Abstract:

This thesis focuses on the comprehensive analysis of a communication system for a 3-unit CubeSat, VibesSat, developed to research micro vibrations in microgravity environments. The satellite employs an FPGA-based onboard processor to generate an IQ data stream for RF modulation, while the ground station utilizes a 1.9-meter dish antenna to process received signals. The study aims to optimize the end-to-end communication link by addressing challenges such as noise, path attenuation, and channel impairments that may degrade signal integrity.

Key objectives include evaluating the frequency spectrum, bandwidth, power efficiency, and signal quality through metrics like Bit Error Rate (BER) and Error Vector Magnitude (EVM). The methodology integrates Python-based simulations, AWR VSS tools for virtual system analysis, and hardware measurements to validate performance. The research will also assess phenomena such as multipath effects, Doppler shifts, and polarization mismatches, culminating in a detailed link budget analysis.

Expected outcomes include a robust communication link design with optimized signal processing algorithms, enhanced reliability, and detailed documentation to guide future CubeSat missions. This work contributes significantly to the field of small satellite communication systems, ensuring effective data transmission and operational success in space research.

**TABLE OF CONTENTS**

**Author's Declaration** ii

**Abstract** iii

**Acknowledgements** iv

**List of Figures** viii

**List of Tables** x

**1 Introduction 1**

1.1 CubeSat Communication Systems Overview . . . . . . . . . . . . . . . . . . . .

1.2 Vibes Sat Mission . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .

1.3 Communication Link Fundamentals . . . . . . . . . . . . . . . . . . . . . . . .

1.4 Signal Processing Chain . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 6

1.4.1 IQ Data Stream Generation . . . . . . . . . . . . . . . . . . . . . . . . 71.

1.5 Materials and Methods . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 8

1.6 Motivation and Objectives . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 9

**2 CubeSat Communication System Architecture 11**

2.1 Satellite Hardware Platform . . . . . . . . . . . . . . . . . . . . . . . . . . . . 11

2.1.1 Pynq Platform Overview . . . . . . . . . . . . . . . . . . . . . . . . . . 11

2.1.2 FPGA Implementation for Baseband Processing . . . . . . . . . . . . . 13

2.2 Ground Station Architecture . . . . . . . . . . . . . . . . . . . . . . . . . . . . 14

2.2.1 RF Frontend . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 15

2.2.2 Digital Receiver . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 16

2.3 Signal Modulation Techniques . . . . . . . . . . . . . . . . . . . . . . . . . . . 17

2.3.1 Modulation Schemes . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 18

2.3.2 Trade-offs in Modulation Selection . . . . . . . . . . . . . . . . . . . . . 19

**3 System Analysis Methodology 21**

3.1 Python Script-Based Analysis . . . . . . . . . . . . . . . . . . . . . . . . . . . 21

3.1.1 Simulation Environment Setup . . . . . . . . . . . . . . . . . . . . . . . 22

3.1.2 Channel Modeling . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 23

3.2 AWR Virtual System Simulator Implementation . . . . . . . . . . . . . . . . . 25

3.2.1 RF Component Modeling . . . . . . . . . . . . . . . . . . . . . . . . . . 26

3.2.2 Impairment Simulation . . . . . . . . . . . . . . . . . . . . . . . . . . . 27

3.3 Hardware-Based Measurement Setup . . . . . . . . . . . . . . . . . . . . . . . 28

3.3.1 Test Equipment Configuration . . . . . . . . . . . . . . . . . . . . . . . 29

3.3.2 Measurement Procedures . . . . . . . . . . . . . . . . . . . . . . . . . . 30

**4 Spectrum Analysis 32**

4.1 Transmitter Spectrum Characterization . . . . . . . . . . . . . . . . . . . . . . 32

4.2 Receiver Spectrum Analysis . . . . . . . . . . . . . . . . . . . . . . . . . . . . 34

4.3 Bandwidth Optimization . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 36

4.4 Interference Analysis . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 37

**5 Signal Quality Assessment 40**

5.1 Power Efficiency Analysis . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 40

5.1.1 Signal-to-Noise Ratio Evaluation . . . . . . . . . . . . . . . . . . . . . 41

5.1.2 Energy per Bit Optimization . . . . . . . . . . . . . . . . . . . . . . . . 43

5.2 Frequency Stability Assessment . . . . . . . . . . . . . . . . . . . . . . . . . . 44

5.2.1 Phase Noise Analysis . . . . . . . . . . . . . . . . . . . . . . . . . . . . 45

5.2.2 Local Oscillator Requirements . . . . . . . . . . . . . . . . . . . . . . . 46

5.3 Nonlinear Distortion Effects . . . . . . . . . . . . . . . . . . . . . . . . . . . . 47

5.3.1 Power Amplifier Characterization . . . . . . . . . . . . . . . . . . . . . 48

5.3.2 Vector Error Analysis . . . . . . . . . . . . . . . . . . . . . . . . . . . . 49

5.4 Eye Pattern Analysis . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 50

5.5 Error Vector Magnitude Measurement . . . . . . . . . . . . . . . . . . . . . . . 52

**6 Communication Link Performance 54**

6.1 Bit Error Rate Analysis . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 54

6.1.1 AWGN Channel Performance . . . . . . . . . . . . . . . . . . . . . . . . 55

6.1.2 Robustness Assessment . . . . . . . . . . . . . . . . . . . . . . . . . . . 57

6.2 Path Attenuation Study . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 58

6.2.1 Free Space Path Loss . . . . . . . . . . . . . . . . . . . . . . . . . . . . 59

6.2.2 Atmospheric Effects . . . . . . . . . . . . . . . . . . . . . . . . . . . . 60

6.3 Polarization and Pointing Mismatch Analysis . . . . . . . . . . . . . . . . . . 61

6.4 Multipath Effects Evaluation . . . . . . . . . . . . . . . . . . . . . . . . . . . 63

6.5 Doppler Shift Compensation . . . . . . . . . . . . . . . . . . . . . . . . . . . . 65

6.5.1 Orbit Analysis . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 66

6.5.2 Compensation Techniques . . . . . . . . . . . . . . . . . . . . . . . . . . 67

**7 Link Budget Analysis 69**

7.1 Transmitter Parameters . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 69

7.2 Channel Effects . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 71

7.3 Receiver Parameters . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 73

7.4 Comprehensive Link Budget . . . . . . . . . . . . . . . . . . . . . . . . . . . . 74

7.5 Margin Analysis . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 76

**8 Comparison of Analysis Methods 78**

8.1 Python Simulation vs. VSS Results . . . . . . . . . . . . . . . . . . . . . . . . 78

8.2 Simulation vs. Hardware Measurements . . . . . . . . . . . . . . . . . . . . . . 80

8.3 Discrepancy Analysis . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 82

8.4 Method Selection Guidelines . . . . . . . . . . . . . . . . . . . . . . . . . . . . 84

**9 Conclusions 86**

9.1 Key Findings . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 86

9.2 System Optimization Recommendations . . . . . . . . . . . . . . . . . . . . . . 88

9.3 Future Work . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 90

**References** 92

**Appendix A: List of Symbols and Abbreviations A-1**

A.1 List of Symbols . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . A-1

A.2 List of Abbreviations . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . A-2

**Appendix B: Python Analysis Scripts B-1**

B.1 Channel Simulation Code . . . . . . . . . . . . . . . . . . . . . . . . . . . . . B-1

B.2 Signal Processing Algorithms . . . . . . . . . . . . . . . . . . . . . . . . . . . B-3

B.3 Link Budget Calculation Script . . . . . . . . . . . . . . . . . . . . . . . . . . B-7

**Appendix C: AWR VSS Models C-1**

C.1 System Component Models . . . . . . . . . . . . . . . . . . . . . . . . . . . . . C-1

C.2 Simulation Configurations . . . . . . . . . . . . . . . . . . . . . . . . . . . . . C-4

C.3 Parameter Sweep Scripts . . . . . . . . . . . . . . . . . . . . . . . . . . . . . C-7

**Appendix D: Measurement Data D-1**

D.1 Hardware Test Results . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . D-1

D.2 Data Processing Scripts . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . D-4

D.3 Calibration Procedures . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . D-7

**List of Figures**

1. CubeSat 3U form factor illustration
2. Vibes Sat mission overview diagram
3. Basic communication link block diagram
4. Signal processing chain flowchart
5. IQ data stream generation process
6. Pynq platform architecture
7. FPGA implementation for baseband processing
8. Ground station architecture diagram
9. RF frontend block diagram
10. Digital receiver signal flow
11. Modulation schemes comparison chart
12. Python simulation environment setup
13. Channel model block diagram
14. AWR VSS system model
15. RF component models in VSS
16. Hardware measurement setup schematic
17. Transmitter output spectrum
18. Receiver input spectrum analysis
19. Bandwidth optimization results
20. Interference analysis plot
21. SNR vs. distance graph
22. Energy per bit optimization curve
23. Phase noise plot
24. Power amplifier AM-AM and AM-PM characteristics
25. Vector error analysis constellation diagram
26. Eye pattern for different channel conditions
27. EVM measurement results
28. BER vs. SNR curves for AWGN channel
29. Path attenuation vs. distance plot
30. Polarization mismatch effects graph
31. Multipath fading simulation results
32. Doppler shift vs. orbital position
33. Comprehensive link budget diagram
34. Link margin analysis chart
35. Python vs. VSS simulation results comparison
36. Simulation vs. hardware measurement comparison
37. Method selection decision tree

**1.1 CubeSat Communication Systems Overview**

CubeSats represent a revolutionary approach to satellite development, offering standardized, low-cost platforms that have democratized access to space. These miniaturized satellites, typically developed in standard 1U (10cm × 10cm × 10cm), 2U, 3U, or larger configurations, rely on sophisticated yet highly constrained communication systems to fulfill their mission objectives. This overview examines the fundamental aspects, challenges, and design considerations of CubeSat communication systems.

**Fundamental Architecture**

A typical CubeSat communication system consists of both space and ground segments, each with distinct components and requirements:

**Space Segment**

The onboard communication subsystem of a CubeSat includes:

1. **Baseband Processor**: Often implemented within a programmable logic device like an FPGA (Field-Programmable Gate Array), this component handles digital signal processing functions including:
   * Data encoding and error correction
   * Modulation of digital data into IQ (In-phase and Quadrature) data streams
   * Data framing and packetization
   * Command and telemetry processing
2. **RF Transceiver**: Converts baseband signals to radio frequency and vice versa, typically operating in VHF, UHF, S-band, or X-band frequencies depending on mission requirements.
3. **Power Amplifier**: Boosts the RF signal to the required transmission power, typically limited to 1-2W due to power constraints.
4. **Antenna System**: Ranges from simple monopole/dipole antennas to more sophisticated deployable structures, patch arrays, or reflector designs.
5. **Processing Platform**: Modern CubeSats increasingly utilize integrated platforms such as Pynq, which combines programmable logic with processing systems to provide flexible signal processing capabilities while minimizing size, weight, and power requirements.

**Ground Segment**

The ground station infrastructure typically includes:

1. **Antenna Systems**: Ranging from simple Yagi antennas to large dish antennas (such as the 1.9-meter dish mentioned in the Vibes Sat mission), designed to provide sufficient gain for reliable signal reception.
2. **RF Frontend**: Comprises low-noise amplifiers (LNAs), filters, mixers, and frequency converters that process the received RF signal.
3. **Digital Receiver**: Performs digitization, demodulation, decoding, and data extraction to recover the transmitted information.
4. **Control Software**: Manages antenna pointing, frequency correction for Doppler shifts, scheduling of communication passes, and data management.

**Communication Link Characteristics**

CubeSat communication links operate under several unique constraints and considerations:

**Frequency Allocation**

CubeSats typically operate in:

* **VHF/UHF Bands** (144-146 MHz, 435-438 MHz): Common for amateur radio-based CubeSats, offering good propagation characteristics but limited bandwidth
* **S-Band** (2.2-2.3 GHz): Provides increased bandwidth for higher data rates
* **X-Band** (8.0-8.4 GHz): Enables even higher data rates but requires more sophisticated RF components and precise antenna pointing

**Link Challenges**

Several factors affect the quality and reliability of CubeSat communication links:

1. **Power Limitations**: CubeSats typically have severe power constraints due to limited solar panel area and battery capacity, restricting transmitter power to levels often below 2W.
2. **Antenna Limitations**: Physical size constraints limit antenna gain, particularly at lower frequencies, affecting link budget calculations.
3. **Path Attenuation**: Signal strength decreases with the square of distance, creating significant challenges for CubeSats in higher orbits.
4. **Doppler Shift**: The relative movement between satellite and ground station introduces frequency shifts that must be compensated for during signal reception.
5. **Limited Contact Time**: Depending on the orbit, communication windows with any single ground station may be limited to 5-15 minutes per pass.
6. **Environmental Factors**: Atmospheric effects, multipath propagation, polarization mismatches, and pointing errors all contribute to signal degradation.

**Signal Processing Considerations**

The signal processing chain in CubeSat communications involves several key stages that must be carefully designed and optimized:

**Modulation Schemes**

CubeSats employ various modulation techniques based on mission requirements:

* **BPSK (Binary Phase Shift Keying)**: Commonly used for its robustness and power efficiency, ideal for telemetry links
* **QPSK (Quadrature Phase Shift Keying)**: Offers double the spectral efficiency of BPSK with minimal power penalty
* **Higher-order modulations** (8PSK, 16QAM, etc.): Provide increased data rates at the expense of requiring higher signal-to-noise ratios

**Error Correction Coding**

To enhance link reliability, various coding schemes are employed:

* **Convolutional Codes**: Provide good performance with relatively simple implementation
* **Reed-Solomon Codes**: Effective against burst errors
* **Turbo Codes and LDPC (Low-Density Parity-Check) Codes**: Offer performance approaching theoretical limits but with higher complexity

**IQ Data Stream Generation**

Modern CubeSat communication systems, like the one in the Vibes Sat mission, often generate IQ data streams within the baseband processor:

* **I (In-phase) Component**: Represents the real part of the complex baseband signal
* **Q (Quadrature) Component**: Represents the imaginary part, orthogonal to the I component

This approach allows for efficient digital implementation of various modulation schemes and facilitates the transition to analog RF signals.

**Performance Metrics and Analysis**

Several metrics are essential for evaluating and optimizing CubeSat communication links:

1. **Spectrum Analysis**: Ensures optimal bandwidth utilization and identifies potential interference sources
2. **Signal-to-Noise Ratio (SNR)**: Determines the fundamental limit of detection capability
3. **Bit Error Rate (BER)**: The ultimate performance metric indicating data integrity under various channel conditions
4. **Error Vector Magnitude (EVM)**: Quantifies modulation accuracy and identifies distortions
5. **Eye Pattern Analysis**: Evaluates signal quality and identifies timing errors and jitter
6. **Link Budget**: Comprehensive accounting of all gains and losses in the communication path, including:
   * Transmitter power and antenna gain
   * Free space path loss
   * Atmospheric attenuation
   * Receiver sensitivity and noise figure
   * Implementation losses

**Advanced Techniques and Future Trends**

CubeSat communication systems continue to evolve with several emerging trends:

1. **Software-Defined Radio (SDR)**: Provides flexibility to implement different waveforms and adapt to changing requirements
2. **MIMO (Multiple-Input Multiple-Output)**: Enhances throughput and reliability through spatial diversity
3. **Optical Communications**: Offers potential for dramatically increased data rates using laser-based links
4. **Intersatellite Links**: Enables formation of CubeSat constellations with mesh networking capabilities
5. **Ground Station Networks**: Distributed networks of ground stations increase communication opportunities and data throughput

As CubeSat missions become more ambitious, involving more sensors and generating larger volumes of data, communication systems must continue to evolve to balance increased data requirements against the fundamental constraints of these small satellite platforms.

Based on the provided documents, I'll extract and summarize the key information about the VIBES satellite mission that's relevant to your thesis.

**1.2 VIBES Satellite Mission**

VIBES Pioneer is a 3-unit CubeSat mission with the primary goal of researching microvibrations in microgravity environments. The mission involves both hardware development and communication system design for data transmission between the satellite and ground stations.

**Communication Systems (TT&C - Tracking, Telemetry and Telecommand)**

The satellite employs a dual-band communication architecture:

1. **UHF-Band Communication (430-440 MHz)**
   * Provides both uplink and downlink capabilities
   * Used for low data rate transmissions (commands and housekeeping data)
   * Communication with DLR Bremen ground station
   * Uses EnduroSat UHF Antenna III (provided by DLR)
   * The antenna has a special modification allowing for camera integration (12mm × 32.4mm aperture)
   * Requires a UHF-Board to be acquired from GAUSS
   * Link budget calculations show a favorable signal-to-noise ratio of 32.1dB
2. **S-Band Communication (2.385 MHz)**
   * Downlink only
   * Used for high data rate transmissions (images and measurement data)
   * Communication with OHB Beacon ground station
   * Uses internally developed components:
     + Four patch antennas (similar to the Aquasonic concept) developed by Master's student Julian Rose
     + S-Band board developed by Bachelor students Miko Kranich and Lars Nickisch
   * Requires omnidirectional capability with TRL 4 (Technology Readiness Level)

**System Integration and Development Status**

* A mock-up has been created to test the integration of UHF antenna with camera payload and to estimate space requirements for the S-Band antenna cabling
* Frequency registration has been initiated with ITU (International Telecommunication Union)
* Amateur radio callsigns are being arranged through DLR and OHB representatives
* IARU (International Amateur Radio Union) application is in preparation

**Communication System Processing**

As noted in your thesis document, the satellite is equipped with:

* An onboard processor based on the Pynq platform integrating a programmable logic FPGA and processing system
* A baseband processor implemented within the FPGA capable of generating IQ data streams for RF modulation
* The ground station includes a 1.9-meter dish antenna, RF frontend, and digital receiver for signal processing

**Your Thesis Context**

Your thesis will focus on analyzing and optimizing the complete signal path from the satellite to ground stations, with specific attention to:

* Spectrum analysis
* Bandwidth optimization
* Power efficiency
* Frequency stability
* Signal quality assessment through multiple methodologies (Python simulations, AWR VSS simulations, and hardware measurements)

The work will directly contribute to ensuring reliable data transmission for VIBES Pioneer's mission of researching microvibrations in the space environment.

Based on the diagram shown and the nature of your CubeSat communication system thesis, the missing part of page 2 would likely contain:

1. **Receiver Architecture** - The current diagram only shows the transmitter side (Aquabrain). The missing portion would likely show the corresponding ground station receiver architecture that processes the transmitted signals, including:
   * RF frontend components
   * Down-conversion stages
   * Digital signal processing blocks
   * Demodulation and decoding systems
2. **Complete Signal Path Diagram** - A full end-to-end representation showing:
   * How the IQ signals from the Aquabrain are modulated onto an RF carrier
   * Power amplification stages
   * Antenna systems (both satellite and ground)
   * Signal propagation through space
   * Ground station reception chain
3. **System Parameters and Specifications** - Technical details such as:
   * Operating frequencies
   * Transmission power levels
   * Antenna gain specifications
   * Expected link budget parameters
   * Bandwidth allocations
   * Signal-to-noise ratio requirements
4. **Communication Protocol Details** - Further elaboration on:
   * Data packet structures
   * Error detection and correction mechanisms
   * Link adaptation techniques
   * Handshaking protocols between satellite and ground station
5. **Integration with CubeSat Platform** - Information about:
   * Physical integration with other CubeSat subsystems
   * Power consumption requirements
   * Thermal considerations
   * Operational modes (normal, low-power, emergency)

These components would provide the complete picture needed for your system analysis, showing both the transmission side (which you have) and the reception side, allowing you to analyze the full communication link as outlined in your thesis objectives.

Based on the Aquabrain diagram and the overall structure of your thesis, here's content you could incorporate into your CubeSat communication system thesis:

**For Section 1.4: Signal Processing Chain**

The Vibes Sat communication system implements a multi-layered signal processing architecture designed to efficiently transmit sensor data while ensuring robust performance in the challenging space environment. Figure 1.X illustrates the complete signal processing chain implemented within the satellite's onboard processor.

At the core of this system is the Aquabrain processing module, which handles all aspects of data flow from acquisition to transmission. The process begins with sensor data collection, where environmental and experimental measurements are gathered and fed into the preprocessing stage. This initial stage performs critical functions including error checking, preliminary signal processing, and storage of data in nonvolatile memory to prevent data loss during potential system resets.

Following preprocessing, the Data Link Layer organizes information into structured packets with fixed-length formatting. This standardization is crucial for reliable transmission, as it allows for consistent processing throughout the communication chain. Each packet contains not only the sensor data but also header information necessary for proper reassembly at the ground station.

The Physical Layer represents a critical juncture where data transitions from purely digital information to transmission-ready signals. Here, Reed-Solomon forward error correction (FEC) coding is applied to provide resilience against burst errors that commonly occur in satellite communications. Additionally, checksums and synchronization bits are incorporated to ensure data integrity and to facilitate proper signal recovery at the receiver.

The system then generates an IQ-Stream by splitting the digital bitstream into in-phase (I) and quadrature (Q) components at a symbol rate of 50 ksym/s, converted from the incoming 100 kbit/s data rate. This IQ representation enables the implementation of bandwidth-efficient modulation schemes. Prior to transmission, pulse shaping is applied using a Root-Raised Cosine (RRC) filter with a roll-off factor α=0.35, which optimizes the spectral efficiency while minimizing intersymbol interference. The resulting signal undergoes oversampling and interweaving to produce the final physical signal with a sampling rate of 400 ksamp/s at 10-bit resolution.

**For Section 2.1.2: FPGA Implementation for Baseband Processing**

The baseband processing functionality of the Vibes Sat is implemented within the programmable logic (FPGA) portion of the Pynq platform. Figure 2.X presents the architecture of the Aquabrain processing module, which forms the heart of the satellite's communication system.

The FPGA implementation leverages the reconfigurable nature of programmable logic to create an efficient signal processing pipeline that can be optimized for the specific requirements of the CubeSat mission. The design follows a layered approach that mirrors the OSI communication model, with distinct modules handling different aspects of the signal chain.

Data flow begins at the preprocessing module, which interfaces directly with the satellite's sensor array. This module implements multiple functions crucial for reliable operation, including data collection protocols, error detection mechanisms, signal processing algorithms, and interfaces to nonvolatile storage. The preprocessing stage ensures that only valid data continues through the processing chain, improving overall system efficiency.

The implementation of the Data Link Layer within the FPGA fabric focuses on efficient data organization. This module packs sensor readings and system information into structured data formats, assembles these into transmission packets, and enforces fixed-length formatting to maintain consistency throughout the processing chain. The standardized output from this stage simplifies downstream processing and improves reliability.

The Physical Layer implementation represents the most computationally intensive portion of the baseband processor. Reed-Solomon encoders provide forward error correction capabilities, critical for maintaining link performance in the space environment where signal degradation is expected. Additional logic adds checksums for error detection and synchronization bits to facilitate receiver synchronization. The FPGA implementation achieves a throughput of 100 kbit/s at this stage, sufficient for the mission's telemetry requirements.

The IQ-Stream module splits the encoded bitstream into in-phase and quadrature components, effectively preparing the data for quadrature modulation. This FPGA module handles the critical timing requirements necessary for proper phase relationships between the I and Q channels, operating at a symbol rate of 50 ksym/s.

The final stage in the FPGA processing chain implements pulse shaping using Root-Raised Cosine filtering. This module is parameterized with a roll-off factor of 0.35, selected as an optimal compromise between spectral efficiency and implementation complexity. The pulse shaping stage includes oversampling logic and interweaving functions, producing output samples at 400 ksamp/s with 10-bit resolution, which are then passed to the RF section for modulation and transmission.

The modular design of the FPGA implementation allows for individual testing and validation of each processing block, facilitating both development and troubleshooting. Furthermore, this architecture provides flexibility for potential in-orbit reconfiguration should mission requirements change during operation.