COLLEGE OF ENGINEERING

Design Document

PCG: Programmable Communication Group

Submitted To:

Professor Dennis Silage
Senior Design Project I and II
Temple University
College of Engineering
1947 North 12th Street
Philadelphia, Pennsylvania 19122

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Prepared By:

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DAS

PCG

B. Keith, B. Thibodeau, and C. Destin
Faculty Advisor(s): Dr. Dennis Silage
Programmable Communication Group
Temple University
College of Engineering
1947 North 12th Street
Philadelphia, Pennsylvania 19122

For further information, please contact Dr. Dennis Silage (email: silage@temple.edu).

Team SD1-01	Programmable Communication Group	PGC
Team Members	Brandon Keith, Brian Thibodeau, Cedric Destin	
Advisor(s)	Dennis Silage	
Coordinator	Thomas Sullivan	
Department(s)	Electrical and Computer Engineering	
Project Title	Using FPGA Technology to Modernize the KD2BD Amateur Radio Satellite Modem	
Abstract	In 1993, John Magliacane (callsign: KD2BD) designed a 1200 bps BPSK modem using discrete electronic components. The objective of his design was to provide a low-cost, high-performance modem that interfaces between a packet radio terminal node controller (TNC) and an amateur satellite ground station. In our senior design project, we ~~implement the KD2BD~~ modem design ~~sole~~ly using an FPGA and peripheral ADC/DAC. We replace the on-board modem of a TNC with this FPGA-based modem and attempt to receive telemetry data from a low-earth orbiting amateur radio satellite. The FPGA-based modem implements two receiver schemes: 1) square and divide-by-two method as used in the KD2BD modem, and 2) coherent demodulation method known as the Costas Loop. We compare the performance of these two receiver schemes.	
URL	https://sites.google.com/a/temple.edu/programmable-communication-group/	

"go beyond"
see reference 8

before a "1.1.1" there should be a "1.0" which introduces the sections

define

TABLE OF CONTENTS

3. DESIGN REQUIREMENTS

Functional **DESIGN CONSTRAINTS**

define

1.1.1. Deriving the worst-case BER requirement

define "modulator-demodulator"

This modem is designed to communicate with any low-Earth orbiting (LEO) amateur radio satellite transmitting a 1200 bps BPSK downlink and receiving a 1200 bps AFSK uplink. Examples of LEO satellites capable of communicating with this downlink and uplink include the Fuji-Oscar 29 (FO-29) satellite and the AMRAD Oscar 16 (AO-16) satellite. Particularly, the FO-29 satellite transmits telemetry reports in a group packet. A group packet consists of two consecutively transmitted data packets. Each data packet is structured in its own unnumbered information (UI) frame as specified in the AX.25 data link layer protocol.

define

9600 b/sec also

This modem is designed to accurately receive ~~at least ten~~ 10 telemetry reports when the FO-29 satellite passes ~~by~~. Hence, the modem is designed to receive at ~~least ten~~ group packets without error ~~when the FO-29 satellite passes by~~. Each group packet consists of 186 bytes of telemetry data. Since each group packet consists of two separate, consecutive data packets, and since each data packet in its own UI frame, a total of 226 bytes are transmitted for one full telemetry report.

overhead

redundancy

changing standard, could be more

Assuming that we know the total amount of received group packets (FR) during a satellite pass and assuming that we know the amount of group packets (FC) we desire to accurately receive during the satellite pass, we can find the necessary worst-case BER (p_e) for the Modem:

$$p_e = 1 - \left(1 - \frac{F_R - F_C}{F_R}\right)^{\frac{1}{N}}$$

ref?

where N is the number of consecutive bits to receive without error. This formula was realized using the following packet error rate equation (p_p) and solving for p_e:

$$p_p = 1 - (1 - p_e)^N = \frac{F_R - F_C}{F_R}$$

ref?

As with any low-earth orbiting satellite, the FO-29 satellite passes will be between 6 and 18 minutes in duration. For finding the worst-case BER performance, let us consider the worst case of only 6 minutes before the satellite passes out of range. During a satellite pass, we aim to accurately receive at least ten telemetry reports from the satellite. Hence, during a satellite pass, we aim to accurately receive at least ten group packets. Each group packet consists of two consecutively transmitted data packets and each of these data packets are wrapped in its own UI frame. Put differently, the group packet is wrapped in a UI frame pair. There are 1808 bits (i.e. 226 bytes * 8 bits/byte) per UI frame pair. At a data rate of 1200 bps, the modem is expected to receive 1.507 UI frame pairs per second. Hence, over the period of six minutes, the modem is expected to receive 542.4 UI frame pairs, or conservatively, 542 UI frame pairs. This information yields the worst-case BER requirement for this modem:

$$p_e = 1 - \left(1 - \frac{542 - 10}{542}\right)^{\frac{1}{1808}} = 2.2059 \times 10^{-3}$$ µf ?

1.1.2. Modem-to-Radio interface

use? ?

The ADC and DAC of the modem saturate ~~at~~ the supply voltage of the FPGA board. The supply voltage of the FPGA board is 3.3 V, hence the modem will transmit and receive audio signals with voltage amplitudes no greater than 3.3 V p-p.

The modem expects 1200 bps BPSK signals at its receiver. Additionally, it will transmit 1200 bps AFSK signals at its transmitter. The modem is prepared to receive BPSK signals that are effected by Doppler shift. Consequently, the modem will be able to control a radio transceiver's Doppler-correction circuitry via the "Up" and "Down" buttons.

The modem will interface with a radio as follows:

- Microphone audio
- Receive audio
- Up (AFC)
- Down (AFC)
- Push-to-talk (PTT)
- Ground (PTT and audio common)

1.1.3. Modem-to-TNC interface

The Modem will replace the ~~on-board~~ integral modem of a terminal node controller (TNC). The Modem will interface with the TNC via its modem disconnect header. Specifically, the following five pins of the modem disconnect header will be used by the Modem:

- Carrier Detect Output
- Transmitter clock (16x) Input
- Receive Data Input
- Transmit Data Output
- Ground

do you have the information on the TNC???

At the modem disconnect header of the TNC, the Modem will send and receive signals at standard TTL interface levels. A ribbon cable for 20-pin headers will be linked between the Modem and the modem disconnect header.

IEEE standard is b/sec "capitalize" throughout

once define can use 'BPSK'

2. PROBLEM

2.1. Overall Objectives

A R

With a large community of amateur radio operators, the BPSK modem is an ideal implementation for current and future radio operators seeking reliable communication with Low- Earth Orbiting Amateur Radio Satellites (LEO-SAT). The 1200bps modem is designed to modulate and demodulate Binary Phase Shift Keyed data using ~~Avnet~~'s Spartan 6 FPGA. This allows the modem to be robust and alleviate ~~the complex~~ analog components. The use of an FPGA will allow the modem to have better performance than conventional analog modems and have the advantage of being adjusted for specific stations and is also open for improvements. Amongst all those great advantages, the modem is designed to be inexpensive and able to meet the basic desires of amateur operators. The completion of the modem will allow Temple University's radio club, K3TU, to establish full duplex communication with LEO-SATS that use Frequency Shift Keying (FSK) for uplink and Binary Phase Shift Keying (BPSK) for downlink, in which we plan on monitoring and predicting passing satellites as well as the time window available.

Xilinx

(BER)

Upon simulating ~~and~~ testing the modem we expect to develop a robust demodulation technique with a low Bit Error Rate. Our design is intended to contain a sophisticate algorithm able to allay the effect of the Doppler Shift and the attenuation that the signal may suffer. With our design, the K3TU will be potent to communicate with the satellites regardless of the detrimental effects of the Doppler Shift.

B d s d s

2.2. Historical and Economic Perspective

During the last century

~~In the mid - 1900's~~ the combined effort of the missiles and wireless communication has brought to us the technology that we now call satellites. The development done in wireless communication and controls engineering has enabled engineers to use satellites for a wide range of applications, and essentially provides an economical advantage compare to the conventional wired communication. The use of satellites has been the essence of several innovative technologies in less than 30 years, satellites have been applied for relaying digital information across the earth and also has been used for to provide information directly an individual using appropriate antennas in term of size. Those two applications of the satellites accounted for a total of 35 billion dollars in 2000 [1], and is a number that is still increasing due to the numerous applications of digital communications.

geeee... first satellite in 1961

Amateur Radio operators have also slowly followed the trend of satellites for communication purposes. Although their vantage point in ~~terms of~~ bandwidth and also orbits, Amateur Radio operators have used Low-Earth Orbiting satellites (~~Find altitude~~) to develop several applications which consist of the Slow-Scan Television, Automatic Packet Reporting System for weather reports and telemetry and several others organized by Radio Amateur Satellite Corporation (AMSAT.) The communication between the satellite and the earth stations is established through the modulation of a carrier signal with the desired digital data, several modulation schemes have researched, the dominant ones are the Amplitude modulation, Frequency modulation and finally the Phase modulation, where in each of the those modulation the amplitude A, frequency f and phase \theta of equation # are modulated to represent the digital information. The phase modulation technic is the most effective modulation scheme for establishing a communication with spatial vehicles such as satellites, a very popular usage of the phase modulation is for Global Positioning Systems (GPS) which through the use of a complicated Phase Shift Keying method, the positions are obtained for by stationary or moving receivers.

?

A R its

With the benefits of BPSK modulations, amateur radio operators have taken the advantage of ~~BPSK~~'s robustness against the effects of Doppler shift. Since BPSK has been a fairly new modulation scheme, in contrast to amplitude and frequency modulation, most amateur radio operators did not own the hardware compliable for the communication. One of the designs that has allowed the implementation of BPSK

ref

use ref rather than name

1990s

b/sec

communication in early ~~90's~~ is described by ~~John Magliacane who in~~ 1993 implemented a 1200bit/s modem for PACSAT communication [3]. The modem was a breakthrough design for amateur radio operators which has encouraged radio operators, including the PGC to implement modern satellite communication using BPSK modulation scheme.

??? FCC?

not a sentence

define

Regarding the cost of owning an active amateur satellite station is assumed to be an expensive but on the other hand, it could be affordable to be equipped with a station. A current operator ~~Steve Primer~~ has published the adequacy of having a radio satellite station and listed the cost of setting such station to range between $150-3000, where the cost would include Yagi antennas, an azimuth and elevator rotator (AZ\EL Rotator) which is an essential equipment to follow the position of the satellite, a VHF/UHF transceiver, and finally a receiver amplifier and pre-amplifier [2].

give ref

With the commitment of several operators, amateur radio satellites have played a very important role to the community during natural disasters. In the events of disasters similar to Katrina in Louisiana and Sandy in East Coast, amateur radio operators have ~~benevolently~~ used their station to communicate distress messages.

voluntarily

K3TU uses stationary antennas include in description

2.3. Candidate Solutions

satellites

define

The LEO-AMSAT's that we are interested in communicating with are also known as packet satellites (PACSAT). This is because they use the AX.25 protocol which transmits packets of data. Packets are also known as frames and each frame consists of several fields. These fields include flag, control, and address information in addition to the data to be sent. Since TNC's are responsible for AX.25 encoding and already contain a modem within, we originally considered an FPGA implementation of a TNC. However, the complexity and depth of the AX.25 protocol in addition to a modem design was determined to be too ambitious given the time constraint of two semesters. Instead, we simply chose to design an FPGA modem that would interface with the TNC and transceiver.

2.3.1. Modulator

The design of any modem requires two fundamental components, a modulator and demodulator. The modulator is responsible for taking baseband data and either source encoding it, or translating it passband levels necessary for radio transmission. There are many source encoding schemes that have been developed in the course of digital communication. Each of them has their own benefits as far as bandwidth requirements or self-clocking characteristics. Listed below are a few of the more common schemes encountered in communication systems:

1. Return to Zero (RZ)
2. Non-Return to Zero (NRZ)
3. Non-Return to Zero-Inverted (NRZI)
4. Bi-phase Manchester

strictly speaking these are "line codes"

Miller is a source code

Our modem was designed to interface between the TNC and the transceiver. This means our modem will only perform baseband modulation. From the TNC, the modem receives AX.25 data streams and further processes them using a bi-phase Manchester encoder. The benefit of bi-phase Manchester code is that it is self-clocking which makes timing synchronization easier on the receiving end.

show waveform

2.3.2. Demodulator

The demodulator is responsible for providing either coherent or non-coherent demodulation. Coherent demodulators require phase synchronization between the received signal and the locally generated oscillator. Conversely, Non-coherent demodulation does not require synchronization and makes no attempt

n

to estimate the phase of the received signal. The advantage of non-coherent modulation is that it does not require additional hardware like phase-locked loops which are used to lock onto the incoming carrier phase. However, the LEO-AMSAT's we are interested in communicating with use BPSK for downlink and thus requires the design of a coherent demodulator.

The successful extraction of information from a received signal in a coherent demodulator requires both carrier and timing synchronization. Figure 1 illustrates the architecture of a typical coherent demodulator. [ref]

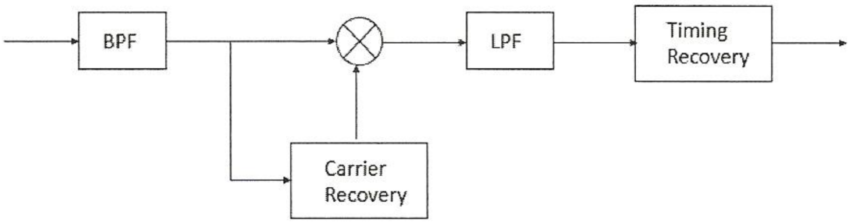

Figure 1. Received waveform takes two paths. First path extracts carrier for coherent demodulation and the second path recovers timing information. This architecture is based on the optimum binary receiver

The received signal from the transceiver is first processed by a band pass filter to remove as much noise as possible and then sent to the carrier recovery circuit. Recovering the carrier is done in one of two ways, the squaring loop or the Costas loop. Each method utilizes phase-lock concepts and has its own advantages and disadvantages in terms of complexity and performance.

2.3.3. Carrier Recovery using Squaring Loop

The squaring loop is a popular choice for coherent demodulation of BPSK waveforms. [ref] It's mathematically easy to analyze and its hardware implementation is not as complex as the Costas loop. As the name implies, the received signal is squared to remove any phase offsets and then processed by a bandpass filter to remove as much noise as possible. After the band pass filter, the signal is fed to a phase-lock loop (PLL) for phase and frequency tracking. Once the output of the voltage controlled oscillator (VCO) is locked in phase and frequency with the received signal, its frequency is divided by two. The resulting carrier is fed back to the mixer where it is mixed with the received waveform and the timing can be recovered. The operation of the squaring is shown in Figure 2.

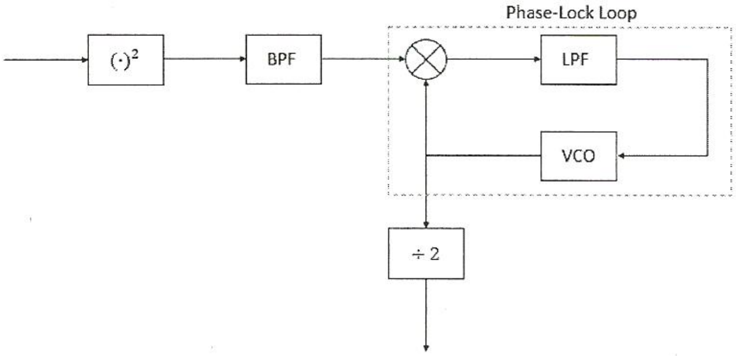

Figure 2. Squaring loop used for carrier recovery in the coherent demodulator. The Phase-Lock Loop utilizes feedback to track and lock onto in the received waveforms suppressed carrier

2.3.4. Carrier Recovery using Costas Loop

que as ref

Another method for carrier recovery was proposed by ~~John P. Costas~~ in his 1957 paper, ~~*Synchronous Communication*~~. Unlike the squaring loop whose only purpose is suppressed carrier reconstruction, the Costas loop is capable of synchronous data detection in addition to suppressed carrier reconstruction. One of its disadvantages is its mathematical complexity compared to the squaring loop, but in terms of hardware components needed for complete coherent demodulation, they both require approximately the same amount.

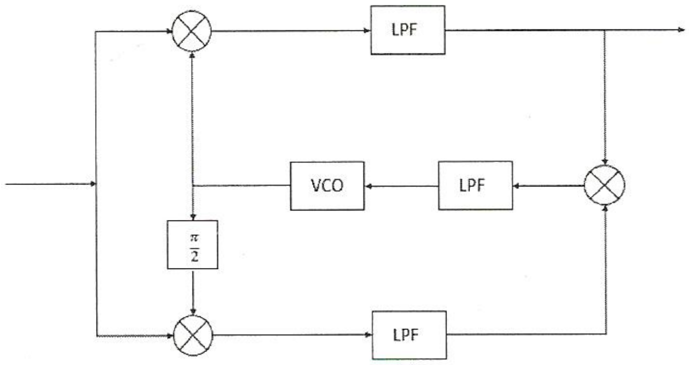

Figure 3. Costas loop used for suppressed carrier reconstruction as well as synchronous data detection.

Coherent modulation utilizing the Costas loop would require one band-pass filter, three low-pass filters, three multipliers and a VCO. Likewise, the squaring loop would also require one band-pass filter, three multipliers (including the squarer) and a VCO. Instead of three low-pass filters needed by the Costas, the squaring loop only requires two. Note also that the squaring loop requires a flip-flop for frequency division, but with today's FPGA's, a single flip-flop is negligible. The decision for implementing the squaring loop versus the Costas loop will ultimately be decided by their tracking and locking performance in the presence of noise and Doppler shifts (See section 1.5, Major Design and Implementation Challenges).

2.3.5. Timing Recovery

2.4. Proposed Solution Concept

In order to provide the Temple University Amateur Radio Club K3TU ~~'s radio club~~ with a robust and reliable modem, it must be able to be interfaced with a transceiver and the TNC. This requires a single analog to digital converter for received signals ~~and~~ and a single digital to analog converter for transmitted signals. Figure 4. Illustrates the how the 1200pbs modem fits into the system level model

b/sec

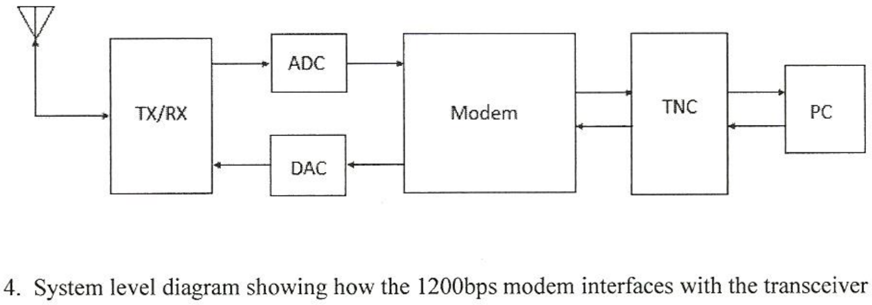

Figure 4. System level diagram showing how the 1200bps modem interfaces with the transceiver and TNC.

Shown in Analysis section

The Xilinx Spartan-6 LX-9 Microboard was selected for our modem implementation because of its good performance and low cost. It also provides the two Pmod expansion ports needed for interfacing Digilent's 12-bit AD1 ADC and 12-bit DA2 DAC.

It was determined through simulation that optimum coherent demodulation was achieved from the use of a (squaring or Costas) loop. The result is a modem design that incorporates a bi-phase Manchester encoder for baseband modulation of AX.25 data streams, and a (squaring or Costas) loop for coherent demodulation of BPSK signals.

2.5. Major Design and Implementation Challenges

The biggest design challenge associated with this project is the development of a carrier reconstruction circuit that is capable of mitigating the effects of Doppler shift. The relative motion of satellites in orbit around earth with respect to the ground station can cause the received frequency to appear 20 kHz above or below its nominal downlink frequency. In John ~~A. Maglieane's 1993~~ design, he derived a control signal from the carrier recovery circuit that simulated a person tuning the transceivers frequency control button. In our design, Doppler shift correction will be done autonomously through the ~~use of~~ a type II PLL. give ref

The challenge is designing a stable control loop that minimizes time to lock and inter-symbol interference but still has a narrow enough bandwidth to reduce noise and the bit error rate. Since the PLL is an inherently non-linear system, it must be linearized in terms of the phase of the received signal. This problem becomes more challenging if the Costas loop is implemented because the arm filters much be matched perfectly. However, the advantage of an all digital Costas loop is that designing two identical filters is much easier than if it were done with analog components.

2.6. Implications of Project Success

b/sec the K3TU

The successful design of a 1200bps modem will enable Temple University Amateur Radio ~~club~~ to communicate with LEO-AMSATs ~~that~~ use FSK for uplink and BPSK for downlink. Although software is available that will perform the modem functions, an FPGA modem demonstrates the potential for high speed processing in re-programmable logic circuitry.

3. DESIGN REQUIREMENTS

3.1. Functional Design Constraints

3.1.1. Deriving the worst-case BER requirement

W C

b/sec

This modem is designed to communicate with any low-Earth orbiting (LEO) amateur radio satellite transmitting a 1200 bps BPSK downlink and receiving a 1200 bps AFSK uplink. Examples of LEO satellites capable of communicating with this downlink and uplink include the Fuji-Oscar 29 (FO-29) satellite and the AMRAD Oscar 16 (AO-16) satellite. Particularly, the FO-29 satellite transmits telemetry reports in a group packet. A group packet consists of two consecutively transmitted data packets. Each data packet is structured in its own unnumbered information (UI) frame as specified in the AX.25 data link layer protocol.

give table of Operating Satellites

This modem is designed to accurately receive at least ten telemetry reports when the FO-29 satellite passes by. Hence, the modem is designed to receive at least ten group packets without error when the FO-29 satellite passes by. Each group packet consists of 186 bytes of telemetry data. Since each group packet consists of two separate, consecutive data packets, and since each data packet in its own UI frame, a total of 226 bytes are transmitted for one full telemetry report.

or more

Assuming that we know the total amount of received group packets (F_R) during a satellite pass and assuming that we know the amount of group packets (F_C) we desire to accurately receive during the satellite pass, we can find the necessary worst-case BER (p_e) for the Modem:

$$p_e = 1 - \left(1 - \frac{F_R - F_C}{F_R}\right)^{\frac{1}{N}}$$

ref?

where N is the number of consecutive bits to receive without error. This formula was realized using the following packet error rate equation (p_p) and solving for p_e:

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¶ paragraph break

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3.1.2. Modem-to-Radio interface

define

The ADC and DAC of the modem saturate at the supply voltage of the FPGA board. The supply voltage of the FPGA board is 3.3 V, hence the modem will transmit and receive audio signals with voltage amplitudes no greater than 3.3 V (p-p).

b/s c

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3.2. Non-Functional Design Constraints

4. APPROACH

5. EVALUATION

6. SUMMARY AND FUTURE WORK

7. ACKNOWLEDGEMENTS

8. REFERENCES