Evaluation of radiation tolerant satellite communication modem

Venkata Srikanth Bhuma
Santosh Kumar Balsu
This thesis is submitted to the School of Computing at Blekinge Institute of Technology in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering. The thesis is equivalent to 20 weeks of full time studies.

Contact Information:
Author(s):
Venkata Srikanth Bhuma
E-mail: sreekanthbv@gmail.com
Santosh Kumar Balsu
E-mail: santhu0025@gmail.com

External advisor(s):
Jan Schulte
ÅAC Microtec AB
Dag Hammarskjölds väg 54,
SE-751 83 Uppsala
Sweden
Phone: +46700910429

University advisor(s):
Craig A. Lindley
School of Computing

University Examiner(s):
Patrik Arlos
School of Computing

School of Computing
Blekinge Institute of Technology
371 79 Karlskrona
Sweden

Internet : www.bth.se/com
Phone : +46 455 38 50 00
Fax : +46 455 38 50 57
ABSTRACT

The design specification of CubeSat standards by California Polytechnique University has become a major milestone in development and deployment of nano satellites. The number of CubeSats that are being deployed into the orbit has increased in recent years. The design and development have been transformed from traditional hardware devices to software defined radios. However there is a lack of clear understanding and concrete findings on developing proper communication transceivers. The lack of knowledge of proper guidelines to be followed to design and develop communication subsystems prompts and acts as a base for us in understanding the communication subsystem design standards followed by CubeSat projects in various universities. Particular attention is given to those CubeSats that are currently in the orbit and are under development. The main aim of the thesis is to identify the challenges faced by the CubeSat developers and provide guidelines for future developers in order to overcome those challenges to reduce the development time and costs which are major constraints in CubeSat developments. A traditional literature review process was followed in order to identify the potential issues and in parallel a modem was designed and implemented in order to know some more challenges while developing a CubeSat modem. From the literature review method, eight potential issues were identified and an additional two more challenges were experienced while implementing a modem. Potential advantages and disadvantages of using nanoRTU have also been identified as part of the work.

Keywords: CubeSat, communication subsystem, software defined radio modem, challenges.
ACKNOWLEDGEMENT

We would like to express our immense gratitude to our supervisor Prof. Craig A. Lindley for his valuable guidance, support and motivating us throughout the research. We appreciate his vast knowledge and skill in many areas, which have made us to improve our areas of research.

We would like to thank Dr. Fredrik Bruhn and Mr. Jan Schulte for their support and supervision throughout this work. Very special thanks to ÅAC Microtec AB for providing us with all the necessary equipment.

We are greatly thankful to our beloved parents for their relentless support that helped us to reach our goals.

Finally, we offer our sincere thanks to our friends and colleagues for their valuable contributions and making this work, a success.

Regards,
Santosh and Srikanth.
# CONTENTS

ABSTRACT .................................................................................................................................................. I

ACKNOWLEDGEMENT ............................................................................................................................. II

CONTENTS ................................................................................................................................................ III

LIST OF FIGURES ..................................................................................................................................... III

LIST OF TABLES ........................................................................................................................................ IV

LIST OF ABBREVIATIONS ...................................................................................................................... V

1 INTRODUCTION ...................................................................................................................................... 1

1.1 MOTIVATION .................................................................................................................................... 2

1.2 AIM.................................................................................................................................................. 2

1.3 RESEARCH QUESTIONS .................................................................................................................. 2

1.4 OUTLINE ........................................................................................................................................ 3

2 BACKGROUND ...................................................................................................................................... 4

2.1 KEY CONCEPTS .............................................................................................................................. 4

2.1.1 CubeSat ................................................................................................................................... 4

2.1.2 Communication subsystem ...................................................................................................... 5

2.1.3 modem ................................................................................................................................... 6

2.1.4 Modulation and Demodulation techniques ............................................................................. 6

2.1.5 Communication Protocol ........................................................................................................ 8

2.1.6 NanoRTU .................................................................................................................................. 8

2.1.7 Radiation .................................................................................................................................. 8

2.1.8 FPGA and VHDL ...................................................................................................................... 9

2.1.9 FPGA vs. DSP .......................................................................................................................... 9

2.1.10 Software Defined Radio (SDR) ........................................................................................... 9

2.1.11 Plug and Play ......................................................................................................................... 10

2.2 SURVEY OF RELATED WORK ..................................................................................................... 10

3 RESEARCH METHODOLOGY AND IMPLEMENTATION .................................................................. 12

3.1 RESEARCH METHODOLOGY ....................................................................................................... 12

3.2 IMPLEMENTATION ........................................................................................................................ 13

3.2.1 Literature Review ................................................................................................................... 14

3.2.2 Design and implementation of modem ................................................................................ 16

4 RESULTS & ANALYSIS ....................................................................................................................... 22

4.1 STATE OF ART ............................................................................................................................. 22

4.1.1 Successful CubeSat launches ................................................................................................. 22

4.1.2 CubeSats in development ...................................................................................................... 26

4.2 CRITERIA FOR MODEM IMPLEMENTATION ........................................................................... 32

4.2.1 Challenges faced by CubeSat developers – Results after literature review ....................... 32

4.2.2 Challenges encountered during experimentation ................................................................. 34

4.3 ADVANTAGES AND DISADVANTAGES NANO RTU W.R.T CRITERIA ................................. 35

5 CONCLUSION & FUTURE WORK ...................................................................................................... 36

5.1 CONCLUSION .............................................................................................................................. 36

5.2 FUTURE WORK ............................................................................................................................ 37

6 BIBLIOGRAPHY ................................................................................................................................ 38

7 APPENDIX A ........................................................................................................................................ 43
LIST OF FIGURES

Figure 2.1 The prototype of the CubeSat with the mother board ..............................................4
Figure 2.2 A general overview of the communication subsystem .................................................6
Figure 2.3 AX.25 protocol stack .................................................................8
Figure 3.1 Constructive research flow ..................................................................................12
Figure 3.2 Research flow ...................................................................................................14
Figure 3.3 Illustration of the digital satellite communication modem ......................................16
Figure 3.4 ÅAC nanoRTU 211 ..............................................................................................17
Figure 3.5 Modem intercommunication .............................................................................17
Figure 3.6 Process flow .......................................................................................................18
Figure 3.7 AFSK Demodulation algorithm [55] .................................................................19
Figure 3.8 BPSK Modulation algorithm .............................................................................19
Figure 3.9 AFSK demodulation simulation ..........................................................................20
Figure 3.10 BPSK modulation simulation ............................................................................21
Figure 3.11 Programming FPGA .......................................................................................21
Figure 7.1 Hardware consumption for the AFSK demodulator algorithm (code 1) .............43
Figure 7.2 Hardware consumption for the AFSK demodulator algorithm (code 2) ..........44
LIST OF TABLES

Table 4.1 CubeSat communication subsystems from 2011 to till date ........................................28
Table 4.2 CubeSat communication subsystems from 2003-2011 [60] ........................................31
Table 4.3 Verification of nanoRTU with the stated problems in LR ..............................................35
LIST OF ABBREVIATIONS

ADC Analog to Digital Converter
ADCS Attitude Determination and Control System
AFSK Audio Frequency Shift Keying
ASK Amplitude Shift Keying
BPSK Binary Phase Shift Keying
BPS Bits per Second
COTS Commercial Off-The-Shelf
DAC Digital to Analog Converter
DSP Digital Signal Processor
DTMF Dual Tone Multi-Frequency
EDAC Error Detection and Correction
EPS Electrical Power Systems
FPGA Field-Programmable Gate Array
FSK Frequency Shift Keying
GMSK Gaussian Minimum Shift Keying
HDL Hardware Description Language
JPEG Joint Photographic Experts Group
LR literature Review
OBDH On-Board Data Handling
PnP Plug and Play
PSK Phase Shift Keying
QAM Quadrature Amplitude Modulation
RTU Remote Terminal Unit
SDR Software Defined Radio
SPA Space Plug and Play Avionics
TC Telecommand
TM Telemetry
TNC Terminal Node Controller
TT&C Tracking Telemetry and Command
VHDL Very high speed integrated circuit Hardware Description Language
1 INTRODUCTION

Technological advancements have led to minimizing the size of innovative devices. Mobile phones, computers, processors etc. are getting smaller as a result of new and improved technology and the same is true in the space industry. With the rapid development of space technology, researchers are oriented towards designing and building smaller satellites for various commercial, scientific and educational purposes. CubeSats are a result of this major revolution in the space industry. Time consuming processes, bulk sizes and costs involved in building traditional satellites for educational purposes have led the scientific community to develop low cost and light nano-satellites. One of the major factors differentiating traditional satellites from CubeSats is the scope for innovation in latest space technology. Traditional satellites do not allow for much scope in renovating and innovating newer space standards but CubeSats expand the opportunities for experimenting and working with the latest technology. The CubeSat standard was developed in 1999 by the California polytechnic state university and Stanford University. Since then there have been 250 CubeSats deployed in orbit or in development state [18].

CubeSats, or nano-satellites, are very small satellites with specified dimensions of 10x10x10 cm. The primary goal of developing CubeSats is to provide better educational opportunities for students and researchers in space technology and to test the latest technology in the space industry. Although there are a number of advantages to building and operating CubeSats, there are a few limitations such as payload restrictions, slower communication links, low solar power generated from the surface of CubeSats and radiation, which can be traded off against the huge benefits of using such satellites. A CubeSat comprises of different subsystems. Each subsystem has a specific and important role in effective functioning of the satellite. The communication subsystem is one of the most important subsystems and is responsible for communication between the satellite and the ground station.

Communication subsystems of different CubeSats vary and depend on the use and application of the CubeSat being developed. These subsystems are designed according to the specific requirements of the CubeSat. To make the development process more flexible, cheaper, easy and fast, most university CubeSat projects use commercial off-the-shelf (COTS) components as they are cost effective and easy to integrate with the onboard systems. Most CubeSats were designed using these COTS components. Further development of the communication subsystem is a good choice of area for a thesis project in order to improve the communication link between the On-Board Data Handling (OBDH) system and ground stations, keeping the cost and size of the CubeSat down.

The terminal node controller along with the modem is the heart of the communication subsystem. A proper design of the CubeSat modem can establish a good communication link between the OBDH and the ground station. The two most important constraining factors during the design of a modem are the limited transmitter power available for use and the size of the subsystem [14]. In this thesis work, an attempt is made to design a communication subsystem by replacing the terminal node controller with a Plug and Play device (PnP) called nano Remote Terminal Unit (nanoRTU) on which a modem is integrated taking into consideration the power and size constraints. The modem in this subsystem is designed on a Field-programmable gate array (FPGA) using software defined radio technology.
The work established in this thesis aims to study the various design processes of different communication subsystems to gain a thorough understanding of the concepts involved during the development and the complications encountered. A specific purpose of this thesis is to develop criteria for developing a CubeSat modem which can act as a guideline for future developers. The criteria developed are based on our attempt to design and develop a modem based on software defined radio technology integrated on the nanoRTU.

In order to achieve these research objectives, a literature review was conducted to identify the potential problems that evolved in designing a modem and a software based modem was designed and implemented to identify the challenges faced in real time.

1.1 Motivation

Extensive research has been carried out in developing communication subsystems for CubeSats which are used for different applications. Researchers so far, have stressed and concentrated on the development process but very few of them extensively analyzed the problems faced during the development and launch of these systems on board the CubeSat. Measures to be taken to avoid such problems are also left unanswered. Also, no specific evaluation criteria for modems have been proposed to allow future work in the area to be more agile and easily comprehensible. These drawbacks in current research have motivated us to carry out the work in our thesis. In this thesis, a literature review of all possible cases involved in developing a communication subsystem for a CubeSat was performed to analyze and specifically point out the problems that may occur during the process of design and development. The state of the art survey carried out not only suggests complications faced while developing a communication subsystem but this also led to identification of the important measures to be taken during subsystem development, providing evaluation criteria for modems for design in the future. To enrich the thesis in a more practical way, problems faced during the experiment by using a nanoRTU in the subsystem are mentioned to avoid any future obstacles in the development process.

1.2 Aim

The main aim of the thesis is to establish a set of criteria to evaluate modem designs for future CubeSat projects through an extensive state of art literature review of current CubeSat communication subsystem designs and practical implementation on a nanoRTU. In addition, evaluating advantages and disadvantages of the nanoRTU with respect to the established criteria forms the secondary aim.

1.3 Research Questions

The research questions driving the thesis project are:

1. What is the state-of-art in the current research and development of CubeSat communication subsystems?

2. What are the criteria for evaluating alternative modem implementations (software/hardware) for CubeSat spacecraft systems?
3. What are the respective advantages and disadvantages of the nanoRTU, in relation to other systems and (how) can this be quantified?

1.4 Outline

The remaining parts of this document are organized as follows. A brief introduction of the concepts used for this thesis and survey of related works are presented in Chapter 2. The methodology and implementation of the experiment are discussed in Chapter 3. The results and analysis are presented in Chapter 4. Finally, conclusion and future work are presented in Chapter 5.


# Background

This chapter presents the key concepts and the Survey of Related works.

## 2.1 Key concepts

This section briefly presents the necessary concepts to understand this thesis.

### 2.1.1 CubeSat

A CubeSat is Nano satellite designed for Low Earth orbit. It is 10x10x10 cm cube which weighs about 1Kg [2]. The CubeSat project was initially started by California Polytechnic State University (Cal Poly) and Stanford University in the year 1999. The aim of the project was to develop a low cost Nano satellite for Low earth orbit in support of education programs in space engineering [1]. A standard design specification was developed for CubeSat projects to reduce the cost and development time for future developers of educational satellites.

![CubeSat Prototype](image)

Figure 2.1 The prototype of the CubeSat with the mother board

The fig 2.1 shows the prototype of the CubeSat. The available amount of space is very limited. The low surface area of a CubeSat restricts the amount of solar power that may be generated, restricting power available for computation, communications, and payloads. Restrictions on space, power and cost can result in problems like slow communication links, limited payloads, and minimal information processing capabilities. In order to incorporate all subsystems and for effective operation, the
designing of the CubeSat has become very complex. The major departments of the CubeSat are onboard data handler, communication sub-system, the electrical power system, attitude determination and control system and the payloads. Each department has a specific task of its own [3].

**Onboard data handler (OBDH)**

OBDH is the most important subsystem for the overall working of the satellite. This subsystem acts as a main module which controls and manages the remaining subsystems.

**Attitude determination and control system (ADCS)**

This system is very crucial in order to make a mission successful and effective i.e. directing the space craft towards a target.

**Payloads**

The overall CubeSat mission is planned because of the payload. The payloads are some sensors or scientific experiments which have a particular task to perform.

**Electrical power systems (EPS)**

The main functions of the EPS are distribution and control of the power to all other power subsystems based on their electrical power consumption. The length of the mission can be determined on the ability of the power system.

**Communication subsystem**

This subsystem is responsible for the communication between the satellite and the ground station. In this thesis, we focus on the communication sub-systems.

### 2.1.2 Communication subsystem

A communication sub-system is designed to handle three functions (1) to transmit a tracking signal, (2) download telemetry to a ground station and (3) to receive commands from a ground station. A satellite communication system is often referred to as a TT&C (Tracking, Telemetry and Command) system after these functions. The communication between the satellite and the ground station is known as data link, is two way communication channels where the uplink is the data commands transmitted from the ground station to the satellite and the downlink is the telemetry data or the beacon transmitted from the satellite to the ground station [4].

The fig 2.2 shows the block diagram of the communication subsystem and its communication with the ground station. Here the OBDH is the heart of satellite or the main control module. The modem or the Terminal Node Controller (TNC) converts the signals received from the ground station and forwards the data to the OBDH. Both the satellite and ground station should follow a common protocol in order to establish a proper communication channel between them. In this thesis, we are concerned with modem design and development which is discussed in this chapter. The protocol used is also later discussed in this chapter.
2.1.3 Modem

Modem is a device which is combination of modulator and demodulator. At the transmitting end, Modem acts as a device that accepts binary data from a data source which is modulated to create a signal which is suitable for transmission and at the receiving end it acts as complementary for transmitting end [7]. Modems are classified based on the amount of data transferring capability which measured in terms of bits per second (bps) or baud rate. In order to encode and decode the data we need to have a proper modulation and demodulation technique. The designing of modem which can establish a good communication link between the onboard data handler (OBDH) and ground station with the available transmitter power is constrained by these above mentioned power and size factors [3]. In this thesis we would design a modem based on FPGA which is the main module in the communication subsystem. This modem is embedded on a nanoRTU which is discussed later in this chapter.

2.1.4 Modulation and Demodulation techniques

Modulation is process of imposing the properties of a message signal onto a high frequency carrier signal. Modulation schemes are mainly classified into Analog modulation methods and Digital modulation methods. Analog modulation techniques are further classified based on amplitude, frequency and phase modulation techniques. Digital modulation schemes are further classified based on type of keying. The most fundamental digital modulation techniques are Phase shift keying (PSK), Frequency shift keying (FSK), Amplitude shift keying (ASK) and Quadrature amplitude modulation (QAM). Demodulation is process of retrieving back the original information from the modulated signal. In this thesis we are going to use BPSK
(Binary Phase Shift Keying) modulation and AFSK (Audio Frequency Shift Keying) demodulation.

**Binary Phase Shift Keying (BPSK)**

BPSK is one of three basic binary modulation techniques. BPSK modulation is a technique where the phase of a carrier sinusoidal signal changes abruptly by 180° or phase reversal occurs for every transition of modulating binary sequence (input bit) [6]. The general form of the BPSK signal is based on the following equation [23]. The binary data is represented by two signals with different phases in BPSK. \( s_1(t) \) and \( s_2(t) \) are the two signals at point of time \( t \).

\[
s_i(t) = \begin{cases} 
-Asin(2\pi f_c t), & \text{if } 0_T \\
+Asin(2\pi f_c t), & \text{if } 1_T 
\end{cases}
\]

Where:
- \( A \) is the amplitude
- \( f_c \) is the frequency of the carrier and
- \( T \) is the time.

The phase of the transmitted signal remains the same if a “1” was transmitted and is shifted by 180° if a “0” is transmitted [8].

**ADVANTAGES:**

- BPSK has high spectrum efficiency, good spectral characteristics, strong anti-interference performance, and has faster transfer rates [12].
- Due to its robustness it is extensively used in satellite communication systems.

**DISADVANTAGES:**

- It is simple to implement, but it is inefficient in terms of using available bandwidth.

**Audio Frequency Shift Keying (AFSK)**

AFSK is a modulation scheme in which the data is represented by changes in the frequency of an audio tone. The changes in the frequency are between mark and space frequencies represented by binary zero and one respectively.

**ADVANTAGES:**

- AFSK encoded signals pass through AC-coupled links that are included in most devices designed to carry music or speech.
- Implementing an audio modulation scheme allows us operate on many digital modes that have been developed by amateurs.

**DISADVANTAGES:**

- AFSK is inefficient in terms of using available bandwidth and power.
2.1.5 Communication Protocol

The AX.25 protocol is a data link layer protocol. It is basically designed for amateur radio communications and extensively used in amateur radio networks [5]. The aim of this protocol is to establish a reliable communication link between two terminals. When a connection is established between the two stations the AX.25 data frames are passed from one station to the other and are traversed back. [10]

<table>
<thead>
<tr>
<th>Flag (1)</th>
<th>Address(14)</th>
<th>Control(1/2)</th>
<th>PID(1)</th>
<th>Info(&lt;256)</th>
<th>FCS(2)</th>
<th>Flag(1)</th>
</tr>
</thead>
</table>

Figure 2.3 AX.25 protocol stack

The Fig 2.3 shows the frame format of the AX25 protocol. The functionality of each field of the frame is

1. FLAG: indicates the start and stop of the frame.
2. ADDRESS: identifies the sender and the receiver
3. PID (protocol identifier): identifies the type of top level protocol
4. INFO: contains from zero to 256 bytes of data
5. FCS (frame check sequence): contains a cyclic redundancy check (CRC).
6. CONTROL: identifies the type of frame. There are three types of control field formats.
   I. Information frame (I frame): Contains information about the sender’s send and receive sequence number.
   II. Supervisory frame (S frame): Provide supervisory link control such as acknowledging or requesting retransmission of I frames and link layer window control.
   III. Unnamed frame (U frame): U frames are responsible for establishing and terminating link connections.

2.1.6 NanoRTU

A Remote Terminal Unit (RTU) is a miniaturized flexible and microprocessor controlled device used to interface with an OBDH. In order to reduce development time, the US Air Force Research Laboratory proposed a plug and play standard known as Space PnP Avionics (SPA). This standard allows for self- discovery and self-configuration of both hardware components and software applications within a satellite network [20]. One such PnP component is the nanoRTU. It is low cost, low power consumption, high reliability module which is a small size module that can be easily mounted on the satellite subsystem. These units are basically designed for Nano/micro satellites. In this thesis, we used a nanoRTU developed by ÅAC microtec AB, Uppsala. The specifications, easy integration with payloads and the applications of the nanoRTU are described in the data sheet [9].

2.1.7 Radiation

Space-based radiation is an important aspect to consider in system design. When electronic systems are exposed to space radiation like high energy ion radiation, magnetic fields and plasma interactions, there are chances of memory corruption,
degradation or permanent damage of components/systems [4]. It is therefore desirable to use radiation tolerant devices in order to achieve high processing capabilities to minimize this damage and its consequences [9].

2.1.8 FPGA and VHDL

A field programmable gate array (FPGA) is a programmable digital logic chip. FPGAs contain two dimensional arrays of logic cells and switches. A logic cell is programmed to perform certain actions and a switch can be used to interconnect these logic cells. Once the desired logic is designed and synthesized, the design can be dumped into the FPGA using a simple adaptor. The logic cells are programmed either by the customer or by the manufacturer using a hardware descriptive language (HDL) [11]. HDL is used to program the FPGA indeed to create a perfect logic device. Verilog and VHDL (Very high speed integrated circuit HDL) are the most commonly used hardware description languages. For this thesis the authors used VHDL to design and implement the AFSK and BPSK modulation schemes.

2.1.9 FPGA vs. DSP

The implementation of a modem is a digital signal processing issue. Two types of programmable platform could be used to realize the modem, i.e., a Digital Signal Processor (DSP) or an FPGA.

- DSP’s are one time programmable devices whereas FPGA’s can be programmed as many times as required. The FPGA also has an advantage of scalability and expandability.
- FPGA has an advantage of parallel (multi)processing when compared to a DSP which is a dedicated processor. As a result of this multi-processing the performance of an FPGA is more than a DSP.
- FPGA’s are enormously faster, flexible and less expensive when compared to DSP’s.
- DSP’s have better power efficiency than FPGA’s.

2.1.10 Software Defined Radio (SDR)

The term “software defined radio” was coined by Joseph Mitola in 1991, referring to a shift from traditional hardware radio systems to software, where the major functionality is defined [24]. It is defined as a radio communication system whose hardware components are replaced by software implemented on embedded computing devices [25]; also, systems that depend on software to perform their base band functionalities are also called software defined radio’s [28]. The same hardware can be used for communication on different transmission and reception channels just by changing the software. Hardware defined radios are expensive compared to software defined radios. Re-Configurability is one of the main advantage that software defined radio have. The important blocks of SDR are intelligent antenna, programmable RF modules, high performance Digital-to-Analog (DAC) and Analog-to-Digital (ADC) converters, DSP techniques and the interconnect technology [26].
2.1.11 Plug and Play

The plug and play architecture for the avionics subsystems of a satellite allows distinct applications to make use of a common set of avionics modules in a common enclosure. Multiple subsystems can operate simultaneously to perform redundant operations or joint operations. To develop avionics subsystems using a plug and play methodology, three elements should be considered. They are: the open bus architecture, radiation tolerant FPGA implementation of bus interfaces and use of a common enclosure design [20].

2.2 Survey of related work

In [14] the overall operation of the communication subsystems in satellites is discussed. A successful design of low-complexity GMSK (Gaussian minimum shift keying) modem software which acts as a backend process in eliminating the use of an external modem was reported. A DSP (TMS320C54x) processor was chosen for the Telemetry/Telecommand (TM/TC) circuit. The design of TM/TC circuit adopted in [14] helped to cut down the Nano-satellite cost. The TM/TC circuit is small and can be easily mounted on any small satellite. The authors described the hardware and software solutions they achieved to design a good TM/TC system.

Along with the above implementation, an additional AFSK modem was designed to store and forward automatic packet reporting system (APRS) payload data in [15]. A general purpose DSP microcontroller TMS320C5416 was chosen for designing the modem. In both [14] and [15] the communication was based on the AX.25 protocol which is data link layer protocol derived from the ITU-TX.25 protocol suite.

A low power frequency shift-keying (FSK) modem was designed using a DSP processor for CubeSat satellites in [16] and the communication was achieved successfully via a kiss protocol. The original intention was to implement a modem that could switch between two different baud rates (1200 and 9600 baud), but due to time constraints they eventually ended up only implementing a 1200 baud rate.

The authors of the [12] have designed and implemented a BPSK modem as part of a Software defined radio (SDR) transceiver system. The paper clearly states the algorithms used in designing the BPSK modulator and the demodulator. When designing the demodulator the authors used a Costas loop to achieve carrier synchronization. Both the modulation and demodulation algorithms are firstly simulated in MATLAB. Verilog HDL was the language used to design the system and then it was simulated again using Modelsim SE 6.5 in order to prove the feasibility and superiority of the proposed solution. Then the design was tested in a Virtex5 series FPGA (Xilinx). The modulation and demodulation techniques are the core content in the SDR communication system.

The space systems research laboratory at Saint Louis University designed a SLUCUBE as part of their space program [21]. The main aim of the program was to cut down the cost and provide rapid access to space using commercial off the shelf components. In this program, they developed a prototype software defined radio that supports a wide range of communications and modes. A COTS Stensat UHF/VHF transceiver that supports AX.25 packet standard was used as the primary device for communication. The newly developed modem supports UHF (uplink) and VHF (downlink) frequency bands using a narrow band Frequency modulation scheme. The software defined radio modem was flight tested for the first time on the SLUCUBE.
In [22] the author proposes a solution to tackle the problems of traditional RF hardware by designing a software defined radio modem that can operate in UHF and VHF amateur radio bands. An ADSP-BF537 blackfin DSP is proposed and the software for the DSP will be created with National instruments lab-VIEW using an embedded module for ADI Blackfin Processors. Various tests including thermal, vacuum and vibration testing will be performed on the newly developed modem by the Saint Louis University.

An onboard communication subsystem was developed by the students of Sathyabama University for their CubeSat mission. Various design aspects related to both hardware and software were discussed in [27]. Microchip dsPIC32 DSC controller was used for implementing AX.25 protocol. MHX425 Transceiver is used for transmission and reception using a FSK modulation technique. The communication subsystem source code is implemented using a C compiler and MPLAB IDE for performing various functionalities including CW beacon, Transceiver interface and software TNC.
3 RESEARCH METHODOLOGY AND IMPLEMENTATION

This chapter is organized into two sections. The first section covers the research methodology that should be followed in order to answer the research questions. The second section describes the implementation of the research methodology.

3.1 Research Methodology

The type of methodology used to answer the research questions is constructive research.

Constructive Research

The basic idea behind constructive research approach is to develop a construct for a specific problem. A construct can either be a model, an algorithm, new software or a framework which can be used a reference in future research works carried out in similar fields. The problem which is identified during the process of constructive approach is either derived from theory or from practice. Theoretical derivation of the problem includes extensive literature review of similar works in the past and practical derivation implies existing or previous experiments conducted.

![Constructive research flow diagram]

Figure 3.1 Constructive research flow
Constructive approach

Fuzzy info

A state of the art literature review has been performed to gather all the information pertaining to the design and development of communication subsystems in several CubeSats which have been deployed into orbit and which are in development.

Theoretical body of knowledge

Fuzzy info provided us with a broad theoretical understanding of what has been done in the fields of CubeSat communication design. This body of knowledge helped us forming a base in framing the main problem for which this thesis is carried out. It has also helped us in performing a thorough examination of a number of studies stating the challenges that are encountered by CubeSat developers while developing a communication subsystem.

Practical utility

A software defined radio modem based on nanoRTU has been designed and implemented. This experiment has resulted in additional challenges faced during the development.

Framework

A list of all the challenges that evolved during practical implementation of a modem design and from theoretical knowledge helped us designing a framework for future reference. The framework designed in this thesis describes in detail all the problems encountered during state of art and experiment and proposes suitable solutions.

Practical relevance

In order to test the framework, the same experimental setup used to identify the challenges faced during the design of a modem is used as a testing reference. All the challenges encountered are tested on the implementation of software defined radio modem based on nanoRTU.

3.2 Implementation

This section describes the implementation of the above described methodology. An overview of the process is clearly explained in fig 3.2.

In order to answer the research questions, we needed to conduct a literature review of the existing problems documented when implementing a CubeSat modem and combine these with problems that are encountered during the practical process of designing and implementing an FPGA based modem. Taking both the sets of problems into consideration we create a set of criteria that are to be considered in designing a modem for a CubeSat.
3.2.1 Literature Review

The literature review is the most important step in any research. It is a means of identifying, evaluating and interpreting problems and existing solutions relevant to the research based on study and analysis of publicly available scientific articles, books and other resources relevant to particular research area [29]. There are different reasons for undertaking literature, the most common reasons according to B. Kitchenham [29].

- Summarizing the existing evidence concerning the technology in a comprehensive and fair manner.
- Identification of gaps in current research and to put forward some more areas for further research.
- Providing a frame of reference for the future research investigation.
Qualitative approach was followed while conducting literature review. The structure of the literature review conducted is described as a following process.

The main idea behind the literature review is to convey the reader that what others have accomplished in your field and how different is your work from others and the ability to summarize the work of others for the convenience of the reader [61]. The key steps that must be followed in any literature review are 1) Define keywords. 2) Finding the sources 3) Article selection criteria [30].

Defining Keywords

Keywords are very important in finding out the information. A set of keywords like CubeSat, communication subsystem, modem challenges and criteria were defined by taking the research questions and breaking it into words.

Finding the sources

In order to find out the sources related to the research question search strings were formulated by combining the keywords with Boolean AND and OR’s. But there were very few papers so the authors have limited their search by using keywords and combination of keywords in well-known databases including IEEE Xplore, Science direct, Scopus, ACM digital library and Google scholar.

Article selection criteria

The information regarding the communication subsystems of different CubeSats were collected, the investigation of the challenges in designing the modem were done critical and accurate manner by using the below stated inclusion and exclusion criteria. Further papers are filtered by reading the abstract, introduction and conclusions.

Inclusion criteria

- The key words formed from the research questions were implemented on the selected databases including IEEE Xplore, Science direct, Scopus, ACM digital library and Google scholar.
- Research relevant to development of communication subsystem of CubeSat was included.
- Studies covering different types of communication subsystems.
- Studies covering various challenges in development of CubeSat communication subsystems.
- Studies covering the implementation of software defined radio in communication subsystems.
- Studies of various CubeSat launches.

Exclusion criteria

- Papers which are not in English.
- Papers regarding development of traditional satellites and which are not relevant to the topic are excluded.
- Studies those are irrelevant to the research questions.
3.2.2 Design and implementation of modem

After an extensive literature search regarding the challenges that are observed in designing a modem for a good communication subsystem, we observed that there are only a few instances that quoted problems related to hardware. We needed to develop a modem in order to understand the software related challenges more deeply. Along with the literature review here we have designed and implemented a modem which acts as backend software for the nanoRTU. Some of the concepts that are related to the development phase are stated above and the implementation process will be explained and finally the challenges that are observed will be presented below.

Modem development

The development we aimed to design and develop a modem on the ÅAC nanoRTU 211 radiation tolerant hardware platform that is transparent to different RF-front ends, for example for transmission on UHF (400-450 MHz) and reception on VHF (130-160 MHz).

Figure 3.3 Illustration of the digital satellite communication modem

The fig 3.3 shows the modeling of the communication subsystem. The communication subsystem should be capable of receiving and transmitting signals from ground stations as well as providing full control of telecommand data decoding and telemetry data encoding. These signals should be passed through a modem that handles the modulation and demodulation schemes [54]. The received signal from the ground station will be demodulated by the modem and given to the OBDH through the UART. The data from the OBDH will be given to the modem through the UART for modulation and the modulated data will be given to the transmitter for transmission to the ground station.

Modem intercommunication

The modulation and demodulation schemes used in the modem are BPSK and AFSK respectively. The signal received from the ground station to the onboard receiver will be an AFSK modulated signal. The received AFSK modulated signal is given to the analog to digital converter which converts the analog signal to digital bits. The SPI ADC forms the interface between the ADC and AFSK demodulator. The digitally converted AFSK modulated data is then given to the AFSK demodulator through an SPI bus. The demodulated data will be sent to the UART transmitter. The UART transmitter can be used to send the demodulated data to the OBDH from the modem.
On the other side the data from the OBDH is received by the UART receiver which sends it to the BPSK modulator for modulating the data. The modulated data is then given to the SPI DAC which acts as the SPI interface between the BPSK modulator and the Digital to Analog converter. The analog converted signal is transmitted from the onboard transmitter to the ground station. The fig 3.5 shows how the communication is done internally.
Implementation

In order to implement this method first we have to figure out the required technologies that are available to create a software modem. Designing a modem which can transmit and receive data is a signal processing issue. The available chip technologies to handle these signal processing technologies are FPGA and DSP. Here we have chosen an ACTEL FPGA (ProAsic A3P600) on which the modem would be designed and implemented. The reasons for choosing an FPGA are discussed in chapter 2. The Actel Libero IDE (integrated design environment) software toolset was used for coding, simulating, synthesizing and finally dumping the code into the FPGA. VHDL is the hardware descriptive language that was chosen to program the FPGA with the defined set of modulation and demodulation techniques. The process flow of the implementation is shown in fig 3.6.

![Process Flow Diagram](image)

Figure 3.6 Process flow

One of the main steps for implementing a software defined modem is coding the modulation and demodulation techniques in VHDL. The logic required in the design of the modulation and demodulation techniques in VHDL is explained below.

AFSK Demodulation

The AFSK modulated data contains multiple tones. Each tone can be characterized by counting the number of samples between two zero crossings for a given sampling frequency. As we use 1200 Hz to be the mark frequency and 2200 Hz to be the space frequency...
frequency, the number of samples between two zero crossings of the mark frequency will be more than the number of samples between two zero crossings of the space frequency. For example, a 1200 Hz signal sampled at 264 KHz will have 110 samples between two zero crossings and a 2200 Hz signal sampled at 264 KHz will have 60 samples. So the counter that resets for every zero crossing will have two discrete values at the output. A threshold value between these two values 110 and 60 will be taken as a limit. Based on the limit value the input modulated signal is demodulated and output as a digital value. If the number of samples between two zero crossings is greater than the limit value then it is taken as ‘1’ and if the number of samples between two zero crossings is less than the limit value then it is taken as ‘0’. The AFSK demodulation is performed for the 1200, 2400, 4800 and 9600 baud rates.

![AFSK Demodulation algorithm](image)

The number of samples between two zero crossings are calculated by the formula:

$$N = \frac{fs}{(\text{modulated signal frequency}) \times 2}.$$  

**BPSK Modulation**

![BPSK Modulation algorithm](image)
The BPSK modulation is implemented by taking the basic idea of changing the phase of the carrier wave by 180° whenever there is a change in the input bit. So if “1” is given as the input, the modulated signal remains same as the carrier signal. And if “0” is given as the input, then the modulated signal will be the carrier signal with 180° phase shift [56]. For the Bpsk modulation, the carrier wave cosine wave is taken from a look-up table instead of calculating the cosine value. Calculating the cosine value would allow for a pure continuous phase modulated signal but constraints on computing power and the excessive time it takes for calculating the cosine value for each sample eliminates this option. BPSK modulation is done for 1200, 2400, 4800 and 9600 baud rates.

Once coding for the modulation and demodulation was completed, the test benches were created for both the modulation and demodulation process. The code was then tested using the test benches.

The system was then simulated using a modelsim simulator. The simulation results for AFSK demodulation are shown in the fig 3.9.

![AFSK demodulation simulation](image)

Figure 3.9 AFSK demodulation simulation

From the simulation results of AFSK it can be seen that the given input AFSK modulated signal was demodulated. We can see that the mark and the space frequencies were demodulated to binary ‘1’ and binary ‘0’ respectively. The sampling frequency used for the demodulation of the AFSK signal was chosen to be 264 KHz and the clock rate chosen was 1 MHz. The process chosen for demodulation was independent of the used baud rate. The simulations were carried for 1200, 2400, 4800 and 9600 baud rates.

The simulation results of the BPSK modulation are shown in the fig 3.10. From the BPSK simulation results, we can see that the input digital data was modulated. It can be seen that for a given binary ‘1’ input, the output was applied carrier cosine wave and for a given binary ‘0’ input, the output was the applied carrier cosine wave with 180° phase shift. The simulations were carried out for 1200, 2400, 4800 and 9600 baud rates.

After the simulation process the HDL code is synthesized by synplify synthesis tool. The synthesis tool translated text based HDL to a circuit and then optimized the circuit. Once the synthesis was performed, the code was then passed to the place-and-route block of the Libero IDE as the next step where the inputs and the outputs were assigned with proper pins assignments according to the FPGA requirements.
After synthesize and place-and-route stage of the libero IDE we performed post synthesis simulation and post layout simulation to verify the output before it was dumped into the FPGA.

The last and the final step would be to generate a programming file that was ready to be dumped into the FPGA. For dumping the generated files into the FPGA, we need an ACTEL PROASIC cable.

Once the programming was successfully completed it needed to be tested to verify that the set of modulation and demodulation schemes were implemented successfully.
4 RESULTS & ANALYSIS

4.1 State of Art

The State of Art review was done by the authors in order to understand the design techniques employed by different CubeSat developers. The results of state of the art describe in detail, the various successful CubeSat programs that have been created for different educational purposes and applications. The answer to research question 1 is divided into two parts to provide a clearer and more precise explanation of results.

4.1.1 Successful CubeSat launches

The first part describes in detail, the design of communication subsystems and payloads used in those CubeSats which have been successfully launched during the Vega booster launch on February 9th 2012, from CSG space centre in Kourou, French Guiana.

E-st@r

1. Purpose of lunch

The E-st@r CubeSat is an educational program by Politecnico di Torino, Italy. It was designed to demonstrate the feasibility of active control of a CubeSats attitude by magnetic actuation [31]. The main aim of the CubeSat was the demonstration of an active 3-axis attitude determination and control system including an inertial measurement unit.

2. Major payload

The satellite carries an Active Attitude determination and control system as the major payload.

3. Communication subsystem – Design and Specifications

The satellite's communication subsystem used a dipole antenna for transmission and reception. The global weight of the communication subsystem (including the antenna) was 60g [32]. The maximum power consumption of the transmitter was 650 mW with BPSK modulation. The system used a 1200 bit/s link for communications. It had a half-duplex communication channel which was activated by the ground station on demand. AX.25 was the protocol chosen for communication on downlink to share the telemetry data with other CubeSat communities [32].
Goliat

1. Purpose of launch

This was the first CubeSat that developed by students of University of Bucharest and the Romanian space agency. The primary goal of the satellite was to make scientific measurements and earth observations.

2. Major payload

The Goliat CubeSat carries three primary payloads –

   a. CICLOP - To take pictures of Romanian territory
   b. SAMIS - A sensor to measure energy
   c. DOSE-N - A detector to measure the total dose of radiation inside the satellite

3. Communication subsystem – Design and Specifications

The communication subsystem of this satellite had two transceiver architectures, one for a beacon and the other for data transmission [33]. An amateur radio transceiver and a micro hand MHX-2400 transceiver functioned independently with two processors commanding the operation. The MHX 2400 transceiver was initially set to 9600 bps at 1W power output and depending upon the link performance, the baud rate may increase or decrease. It used GFSK modulation for data transfer and followed a proprietary protocol. For the beacon, the modulation schemes were AFSK/FM and the protocol used was AX.25 [33].

PW-SAT

1. Purpose of launch

PW-Sat was a CubeSat project designed by the Faculty of Electronics and Information Technology and by the Faculty of Power and Aeronautical Engineering at Warsaw University of Technology. It was the first Polish CubeSat deployed into space. The main objectives of the CubeSat were testing a deployable atmospheric drag de-orbiting device, using solar sail material. This method may be used in future to remove payloads from LEO orbit [34].

2. Major payload

The PW-SAT had two primary payloads –

   a. Gadadget - To collect data from the satellite via distributed ground stations
   b. Loenidas - To study the effects of satellite de-arbitration

3. Communication subsystem - Design and Specifications

The PW-SAT communication subsystem used the 70cm amateur radio band for communication between the ground stations and the satellite. The radio could send 1200 baud AFSK with the AX.25 packet format. It could communicate at two frequency ranges - 435.032 MHZ (uplink) and
The antenna module had four tape antennas of 55 cm length. The antennas were folded during take-off and it took 30 seconds to unfold the antennas once the satellite was released into orbit [35].

**UNICubeSat-GG**

1. **Purpose of launch**

UNICubeSat was the first CubeSat built by the students of Sapienza University of Rome. This was designed and manufactured by the GAUSS group which has vast experience in developing university satellites (UNISAT) that weigh about 10kg. The on-board data handler had an MSP430 microcontroller as the main processor that controlled all the on-board operations. The main aim of the CubeSat was to study the effects of orbital eccentricity on attitude motion, enhanced by gravity gradient [36].

2. **Major payload**

The satellite carried a Broglio Drag Balance Instrument that aimed to contribute to the development of accurate thermosphere models, achieving in situ measurement of the atmosphere density and to accurately detect weather forecasts [37].

3. **Communication subsystem – Design and Specifications**

The GAUSS group in collaboration with Morehead state university (USA) has designed the communication subsystem. The communication subsystem used a commercial-off-the-shelf UHF transceiver for ground commands made by Astrodev LLC. The Frequency of the radio in UHF band was 437.305 MHz [36] and the modulation was GMSK at 9600bps baud rate and FSK for data transmission at 9600 bps [37].

**Xatcobeo**

1. **Purpose of launch**

Xatcobeo CubeSat was built by students from various departments from the University of Vigo which was headed by Fernando Aguado. This was the first Galician artificial satellite built in collaboration with the National Institute of Aerospace Technology, Spain [38]. The main aim was to provide students with an opportunity to work using space standards.

2. **Major payload**

The CubeSat was developed to carry three payloads.

   a. Software radio for communication – Software defined reconfigurable radio which uses FPGA
   b. Radiation Displacement Damage Sensor- A system for measuring the amount of ionizing radiation
   c. Panel Deployment Mechanism- To test and validate a new mechanism that will provide the CubeSat with additional electrical power, extend lifetime and improve the performance of the spacecraft [39]
The software radio was developed using the C language using an embedded development Kit on a Xilinx Spartan-3E FPGA [40].

3. Communication subsystem – Design and specifications

The communication subsystem used two modes, one to transmit a beacon in the 145.94 MHZ VHF band and the other to transmit digital data in the 437.36 MHZ UHF band with an FFSK modulation scheme and AX.25 as the packet protocol [41].

Masat-1

1. Purpose of launch

Masat-1 was the first Hungarian CubeSat to be deployed into the LEO. This satellite was designed and developed by Budapest University of Technology and Economics. The main objectives of Masat-1 were,

   a. To design and implement the basic subsystems of the satellite using custom built modules.
   b. To gain experience in various departments of designing a satellite in order to develop more complex space projects in future [31].

All the subsystems onboard were considered as experimental by the Masat team since the CubeSat was custom built.

2. Communication subsystem – Design and specifications

The communication subsystems, control functions were performed on gate level. The RF transmit power of the subsystem had two operating modes - a 100mW low power mode and a 400mW high power mode. Every 4th telemetry transmission was set default to be in high power mode [42]. The operating downlink frequency was 435 MHZ and for Uplink it was 145 MHZ. It used two modulation schemes On-Off Keying (OOK) and FSK [43].

OUFTI-1

1. Purpose of launch

OUFTI-1 is a technology demonstration mission by university of Liege, Belgium. The objective of the project was to demonstrate the feasibility of using amateur radio D-STAR communication protocol to communicate through a CubeSat [44]. D-STAR stands for Digital Smart Technologies for Amateur Radio.

2. Major payloads

The OUFTI-1 has two major payloads –

   a. D-STAR- to test the amateur radio protocol which has new built-in features like digital communication.
   b. It carries an innovative electrical power system developed in collaboration with Thales Alenia Space ETCA.
3. Communication subsystem – Design and specifications

The satellite communication subsystem uses four quarter-wave deployable antennas, two about 17 cm long for downlink and two about 50 cm long for uplink [46]. The frequencies used for communication are 145 MHz for the uplink and 435 MHz for the downlink. D-STAR can use an Ethernet connection at 128 kbps and digital data and digital voice at 4.8 kbps in GMSK transmission [48].

ROBUSTA

1. Purpose of launch

Robusta is the CubeSat which was developed by the RADIAC group of University Montpellier 2 (UM2). RADIAC group is the radiation effects group of the university which has 30 years of experience, and one of the world’s leading groups in its field. The main purpose of the mission was to measure the effects of ionizing radiation on the on-board bipolar electronics components. The degradation data of the key parameters were sent back by the payload. Each parameter was measured for every 12 hours, while the radiation dose was measured every 90 minutes and the temperature data every 6 minutes. The data received from the payload was analyzed and compared with the results which were observed during the ground tests. This information from the payload sensor provides information on earth's radiation belts [31].

2. Communication subsystem – Design and implementation

Communication subsystem of ROBUSTA used a custom built transceiver. A PIC performs the data packetization using AX.25 protocol. The radio sends 1200 baud data using AFSK modulation [47].

4.1.2 CubeSats in development

The second part of the answer explains the design of communication subsystems of all the CubeSats which are presently in development stages. An elaborate review of all these CubeSats has been performed and the extensive survey has resulted in miniscule but very specific and important information.

JAXA Launch

The Japan Aerospace Exploration Agency is planning to launch three CubeSat from the “kibo” module of the International Space Station (ISS) to test the capability of the “kibo” module and also to provide more launch options for future CubeSats. FITSAT-1, WE WISH and RAIKO are three CubeSats selected to deploy from the module in September 2012 [49].

FITSAT-1

This CubeSat is developed by the Fukuoka Institute of Technology. This CubeSat is a technology demonstration mission. The main objectives of the satellite are to demonstrate the high speed transmission module for small satellites and also to test the
visible light communication with high power LEDs. Fitsat-1 will use a neodymium magnet for attitude control [49].

An AX.25 transceiver will be used for telemetry and telecommand purposes in 437.445 MHZ VHF band and a CW beacon will also be provided on 437.250 MHZ band. This would be the first satellite to transmit data at a rate of 115.2 Kbps on 5.8 GHZ band. It can send a JPEG picture within 6 seconds [50].

RAIKO

RAIKO satellite is being developed by the students at the University of Wakayama. RAIKO is developed in collaboration with Science University of Tokyo and Tohoku University. It is being developed as a part of “research and development of ultra-small satellite network UNIFORM Japan-led” [51]. The mission has several objectives but the main purpose of the mission is to picture the earth by a fish eye camera.

WE WISH

WE WISH is a non-educational satellite developed by the Meisei Electric co. ltd, a Japan based company. This satellite is selected for the first experiment of the “kibo” module to be allowed into the 350 km LEO orbit along with two other university satellites. The primary mission of the CubeSat is to monitor and investigate the global environment with a satellite [52].

This CubeSat will send IR pictures of the earth’s surface with a resolution of 320x256 pixels that will be downloaded in 110 seconds using SSTV. The downlink will be SSTV, telemetry and Beacon in 437.505 Mhz UHF band whereas the uplink will be in VHF band [53].

All in the information gathered from the state of art of a wide range of CubeSats and their respective communication subsystems have been summarized briefly in the table 4.1.
<table>
<thead>
<tr>
<th>Cubsat</th>
<th>Size</th>
<th>Frequency</th>
<th>Power</th>
<th>Protocol</th>
<th>Baud Rate/Modulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-st@r</td>
<td>1U</td>
<td>437.445 MHz</td>
<td>650mW</td>
<td>AX.25</td>
<td>1200 BPSK</td>
</tr>
<tr>
<td>Goliat</td>
<td>1U</td>
<td>437.485 MHz</td>
<td>1W</td>
<td>Proprietary, AX.25</td>
<td>9600 GMSK, 1200 AFSK</td>
</tr>
<tr>
<td>PW-SAT</td>
<td>1U</td>
<td>145.902 MHZ</td>
<td>2W</td>
<td>AX.25</td>
<td>1200 AFSK</td>
</tr>
<tr>
<td>UNICUBESAT</td>
<td>1U</td>
<td>437.305 MHZ</td>
<td></td>
<td>AX.25</td>
<td>9600 GMSK, 9600 FSK</td>
</tr>
<tr>
<td>XATCOBEO</td>
<td>1U</td>
<td>145.94 MHz</td>
<td>437.36 MHz</td>
<td>AX.25</td>
<td>1200 FFSK</td>
</tr>
<tr>
<td>MASAT-1</td>
<td>1U</td>
<td>145 MHZ</td>
<td>435 MHZ</td>
<td>400mW</td>
<td>AX.25, OOK, FSK</td>
</tr>
<tr>
<td>OUFTI-1</td>
<td>1U</td>
<td>145 MHZ</td>
<td>435 MHZ</td>
<td>AX.25</td>
<td>GMSK</td>
</tr>
<tr>
<td>ROBUSTA</td>
<td>1U</td>
<td>437.325 MHz</td>
<td>800mW</td>
<td>AX.25</td>
<td>1200 AFSK</td>
</tr>
<tr>
<td>FITSAT-1</td>
<td>1U</td>
<td>437.25 MHz</td>
<td></td>
<td>AX.25</td>
<td>FSK</td>
</tr>
<tr>
<td>RAIKO</td>
<td>2U</td>
<td>PI</td>
<td>PI</td>
<td>PI</td>
<td>PI</td>
</tr>
<tr>
<td>WE WISH</td>
<td>1U</td>
<td>437.505 MHz</td>
<td>PI</td>
<td>PI</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1 CubeSat communication subsystems from 2011 to till date

The third part of the result presents a summary of all the CubeSats which have been launched from 2003 until 2011 along with the design specifications of their communication subsystems. This part also analyses all the communication subsystems and infers the analytical results from the authors’ perspectives. The analysis of all the designs would serve as important references for future developers of communication subsystems.
<table>
<thead>
<tr>
<th>Satellite</th>
<th>Size</th>
<th>Frequency</th>
<th>Power</th>
<th>Protocol</th>
<th>Baud rate/Modulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAU1 CubeSat</td>
<td>1U</td>
<td>437.475 MHz</td>
<td>500 mW</td>
<td>AX.25, Mobitex</td>
<td>9600 baud GMSK</td>
</tr>
<tr>
<td>DTU sat-1</td>
<td>1U</td>
<td>437.475 MHz</td>
<td>400 mW</td>
<td>AX.25</td>
<td>2400 baud FSK</td>
</tr>
<tr>
<td>CanX-1</td>
<td>1U</td>
<td>437.880 MHz</td>
<td>500 mW</td>
<td>Custom</td>
<td>1200 baud MSK</td>
</tr>
<tr>
<td>Cute-1 (CO-55)</td>
<td>1U</td>
<td>437.470 MHz</td>
<td>350 mW</td>
<td>AX.25</td>
<td>1200 baud AFSK</td>
</tr>
<tr>
<td>QuakeSat-1</td>
<td>3U</td>
<td>436.675 MHz</td>
<td>2 W</td>
<td>AX.25</td>
<td>9600 baud FSK</td>
</tr>
<tr>
<td>XI-IV (CO-57)</td>
<td>1U</td>
<td>437.490 MHz</td>
<td>1 W</td>
<td>AX.25</td>
<td>1200 baud AFSK</td>
</tr>
<tr>
<td>XI-V (CO-58)</td>
<td>1U</td>
<td>437.345 MHz</td>
<td>1 W</td>
<td>AX.25</td>
<td>1200 baud AFSK</td>
</tr>
<tr>
<td>NCube-2</td>
<td>1U</td>
<td>437.505 MHz</td>
<td>1 W</td>
<td>AX.25</td>
<td>1200 baud AFSK</td>
</tr>
<tr>
<td>UWE-1</td>
<td>1U</td>
<td>437.505 MHz</td>
<td>1 W</td>
<td>AX.25</td>
<td>1200/9600 baud AFSK</td>
</tr>
<tr>
<td>Cute-1.7 APD</td>
<td>2U</td>
<td>435.505 MHz</td>
<td>300 mW</td>
<td>AX.25</td>
<td>1200 AFSK/9600 baud GMSK</td>
</tr>
<tr>
<td>Ion</td>
<td>2U</td>
<td>435.505 MHz</td>
<td>2 W</td>
<td>AX.25</td>
<td>1200 baud AFSK</td>
</tr>
<tr>
<td>Sacred</td>
<td>1U</td>
<td>467.870 MHz</td>
<td>400 mW</td>
<td>AX.25</td>
<td>1200 baud AFSK</td>
</tr>
<tr>
<td>Kutesat Pathfinder</td>
<td>1U</td>
<td>437.385 MHz</td>
<td>500 mW</td>
<td>AX.25</td>
<td>1200 baud AFSK</td>
</tr>
<tr>
<td>Ice Cube-1</td>
<td>1U</td>
<td>437.305 MHz</td>
<td>600 mW</td>
<td>AX.25</td>
<td>9600 baud FSK</td>
</tr>
<tr>
<td>Ice Cube-2</td>
<td>1U</td>
<td>437.425 MHz</td>
<td>600 mW</td>
<td>AX.25</td>
<td>9600 baud FSK</td>
</tr>
<tr>
<td>Rincon1</td>
<td>1U</td>
<td>437.870 MHz</td>
<td>400 mW</td>
<td>AX.25</td>
<td>1200 baud AFSK</td>
</tr>
<tr>
<td>SEEDS</td>
<td>1U</td>
<td>437.485 MHz</td>
<td>450 mW</td>
<td>AX.25</td>
<td>1200 baud AFSK</td>
</tr>
<tr>
<td>HauSat1</td>
<td>1U</td>
<td>437.465 MHz</td>
<td>500 mW</td>
<td>AX.25</td>
<td>1200 baud AFSK</td>
</tr>
<tr>
<td>Ncube1</td>
<td>1U</td>
<td>437.305 MHz</td>
<td>1 W</td>
<td>AX.25</td>
<td>9600 baud GMSK</td>
</tr>
<tr>
<td>Merope</td>
<td>1U</td>
<td>145.980 MHz</td>
<td>500 mW</td>
<td>AX.25</td>
<td>1200 baud AFSK</td>
</tr>
<tr>
<td>AeroCube-1</td>
<td>1U</td>
<td>902.928 MHz</td>
<td>2 W</td>
<td>AX.25</td>
<td>9600 baud GFSK</td>
</tr>
<tr>
<td>CP1</td>
<td>1U</td>
<td>436.845 MHz</td>
<td>500 mW</td>
<td>AX.25</td>
<td>15 baud DTMF</td>
</tr>
<tr>
<td>CP2</td>
<td>1U</td>
<td>437.425 MHz</td>
<td>1 W</td>
<td>AX.25</td>
<td>1200 baud AFSK</td>
</tr>
<tr>
<td>Mea Huaka (Voyager)</td>
<td>1U</td>
<td>437.405 MHz</td>
<td>500 mW</td>
<td>AX.25</td>
<td>1200 AFSK</td>
</tr>
<tr>
<td>GeneSat-1</td>
<td>3U+</td>
<td>2.4 GHz</td>
<td>1 W</td>
<td>Proprietary</td>
<td>15 Kbps</td>
</tr>
<tr>
<td>Name</td>
<td>Type</td>
<td>Frequency</td>
<td>Power</td>
<td>Modulation</td>
<td>Notes</td>
</tr>
<tr>
<td>-------------------</td>
<td>------</td>
<td>-----------</td>
<td>-------</td>
<td>------------------------------</td>
<td>----------------------------</td>
</tr>
<tr>
<td>CSTB1</td>
<td>1U</td>
<td>400.0375 MHz</td>
<td>1 W</td>
<td>Proprietary</td>
<td>1200 baud AFSK</td>
</tr>
<tr>
<td>AeroCube-2</td>
<td>1U</td>
<td>902-920 MHz</td>
<td>2 W</td>
<td>Proprietary</td>
<td>38.4 kbaud</td>
</tr>
<tr>
<td>CP4</td>
<td>1U</td>
<td>437.325 MHz</td>
<td>1 W</td>
<td>AX.25</td>
<td>1200 baud FSK</td>
</tr>
<tr>
<td>Libertab-1</td>
<td>1U</td>
<td>437.405 MHz</td>
<td>400 mW</td>
<td>AX.25</td>
<td>1200 baud AFSK</td>
</tr>
<tr>
<td>CAPE1</td>
<td>1U</td>
<td>436.245 MHz</td>
<td>1 W</td>
<td>AX.25</td>
<td>9600 baud FSK</td>
</tr>
<tr>
<td>CP3</td>
<td>1U</td>
<td>437.845 MHz</td>
<td>1 W</td>
<td>AX.25</td>
<td>1200 baud FSK</td>
</tr>
<tr>
<td>MAST</td>
<td>3U</td>
<td>2.4 GHz</td>
<td>1 W</td>
<td>Proprietary</td>
<td>15 kbps</td>
</tr>
<tr>
<td>Delfi-C3 (CO-64)</td>
<td>3U</td>
<td>435.55 MHz</td>
<td>200 mW</td>
<td>Linear</td>
<td>40 KHz wideband</td>
</tr>
<tr>
<td>Seeds-2 (CO-66)</td>
<td>1U</td>
<td>437.485 MHz</td>
<td>450 mW</td>
<td>AX.25</td>
<td>1200 baud AFSK</td>
</tr>
<tr>
<td>CanX-2</td>
<td>3U</td>
<td>2.2 GHz</td>
<td>500 mW</td>
<td>NSP</td>
<td>16-256 kbps BPSK</td>
</tr>
<tr>
<td>AAUSAT-II</td>
<td>1U</td>
<td>437.425 MHz</td>
<td>300 mW</td>
<td>AX.25</td>
<td>1200 AFSK/9600 GMSK</td>
</tr>
<tr>
<td>Cute 1.7 APD-II</td>
<td>3U+</td>
<td>437.475 MHz</td>
<td>2 W</td>
<td>AX.25 w/Pacsat</td>
<td>9600 baud FSK</td>
</tr>
<tr>
<td>Compass-1</td>
<td>1U</td>
<td>437.405 MHz</td>
<td>300 mW</td>
<td>AX.25</td>
<td>1200 baud AFSK/MSK</td>
</tr>
<tr>
<td>PREsat</td>
<td>3U</td>
<td>437.845 MHz</td>
<td>1 W</td>
<td>AX.25</td>
<td>1200 baud FSK</td>
</tr>
<tr>
<td>NanoSail-D</td>
<td>3U</td>
<td>2.4 GHz</td>
<td>1 W</td>
<td>Proprietary</td>
<td>15 kbps</td>
</tr>
<tr>
<td>PharmaSat</td>
<td>3U</td>
<td>2.4 GHz</td>
<td>1 W</td>
<td>Proprietary</td>
<td>15 kbps</td>
</tr>
<tr>
<td>CP6</td>
<td>1U</td>
<td>437 MHz</td>
<td>1 W</td>
<td>CC1000 AX.25</td>
<td>1200 baud AFSK</td>
</tr>
<tr>
<td>HawkSat-I</td>
<td>3U</td>
<td>425 MHz</td>
<td>1 W</td>
<td>MHX-425 NSP</td>
<td>1200 baud AFSK</td>
</tr>
<tr>
<td>AeroCube-3</td>
<td>1U</td>
<td>900 MHz</td>
<td>2 W</td>
<td>Freewave FHSS</td>
<td>Proprietary</td>
</tr>
<tr>
<td>Aggiesat-2</td>
<td>1U</td>
<td>436.25 MHz</td>
<td>1 W</td>
<td>AX.25</td>
<td>1200 baud AFSK</td>
</tr>
<tr>
<td>ITUpSat1</td>
<td>1U</td>
<td>437.325 MHz</td>
<td>1 W</td>
<td>Custom</td>
<td>GFSK 19.2 kbps</td>
</tr>
<tr>
<td>UWE-2</td>
<td>1U</td>
<td>437.385 MHz</td>
<td>500 mW</td>
<td>AX.25</td>
<td>FSK 9600 BPS</td>
</tr>
<tr>
<td>BeeSat</td>
<td>1U</td>
<td>436 MHz</td>
<td>500 mW</td>
<td>AX.25</td>
<td>4800 and 9600 GMSK</td>
</tr>
<tr>
<td>Hayato (K-Sat)</td>
<td>1U</td>
<td>13.275 GHz</td>
<td></td>
<td>Custom</td>
<td>10 kbps/1 Mbps</td>
</tr>
<tr>
<td>Waseda-Sat1</td>
<td>1U</td>
<td>437.485 MHz</td>
<td>1 W</td>
<td>AX.25</td>
<td>9600 baud FSK</td>
</tr>
<tr>
<td>Negai</td>
<td>1U</td>
<td>427.305 MHz</td>
<td>1 W</td>
<td>AX.25</td>
<td>1200 FSK</td>
</tr>
<tr>
<td>CubeSat</td>
<td>Size</td>
<td>Frequency</td>
<td>Power</td>
<td>Modulation</td>
<td>Bit Rate</td>
</tr>
<tr>
<td>--------------</td>
<td>------</td>
<td>-------------</td>
<td>-------</td>
<td>-----------------</td>
<td>----------</td>
</tr>
<tr>
<td>TiSat-1</td>
<td>1U</td>
<td>437.305 MHz</td>
<td>400 mW</td>
<td>Custom CW</td>
<td>110 WPM</td>
</tr>
<tr>
<td>StudSat</td>
<td>1U</td>
<td>437.505 MHz</td>
<td>450 mW</td>
<td>AX.25</td>
<td>9600 baud FSK</td>
</tr>
<tr>
<td>O/OREOS</td>
<td>3U</td>
<td>437.305 MHz</td>
<td>1 W</td>
<td>AX.25</td>
<td>1200 FSK</td>
</tr>
<tr>
<td>RAX1</td>
<td>3U</td>
<td>437.505 MHz</td>
<td>2 W</td>
<td>AX.25</td>
<td>9600 baud FSK</td>
</tr>
<tr>
<td>NanoSail-D2</td>
<td>3U</td>
<td>437.275 MHz</td>
<td>1 W</td>
<td>AX.25</td>
<td>1200 baud FSK</td>
</tr>
<tr>
<td>Perseus (4)</td>
<td>1.5U</td>
<td>PI</td>
<td>PI</td>
<td>PI</td>
<td>PI</td>
</tr>
<tr>
<td>QbX (2)</td>
<td>3U</td>
<td>PI</td>
<td>PI</td>
<td>PI</td>
<td>PI</td>
</tr>
<tr>
<td>SMDC-ONE</td>
<td>3U</td>
<td>UHF</td>
<td>PI</td>
<td>PI</td>
<td>PI</td>
</tr>
<tr>
<td>Mayflower</td>
<td>3U</td>
<td>437.600 MHz</td>
<td>900 mW</td>
<td>AX.25</td>
<td>1200 AFSK</td>
</tr>
<tr>
<td>E1P</td>
<td>1U</td>
<td>437.505 MHz</td>
<td>1 W</td>
<td>KISS/custom</td>
<td>1200 FSK</td>
</tr>
<tr>
<td>Hermes</td>
<td>1U</td>
<td>2.4 GHz</td>
<td>1 W</td>
<td>MHX-2420</td>
<td>56.2 kbps</td>
</tr>
<tr>
<td>KySat</td>
<td>3U</td>
<td>436.790 MHz</td>
<td>1 W</td>
<td>AX.25</td>
<td>1200 FSK</td>
</tr>
<tr>
<td>JUGNU</td>
<td>3U</td>
<td>437.275 MHz</td>
<td>500 mW</td>
<td>CW</td>
<td>20 WPM</td>
</tr>
<tr>
<td>DICE-1/2</td>
<td>1.5U</td>
<td>460/465 MHz</td>
<td>2 W</td>
<td>PI</td>
<td>1.5 Mbps</td>
</tr>
<tr>
<td>M-Cubed</td>
<td>1U</td>
<td>437.485 MHz</td>
<td>1 W</td>
<td>AX.25</td>
<td>9600 GMSK</td>
</tr>
<tr>
<td>RAX-2</td>
<td>3U</td>
<td>437.345 MHz</td>
<td>2 W</td>
<td>AX.25</td>
<td>9600 FSK</td>
</tr>
<tr>
<td>E1P-2</td>
<td>1U</td>
<td>437.505 MHz</td>
<td>850 mW</td>
<td>AX.25</td>
<td>1200 FSK</td>
</tr>
<tr>
<td>AubieSat-1</td>
<td>1U</td>
<td>437.475 MHz</td>
<td>708 mW</td>
<td>CW</td>
<td>20 WPM</td>
</tr>
</tbody>
</table>

Table 4.2 CubeSat communication subsystems from 2003-2011 [60]

Analysis of the data in tables 4.1 and 4.2 has resulted in the following points.

**Frequency**

Most of the CubeSats used UHF and VHF (amateur radio frequencies). The following reasons explain why these frequencies were used –

1) Easy to get license.
2) Transceivers can be built easily with low cost.
3) Tracking is easy. Anyone with amateur radio equipment can track the satellite.

An important drawback of using amateur radio frequencies is that, the data must be unencrypted and published. Hence, anyone can access the detailed information
about the satellite and its payload. Lower frequency allocations do not support high speed.

Data rates

All the data which is transmitted use a packet protocol. Data rates for the CubeSats studied as part of state of the art, varied between 1200 and 9600 baud rate but most of the CubeSats used 1200 baud rate. 9600 baud rate is the maximum possible data transmission rate available. ITUPSAT 1 is the only CubeSat to use 19200 baud rate. For such baud rates, ground stations would receive data only from CW beacon.

Modulation

AFSK is the most common modulation scheme used because AFSK allows operation on several digital modes which have been developed by amateurs.

4.2 Criteria for modem implementation

4.2.1 Challenges faced by CubeSat developers – Results after literature review

From the analysis, the authors have identified eight potential challenges that are to be considered by future CubeSat developers. The solutions to these challenges serve as evaluation criteria for modem design and development in future.

1. Power consumption [57][17]

Challenge

Power is one of the most important and major requirements of the CubeSat. Considering the amount of power that a CubeSat can generate, power efficiency becomes an even more important factor. The amount of power consumed by the communication subsystem should be as low as possible so that the max power can used for payloads.

Solution

Using COTS components for the communication subsystems can be a better choice since such devices consume low power thus reducing the power consumptions of the overall subsystem.

2. Radiation [58][4]

Challenge

Space-based radiation is an important aspect to consider after a CubeSat is launched as it has direct effects on subsystems. When electronic systems are exposed to space based radiation like high energy ion radiation, magnetic fields and plasma interactions, there are chances of memory corruption, degradation or permanent damage of components/systems.
Solution

It would be efficient to use Radiation tolerant devices in order to achieve high processing capabilities to minimize the damage and its consequences [9].

3. Thermal dissipation [58]

Challenge

After the launch of the CubeSat, as there is no air in the outer space for convective cooling it can cause damage in the components of the communication subsystem.

Solution

Replacing the electrolytic capacitors in the radio with tantalum along with additional conductive foam around the power amplifier will help decrease in thermal dissipation problem.

4. Fault tolerance [59]

Challenge

If there is a problem in the communication subsystem due to some unknown reasons then the satellite may lose contact with the ground station. There should be method that enables an alternative to compensate the loss.

Solution

Some CubeSats use two transceivers which operate in two different bands. If there is a failure in one of the transceivers then there would be a backup option.

5. Long beacon [60]

Challenge

By not including a long beacon, developers face severe tracking problems.

Solution

It would be easy to track a satellite by using a long beacon. Include as much spacecraft telemetry data as possible on this beacon provides diagnostic information about the CubeSat even if the uplink appears not to be working.

6. Flexibility [57][58][22]

Challenge

Some protocols and modulation schemes are proprietary and device specific, requiring an identical radio at the command ground station. Moreover, most of the satellites operate in different frequency ranges and modes.
Solution

This problem can be mostly solved by developing a prototype that uses software defined radio technology.

7. Reset [60]

Challenge

In case the satellite becomes non responsive, the processor can be reset and the space craft would be back in action.

Solution

Include a simple reset algorithm. A DTMF decoder chip which is easily available must be attached to the radio to achieve the satellite hard reset.

8. Common modulation [60]

Challenge

Satellites tend to have different modulation schemes for beacon and telemetry. Because of these differences, the telemetry data cannot be tracked by other ground stations.

Solution

A common modulation scheme should be agreed upon by the CubeSat and amateur radio communities so that all the universities and amateurs can track any space craft easily and send the data.

4.2.2 Challenges encountered during experimentation

1. Hardware consumption

Challenge

During the experimentation phase, we developed VHDL source code for AFSK demodulation. From the synthesis report, we could see the amount of FPGA logic cells used by the source code. Unfortunately it used more than available number of cells of the FPGA (figure 1 in the Appendix A shows the FPGA usage for method 1). We used another algorithm for AFSK demodulation which uses less logic cells (figure 2 in the Appendix A shows the FPGA usage for method 2). Developing complex software for a CubeSat modem results in usage of more hardware which in deed results in performance degradation.

Solution

Software optimization should be done in order to achieve better performance with minimum power or hardware usage.
2. Software integration

The developed modulation/demodulation software should be integrated with the ADC and DAC’s in order to have a proper communication. Software needs to integrate with other software’s on board so that it can produce reliable communication.

4.3 Advantages and Disadvantages of nanoRTU

Evaluation of the nanoRTU requires considering the above issues and assessing the nanoRTU in relation to them.

<table>
<thead>
<tr>
<th>Problems that are identified in Literature review</th>
<th>NanoRTU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power consumption</td>
<td>Yes, No</td>
</tr>
<tr>
<td>Radiation</td>
<td>very low, 250 mW</td>
</tr>
<tr>
<td>Thermal dissipation</td>
<td>No</td>
</tr>
<tr>
<td>Fault tolerant</td>
<td>Error Detection, Analysis and Correction algorithms were implemented that makes the device fault tolerant.</td>
</tr>
<tr>
<td>Long beacon</td>
<td>No</td>
</tr>
<tr>
<td>Flexibility</td>
<td>Because of the software defined radio technology, it is easy to support a wide range of frequencies and modes</td>
</tr>
<tr>
<td>Reset</td>
<td>Yes</td>
</tr>
<tr>
<td>Common modulation scheme</td>
<td>When the common modulation scheme is announced it can configured with that particular technique</td>
</tr>
<tr>
<td>Hardware consumption</td>
<td>Software optimization has been done to use less data.</td>
</tr>
<tr>
<td>Software integration</td>
<td>At the moment, the digital signal processing modules code is not integrated with the other modules, but it can be achieved soon.</td>
</tr>
</tbody>
</table>

Table 4.3 Verification of nanoRTU with the stated problems in LR
5 CONCLUSION & FUTURE WORK

5.1 Conclusion

The results obtained from the literature review have been very informative and have broadened the area of CubeSat research and the future of CubeSat development which is evolving at a rapid pace with time and technology as the results have provided with descriptive details of various parameters needed to design a communication subsystems, the challenges faced and the criteria required for using these parameters in future. The following conclusions were drawn from the entire work carried out –

RQ1: What is the state-of-art in the current research and development of CubeSat communication subsystems?

The results of the state of art survey proved very useful in understanding the design specifications and development processes of almost all the CubeSats which have been launched into orbit or are still in development. Most of the communication subsystems used COTS components. The tables 4.1 and 4.2 provide the frequency ranges, baud rates, modulation techniques and power used by various CubeSats.

RQ2: What are the criteria for evaluating alternative modem implementations (software/hardware) for CubeSat spacecraft systems?

Results to research question 1 along with a thorough study of the state of the art of current and future CubeSat communication subsystems have led to the conclusion that there are 8 potential challenges which must be overcome by developers in future for which appropriate solutions were suggested that could act as references for future designs. In addition two more challenges were mentioned which evolved during the experimentation. Suggestions were made by the authors to minimize the problems which are discussed along with the problems in the results section there by establishing a set of criteria for evaluating a modem for CubeSat.

RQ3: What are the respective advantages and disadvantages of the nanoRTU, in relation to other systems and (how) can this be quantified?

In order to know the advantages and disadvantages of nanoRTU with respect to the criteria answered in research question 2, an experiment was conducted using nanoRTU. The table shows the effects of using nanoRTU in a communication subsystem taking into consideration the challenges faced and criteria evaluated for modem development.
5.2 Future work

The work in this thesis has established a set of challenges and their corresponding solutions which serve as guidelines for future CubeSat developers. These challenges have been tested by considering nanoRTU. From the literature review, it has been clearly recognized that AFSK and BPSK are the predominant modulation schemes used for developing a communication subsystem. AFSK and BPSK were also used during the implementation of nanoRTU as part of the experimental setup. Future work in this area is vast. The existing SPIADC, SPIDAC and UART entities can be integrated with AFSK and BPSK schemes to develop future communication subsystem modules. These modules can be evaluated and their uplink and downlink performances can be tested. This can prove as a major research work in future considering the rapid increase in the use of software defined radios for designing modems. Current developers use AX.25 as the standard protocol for data transmissions. There are other protocols like FX.25 which are available. The use of such protocols and their effects on communication subsystems along with their ability to withstand the challenges mentioned when implemented in a modem can form a huge ground in future CubeSat research.
6 BIBLIOGRAPHY


J. Doughney, D. Pocci, and C. Williams, “CubeSat FSK Modem Implemented on a DSP.”


[40] F. Aguado, C. Martínez, E. Sarmiento, and G. González, “Reconfigurable communications system for cubesats,” in *European Planetary Science Congress*


41


[59] D. Tyler James, “DEVELOPMENT OF A REUSABLE CUBESAT SATELLITE BUS ARCHITECTURE FOR THE KYSAT-1 SPACECRAFT,” University of Kentucky.


Figure 7.1 Hardware consumption for the AFSK demodulator algorithm (code 1)
Figure 7.2 Hardware consumption for the AFSK demodulator algorithm (code 2)