to the following reasons:

1. Tried and tested space heritage.
2. Support of data rates up to 2 Mbps version which allows us to attain the required data rate, which after accounting for error correction, amounts to an effective data rate of 1 Mbps.
3. Built-in HPA.
4. Maximum transmitted power of 30 dBm.
5. Idle power dissipation of 530 mW which is reasonable when factoring in the built-in HPA.
6. Supports convolutional encoding.
7. Low mass < 100g

While these specifications are aligned with the requirements, the budget may pose a constraint to procuring this component. Until a decision on the budget for purchasing our S-band transceiver is made, the Texas Instruments CC2500 S-band transceiver will be used for preliminary testing purposes. A comparative study between the two transceivers is presented in Table 1.

Table 1. Comparative study between S-band transceivers

Parameter	**Clyde Space STX**	**Texas Instruments CC2500**
Operating frequency range (GHz)	[2.4, 2.45]	[2.4, 2.4835]
Operating temperature range (°C)	[-20,61]	[-40,85]
Modulation schemes supported	QPSK, OQPSK	OOK, GMSK, MSK, 2FSK
Maximum data rate supported	2 Mbps	500 kbaud
Maximum TX output power (dBm)	30	1
Presence of an in-built amplifier	Yes	No (separate amplifier is required)

The two transceivers have many common merits, like the support of convolutional coding and their space heritage. However, their differences must be accounted for carefully when drawing inferences from preliminary testing.

4. Antenna Systems

For the implementation of the full-duplex architecture with the S-Band downlink and the UHF uplink, the placement of the respective antennas should be optimal. Their placement should produce a common line of sight to the ground station, determined by the direction of maximum gain of both the antennas.

To achieve this, the simulation of the antenna radiation pattern was performed in Ansys HFSS. The UHF monopole antenna (see Fig 1) was combined with the CubeSat body in the simulation to accurately model the radiation pattern. Based on the result of the simulation, the appropriate placement of the S-band patch antenna was determined. The maximum gain at an angle of 120 degrees to the monopole and patch antenna was placed on the face corresponding to this maximum gain (see Appendix D for the plot).

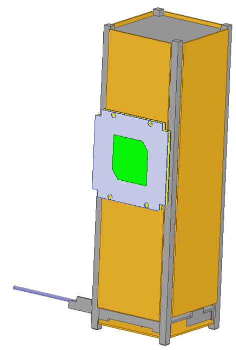

Fig 1. CubeSat body with UHF and S-band antennas

4.1 Antenna Dependencies

The S-Band antenna system has the following subsystem dependencies that need to be kept in mind.

1. EPS - Power constraints owing to the relatively high power requirements of the S-Band Patch Antenna would need to be taken into account. Another point to be noted is that the usage of the patch antenna might decrease power generation as the antenna would require some surface area that would otherwise be used by a solar panel.

2. ADCS - The patch antenna being more directive would demand a significantly higher pointing accuracy in comparison to the UHF monopole.

3. STS - The physical placement of the antenna is handled by STS.

5. Packets

5.1 Approach

Having looked upon various packetizing schemes for CubeSats such as AX. 25, AX. 100, and CCSDS protocols, the CCSDS standard was selected due to its vast space heritage, extensive documentation, and reliable space link. CCSDS protocol having been used in multiple missions consisting of multispectral payloads came as an ideal fit. The following subsections describe the considerations taken while deciding the protocol.

5.1.1 Free and Open Source standards

For amateur missions, it becomes very important to have standards that are open to all for ease of implementation. The use of open-source protocols ensures images can be received by all ground stations having the required resources.

5.1.2 Open Sourced Encoding/Decoding Softwares

Cubesat teams having limited expertise and resources may have to rely on prewritten software (see Table 2) for reliability, ease of implementation, and testing.

Table 2. Softwares used for packet testing

Software/Resource Name	Function
GNU Radio	Open-source software toolkit for signal processing. Libraries of concern were gr-satellites, gr-ccsds, and gr-satnogs
Phil Karn C implementation	Written in the early 2000s these techniques still act as a key backbone to various CCSDS encoding/ decoding techniques.
NASA CFs	Written in C provides users access to almost all of the CCSDS recommended standards with a dedicated community working in improving the system.
CCSDS implementation by Dario Lucia	Written in Java, even this open-sourced library provides users access to various CCSDS standards such as CCSDS File transfer protocol, CCSDS Space Packets, TM/ TC packets, etc.
Python implementation by LibreCube:	Written in Python. This implementation provides decoding/encoding support for various CCSDS standards such as CFDP, Space packets, and TM/TC packets.

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5.1.3 System requirements

Deciding on the end packet structure and its complexity is heavily dependent on the payload requirements and specifications. Our payload demands protocols reliable enough to transmit multispectral images of size 2048*1088*8 bits in S-band with a data rate of around 1Mbps and with a minimum loss, hence CCSDS protocols ideally fit this requirement. However, systems with simpler complexity can adhere to much simpler protocols such as AX. 25 or any default transceiver protocol.

5.1.4 Optimization

This is a key area where satellite teams have to decide things such as packet size, multilayer complexity, and error coding techniques.

5.1.5 System Compatibility

The transceiver must support used protocols, especially for data-link and lower layers.

5.2 Structure

The packet structure is decided after careful consideration of the parameters mentioned above. It consists of CCSDS (TM and TC) frames for the data link layer. The TM frame consists of a half-rate convolutional code constraint at length 7, concatenated with Reed Solomon (255,223) with an Interleaving Depth of 5.

5.3 TM Packets (Telemetry packets for downlink[3])

5.3.1 Packet layout :

1. **Master Channel Identifier** (12 bits) :
    a. Transfer Frame Version Number(2 bits): it shall be set to ‘00’ for TM packets
    b. Spacecraft Identifier (10 bits): Assigned by: the Space Assigned Numbers Authority (SANA)
2. **Virtual Channel Identifier** (3 bits): Identifies the virtual channel of the packet stream
3. **Operational Control Field Fla**g (1 bit)
4. **Master Channel Frame Count** (1 byte): Keeps track of packet primary sequence

5. **Virtual Channel Frame Count** (1 byte): Keeps track of Virtual Channel stream packets.
6. **Transfer Frame Data Field Status** (2 bytes):
   a. Transfer Frame Secondary Header Flag (1 bit): Gives an indication of secondary header
   b. Synchronization Flag (1 bit): It signals the type of data which are inserted into the Transfer Frame Data Field
   c. Packet Order Flag (1 bit): Reserved for future use by CCSDS. Its value is set to ‘0’
   d. Segment Length Identifier (2 bits): Contains segment length identifier. Its value is set to ‘11’.
   e. First Header Pointer (11 bits): Helps in keeping track of space packet (Network Layer) headers.

Followed by the primary header is the data field which contains the image or system data. The size of packets is constrained at 1115 bytes i.e. 6 bytes of primary header and 1109 bytes of data. If the size of SDU (Service data unit) is less than the packet length then the rest of the bits are padded with 0.

5.3.2 Reed Solomon Error Correction:

The Reed-Solomon encoder blocks take data bits and pad them with additional bits. Noise in transmissions generally causes errors in data packets. The RS decoder corrects the packets and recovers the transmitted data. The maximum number of bits that can be corrected depends on the type of code used.

CCSDS RS (223,255) [5] has been chosen for its good performance. Each block of size 255 bytes contains 32 bytes of parity data for FEC (223 data bytes + 32 parity bytes =255-byte block).

5.3.3 Interleaving

When the RS code is used on packets, interleaving of the RS code helps prevent burst errors and hence improves code performance. Interleaving of depth 5 is used due to its optimized performance.

5.3.4 Scrambling

Pseudo-randomization is used to randomize the bits. It aids signal acquisition, bit synchronization, proper decoding and reduction of spurious frequencies, and compliance with power density masks.

5.3.5 Convolutional code

Convolutional code is used along with Reed Solomon together known as concatenated coding for best performance. Half rate convolutional code [5] is used along with K=7 as per transceiver support. Thus improving the link and decreasing BER. For higher coding gains LDPC or turbo codes may be used.

5.4 TC Packets (Telecommand packets for uplink [4])

Error correction codes were deemed unnecessary for the uplink due to an already good link in place. Instead, CRC-16 would be used for error detection. The packets would be crafted using TC data link layer format specified by CCSDS (CCSDS 132.0-B-2) and size constrained to a maximum of 64 bytes owing to the limited transceiver FIFO size.

5.4.1 Packet layout:

1. **8Transfer Frame Version Number** (2 bits) :
   Set to ‘00’
2. **Bypass Flag** (1 bit):
   Set to ‘0’
3. **Control Command Flag** (1 bit):
   Set to ‘1’ as all uplinks would contain control commands only.
4. **RSVD. SPARE** (2 bits)**:**
   Reserved for future application by CCSDS and shall be set to ‘00’
5. **Spacecraft Identifier** (10 bits):
   Assigned by: the Space Assigned Numbers Authority (SANA).
6. **Virtual Channel Identifier** (6 bits): Identifies the virtual channel of the packet stream
7. **Frame Length** (10 bits):
   This 10-bit contains a count of C.
   Where-
   C = (Total Number of Octets in the Transfer Frame) – 1
8. **Frame Sequence Number** (8bits)

5.4.2 CRC - 16

Cyclic redundancy check (CRC) is an error-detecting mechanism that is commonly used to detect errors in various layers in the networks. CCSDS recommends using 16 bit CRC [5] with polynomial equal to

$$G(X) = X^{16} + X^{12} + X^{5} + 1$$

Table 3. The following table shows the efficiency of this algorithm

Error Type	**Percent of errors detected**
Burst errors of length 16 or less	100.000000%

Burst errors of length equal to 17	99.996948%
Burst errors of length greater than 17	99.998474%
Pattern errors containing 1, 2, or 3 errors	100.000000%
Pattern errors with an odd number of errors	100.000000%

6. Link

6.1 Modulation Scheme

When deciding a viable modulation scheme to facilitate the downlink on the S-band, the following were important factors considered during the decision-making process;

1. Bit error rate and Eb/N0 relation
2. Spectral requirements
3. Power constraints
4. Circuit complexity

Considering the dense payload data required to be downlinked, along with the budgetary requirements placing constraints on the complexity of our transceivers, and limited power constraints, the decision of using QPSK for our S-band downlink architecture was made [2].

6.2 Coding Rate and Methods

Another critical component of the architecture is the coding schemes providing resilience to errors. The merits of using a (7, ½) convolutional code which includes a high value (unlike most convolutional codes) of free distance = 10 along with its transparent nature makes it a great choice for space applications. Additionally, using a concatenated code incorporating Reed Solomon (255, 223) code and the convolutional code has been shown to provide great resilience against errors[5].

A simulation run using the "bertool' of MATLAB showing the effectiveness of the Reed Solomon (255, 223) codes and the (7, ½) convolutional codes when compared to uncoded QPSK is shown in Fig 2.

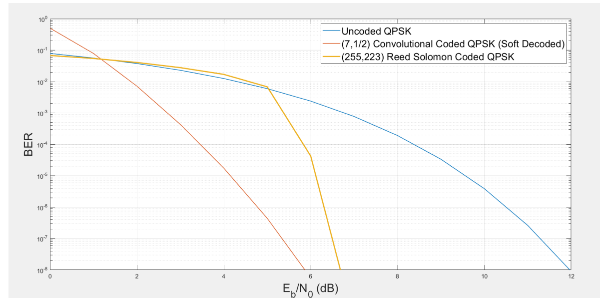

Fig 2. BER vs Eb/N0 for different coding schemes

6.3 Link Budget

A preliminary link budget was created to test the viability of the communication system elaborated over the course of this paper. Values presented in Table 4 have been rounded off to two decimal places.

Table 4. Link Budget

Tx Output Power	**3 dBm**
Cable Losses	**1.5 dB**
HPA Gain	**30 dB**
Tx Antenna Gain	**6 dB**
EIRP	**32 dbm**
Free Space Path Loss	**162 dB**
Pointing Loss	**1 dB**
Polarization Loss	**0 dB**
Atmospheric Loss	**0.5 dB**
Ionospheric Loss	**0.1 dB**
Implementation Loss	**2 dB**
Rx Antenna Noise Temperature	**30 K**
LNA Gain	**35 K**
LNA Noise Temperature	**35.38 K**
Cable Noise Temperature	**124.28 K**
Rx Noise Temperature	**1163.44 K**
Final System Noise Temperature	**65.95 K**
Rx Antenna Gain	**31 dB**

G/T	**12.81 dB/K**
C/N	**77.81dB**
Data Rate	**2.00 Mbps**
Data Rate (logarithmic)	**62.22**
Eb/N0	**14.59 dB**
Coding Gain	**7.50 dB**
Eb/N0 Received	**22.09 dB**
Eb/N0 Required	**11.00 dB**

The Eb/N0 value required was calculated taking our QPSK modulation scheme and a Bit Error Rate (BER) of 10^{-6}. From here, it is concluded that the link closes with a final margin of 11.09 dB.

7. Discussions

The following challenges were faced in developing the S-Band Communication system;

1. Due to operating at 2.4GHz, a lower link margin was available, hence to increase the link margin, half rate convolutional encoding was performed. However, this reduces the effective data rate.
2. The power consumption has also increased significantly and has to be taken into account while designing small satellites.
3. To maintain the link margin higher pointing accuracy is required for the patch antenna as well as its positioning determined on the satellite surface, keeping in account solar panel positioning while ensuring maximum gain.

8 . Conclusions

The Onboard Architecture is chosen to maximize process throughput and to maintain data concurrency. The tasks divided between cores are how this is achieved.

If the S-Band downlink fails, even though a backup UHF downlink wouldn't have the required data rates to downlink the image data, the image metadata and system information however can still be relayed hence ensuring the partial success of the mission.

Shifting to the S-band for downlink has enabled the increase of data rates to 1 Mbps facilitating the downlink of dense payload data. Using CCSDS protocols gives access to a wide variety of online resources and support from various ground stations. The efforts are theoretically supported by the final link margin of 11.09 dB.

Acknowledgments

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Appendix A (Frames)

MASTER CHANNEL ID		VIRTUAL CHANNEL ID	OCF FLAG	MASTER CHANNEL COUNT	VIRTUAL CHANNEL COUNT	TRANSFER FRAME DATA FIELD STATUS				
TRANSFER FRAME VERSION NUMBER	SPACECRAFT ID					TRANSFER FRAME SECONDARY HEADER FLAG	SYNCH FLAG	PACKET ORDER FLAG	SEGMENT LENGTH ID	FIRST HEADER POINTER
2 bits	10 bits	3 bits	1 bit	1 byte	1 byte	1 bit	1 bit	1 bit	2 bits	11 bits
2 bytes						2 bytes				

Frame 1:CCSDS TM space data link layer frame primary header [3]

TRANSFER FRAME VERSION NUMBER	BYPASS FLAG	CONTROL COMMAND FLAG	RSVD. SPARE	SPACECRAFT ID	VIRTUAL CHANNEL ID	FRAME LENGTH	FRAME SEQUENCE NUMBER
2 bits	1 bit	1 bit	2 bits	10 bits	6 bits	10 bits	8 bits
2 bytes					2 bytes		1 byte

Frame 2:CCSDS TC space data link layer frame primary header [4]

Appendix B (Flowcharts)

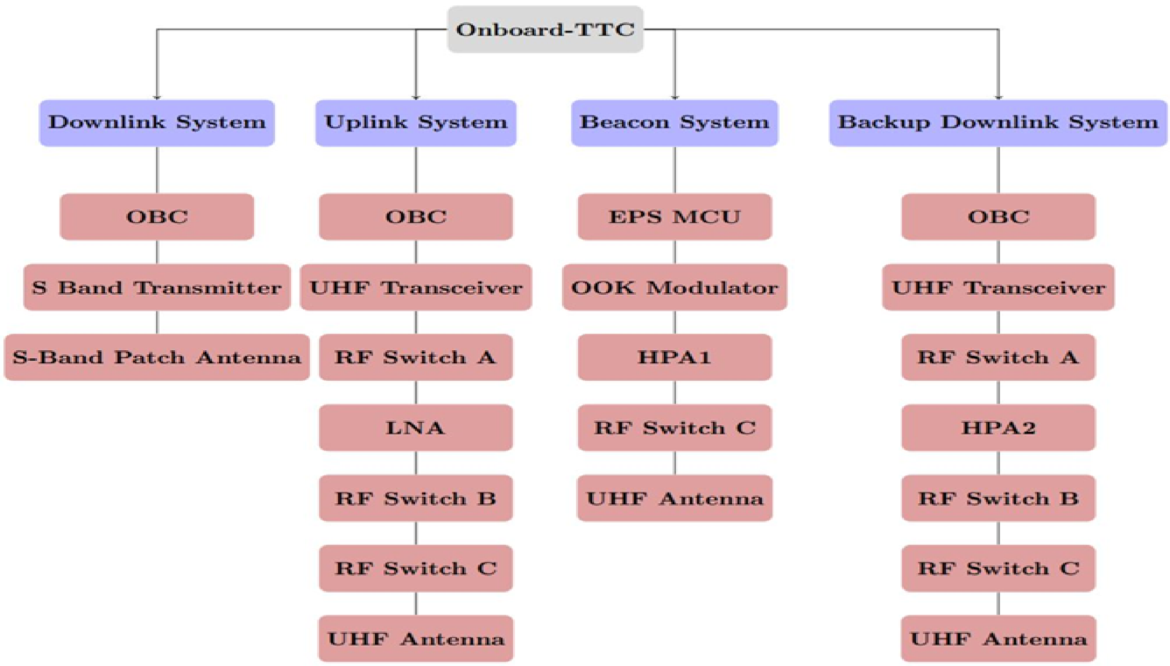

Fig 3. Component selection

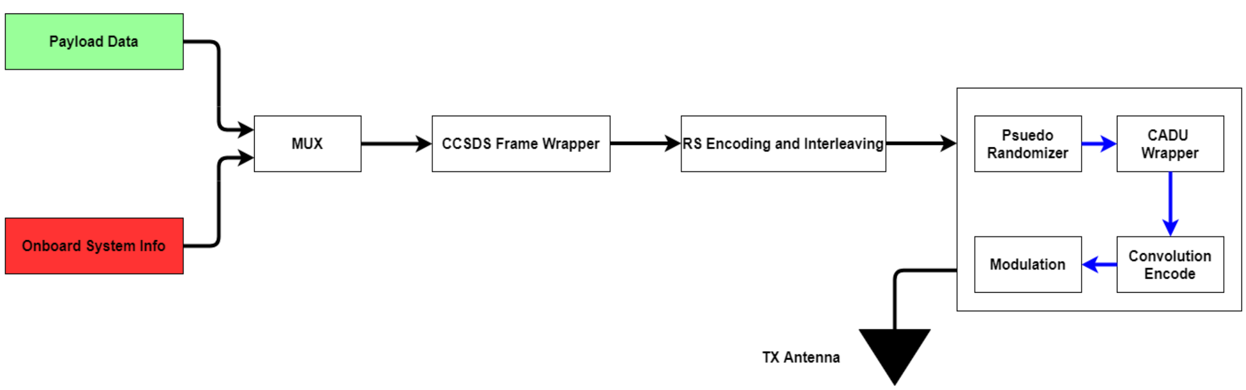

Fig 4. On board transmitting flow

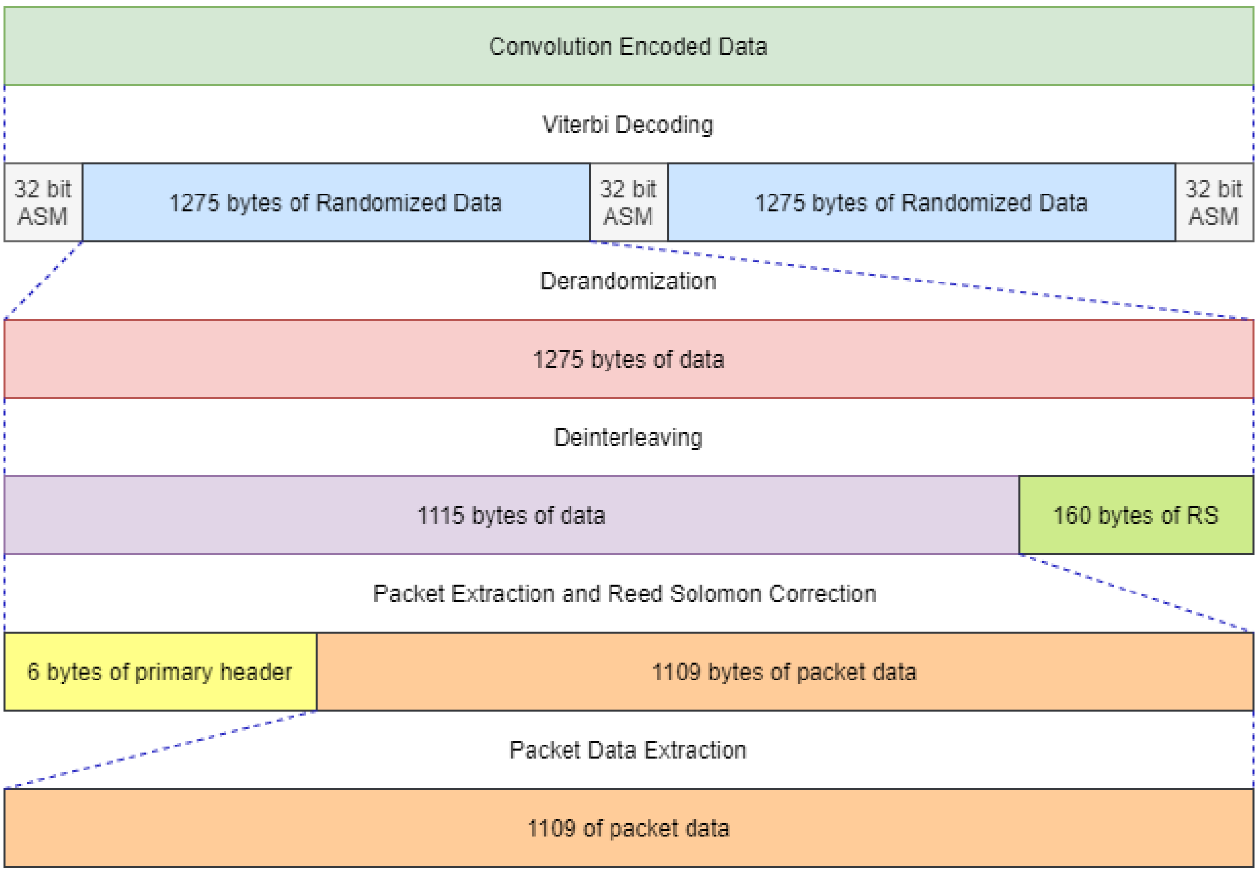

Fig 5. Decoding the received bits

Appendix C (Architecture)

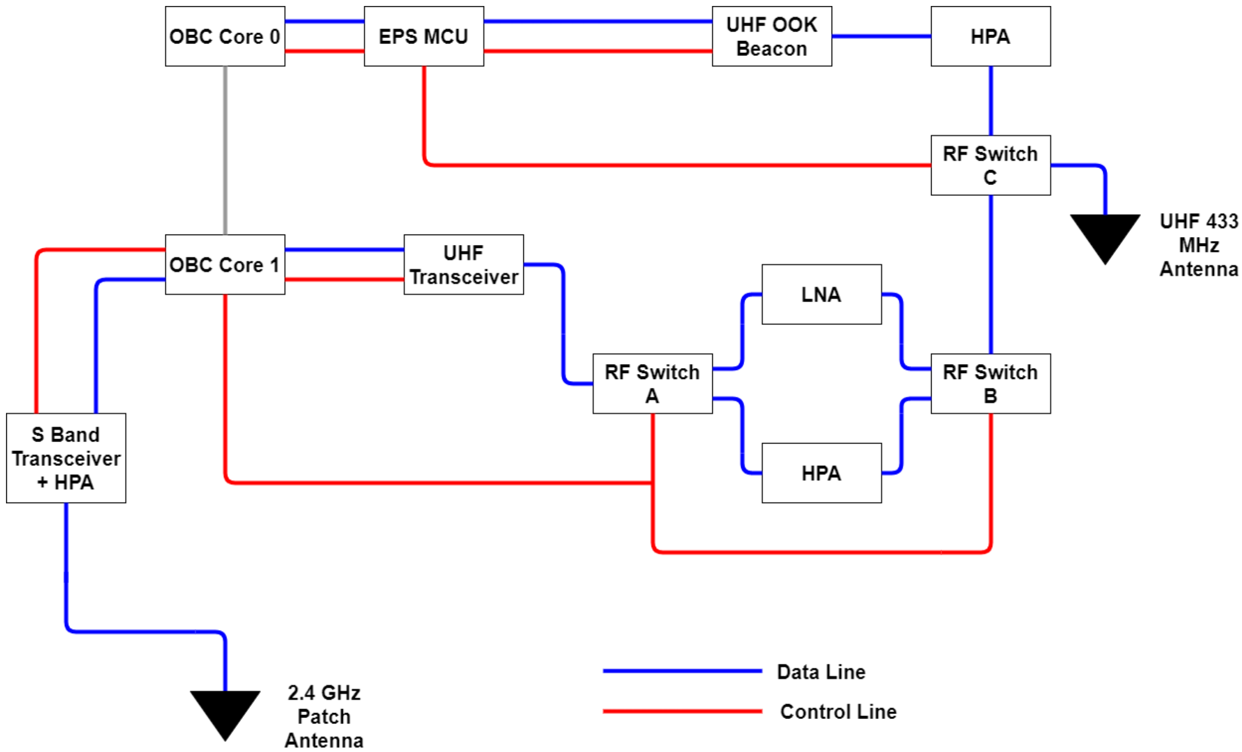

Fig 6. The On-Board Architecture

Appendix D (Figures)

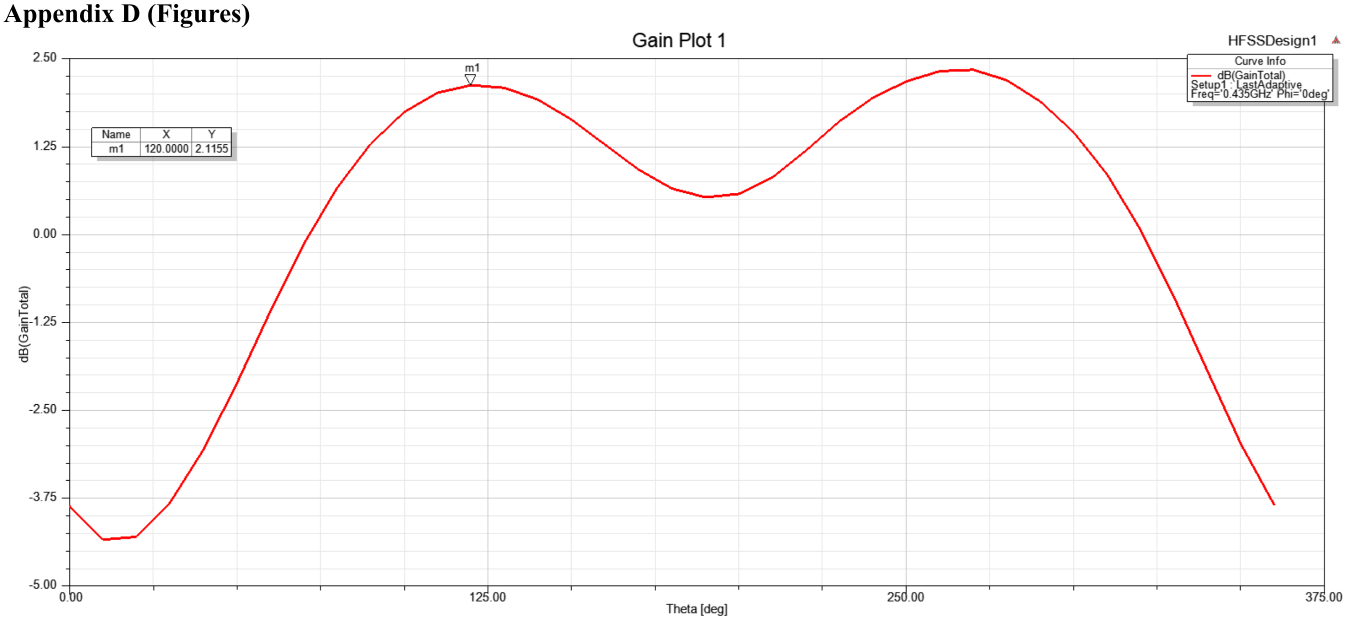

Fig 7. UHF Monopole Gain Plot