DIGITAL CONTROL BOARD FOR PHASED ARRAY ANTENNA BEAM
STEERING IN ADAPTIVE COMMUNICATION APPLICATIONS

A Thesis

presented to

the Faculty of California Polytechnic State University

San Luis Obispo

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Electrical Engineering

by

Mayur Bansal

November 2013

© 2013

Mayur Bansal

ALL RIGHTS RESERVED

COMMITTEE MEMBERSHIP

TITLE: Digital Control Board for Phased Array
Antenna Beam Steering in Adaptive Communication Applications

AUTHOR: Mayur Bansal

DATE SUBMITTED: November 2013

COMMITTEE CHAIR: Bryan Mealy, Ph.D.
Associate Professor
Electrical Engineering Department

COMMITTEE MEMBER: Lynne Slivovsky, Ph.D.
Professor
Electrical Engineering Department

COMMITTEE MEMBER: Dennis Derickson, Ph.D.
Department Chair
Electrical Engineering Department

ABSTRACT

Digital Control Board for Phased Array Antenna Beam Steering in Adaptive Communication Applications

Mayur Bansal

The application of adaptive communication techniques for mobile communications has attracted considerable interest in the last decade. One example of these techniques is spatial filtering through planar antenna array beam forming.

This thesis describes the development of a digital system that adaptively controls a phased array antenna. The radiating structure of the phased antenna array is tetrahedral-shaped and contains four antenna elements on each of its three faces. The overall system comprises of a digital control board with an external computer interface, an RF control board, and the phased antenna array. The RF controls the main lobe direction on the phased array antenna. This thesis describes the design and implementation of the digital control board.

The digital control board's primary responsibilities are implementing interfaces between the external computer and the RF board, which results in two operational modes: the MATLAB graphical user interface (GUI) mode and the adaptive receive mode. The GUI mode allows users to input parameters that provide interactive control of the phased antenna array by interfacing with an external computer and the RF control board. The adaptive receive mode implements an algorithm for an adaptive receive station. This algorithm uses a 58-point scanning technique that locates the maximum receive power direction.

Test results show that the digital control board successfully manages the RF board control voltage with an nominal error of less than 1%, which subsequently

allows for precise control of the antenna's active face. Additionally, testing of the GUI demonstrated the successful interactive application of various system control parameters.

ACKNOWLEDGMENTS

I would like to thank my parents, Meenakshi and Bharat, for encouraging and allowing me to pursue my ambitions. I am also grateful to my entire family for their continual support.

I would like to thank my advisor, Dr. Dean Arakaki, for his guidance and support. I would also like to thank my project partner Steve Brockhoff for his hard work and help, which made this thesis possible.

TABLE OF CONTENTS

LIST OF TABLES	ix
LIST OF FIGURES	x
1 INTRODUCTION	1
2 SYSTEM DESIGN	4
2.1 System Requirements	7
2.1.1 GUI Control	7
2.1.2 Adaptive Receive Mode	9
2.2 System Sub-blocks	10
2.2.1 RF Power Detector	10
2.2.2 Interrupt Feedback Loop	10
3 RF POWER DETECTOR	12
3.1 LT-5534	14
3.2 LT-5538	16
3.3 Log-Amp Power Detector Analysis	18
4 INTERRUPT FEEDBACK LOOP	19
4.1 ADC	20
4.2 Interrupt	23
4.3 DAC	24
4.4 Comparator	27
5 RF SYSTEM INTEGRATION	29
5.1 Phase Shifters	29
5.2 RF Single Pole Double Throw (SPDT) Switch	34
5.3 RF Single Pole Triple Throw (SP3T) Switch	35
5.4 Voltage Control Oscillator (VCO) Control Line	36

6	PRINTED CIRCUIT BOARD DESIGN	39
6.1	Schematic	39
6.2	Layout	40
7	GRAPHICAL USER INTERFACE (GUI) CONTROL SYSTEM	42
7.1	GUI Inputs and Features	43
7.1.1	Drop Down Menus	43
7.1.2	Edit Text	47
7.1.3	Push Buttons	49
7.1.4	Additional Figure Checkboxes	50
7.2	Communication Protocol	51
7.3	Test and Results	53
8	ADAPTIVE RECEIVE MODE	58
8.1	Adaptive Receive Algorithm	58
8.2	Testing	62
9	CONCLUSIONS AND FUTURE WORK	65
	BIBLIOGRAPHY	67
	APPENDICES	69
A	2013 IEEE APS Student Design Challenge: Reconfigurable Antennas	69
B	Contest Proposal	72
C	LT 5534 Demo Board Schematic	75
D	LT 5538 Demo Board Schematic	77
E	Microcontroller Code	79
F	PCB Schematic	90
G	PCB Layout	96
H	Bill Of Materials	98
I	Block Diagrams	100

LIST OF TABLES

2.1	16-Pin IDC Pin-out Between Digital Control Board and RF Board	6
4.1	ADC Conversion Time	22
4.2	ADC Configuration	23
4.3	Interrupt Configuration	23
4.4	DAC Command Codes	26
4.5	DAC Address Codes	26
5.1	Truth Table for SPDT, $V_{HIGH} = 2V$ to $5V$, $V_{LOW} = 0V$ Insertion Loss = 0.5dB, and Isolation = 22dB	34
5.2	SPDT, Antenna Mode Truth Table	35
5.3	Truth Table for HMC245QS16 and the Active Antenna Face . . .	36
5.4	VCO Tuning Circuit Result	38
7.1	Hexadecimal Notation for ASCII Decimal Characters to 8-bit In- tegers	52
7.2	GUI Test Result	54
8.1	Test Data for Adaptive Receive Mode Test Procedure	63

LIST OF FIGURES

1.1	A Radiation Diagram with Main Lobe	2
2.1	System Block Diagram	4
2.2	Tetrahedron Antenna Model	5
2.3	Digital Control Board Block Diagram	5
2.4	IDC connector Pin Positions	6
2.5	Screen shot of MATLAB GUI	8
2.6	Adaptive RX, Example System Configuration	9
2.7	Inner Feedback Loop Block Diagram	11
3.1	DC log-amp BJT implementation	13
3.2	Demo Board DC748A	14
3.3	LT-5534 log-amp Characteristics	15
3.4	Demo Board DC1120A	16
3.5	LT-5538 Output characteristics	17
4.1	Analog to Digital Converter Timing Diagram for Single Conversion Mode	22
4.2	LTC2656 DAC Load Sequence	25
4.3	LM339 Schematic Diagram	28
5.1	JSPHS-2484+ Phase Shifter, Interpolated Data	30
5.2	Operational Amplifier in Non-Inverting Configuration	30
5.3	LTSpice Simulation Schematic, LT6005 Non-Inverting Gain Op-Amp Circuit	31
5.4	LTSpice Simulation results, LT6005 Op-amp Non-Inverting Gain Circuit	32

5.4	LTSpice Simulation results, LT6005 Op-amp Non-Inverting Gain Circuit	33
5.5	Monte Carlo Analysis for Amplification Circuit, Expanded View .	33
5.6	AS179-92LF, SPDT, Pin-out and Block Diagram	34
5.7	HMC245QS16 SP3T RF Switch Pin-out and Functional Diagram	35
5.8	JTOS-2700V, VCO, datasheet characteristic	37
5.9	VCO tuning Schematic, R5 is the tunable resistor	38
6.1	PCB layout	41
7.1	RS-232, 9-pin D-sub connector pinout	42
7.2	MATLAB GUI main screen	43
7.3	MATLAB GUI screen with Face drop down menu	44
7.4	MATLAB GUI Screen with Mode Drop-Down Menu	45
7.5	TRENDnet TU-S9, USB to RS-232 Converter Cable	45
7.6	Device Manager screen shot with COM port highlighted	46
7.7	MATLAB GUI screen with COM drop down menu	47
7.8	Antenna Radiation Pattern Coordinate system	48
7.9	MATLAB GUI Screen Shot, θ and ϕ Control Variables	49
7.10	Phase Shifter JSPHS-2484+ Interpolated Data	50
7.11	Checkbox Selected Images, with $\theta = 30^\circ$ and $\phi = 45^\circ$	51
7.12	RS-232 Frame	51
7.13	Communication Packet Frame	52
7.14	Microcontroller, MATLAB GUI Mode Flowchart	53
7.15	Status LED's for Mode and Face value	55
7.16	GUI Test Measured Radiation Patterns	56
7.16	GUI Test Measured Radiation Patterns	57
8.1	Adaptive Receive scan plot	59
8.2	Raster Scan Pattern	60
8.3	Adaptive Receive Flowchart	61
8.4	ISR Flowchart	62

I.1	Schottky Diode Chip Model	100
I.2	ATmega2560 Block Diagram	101
I.3	Analog to Digital Converter Block Schematic	102
I.4	LTC2656 Block Diagram	103

CHAPTER 1

INTRODUCTION

An adaptive communication system was proposed as a contest entry to the 4th IEEE Antenna Design Challenge, sponsored by the Antenna and Propagation Society (AP-S). This thesis describes an adaptive communication system, which was developed as a contest entry. The main challenge of the contest was to develop an “antenna system with reconfigurable antenna elements that can adapt to different propagation conditions (e.g. line-of-sight versus non-line-of-sight).” The IEEE contest rules are shown in Appendix A. The two page proposal for the design challenge is shown in Appendix B.

A phased adaptive antenna array was proposed for the contest entry. Adaptive phased array antennas can change their radiation pattern electronically or mechanically. In electrically configurable radiation pattern antenna, elements have a relative phase difference while the antenna elements remain stationary. Whereas in mechanical reconfigurable radiation patterns, antenna elements are placed relative to each other but the antenna elements are movable. A tetrahedral structure with four patch antennas on each face of the antenna is developed, as shown in Figure 2.2. Only one face is active at any given moment. A relative phase difference in the four patch antenna changes the radiation pattern’s main lobe direction, which is referred to as beam steering. The main lobe of an antenna radiation pattern contains the maximum power. Figure 1.1 shows a main lobe for a radiation pattern.

Figure 1.1: A Radiation Diagram with Main Lobe

The goal of this thesis is to design and implement a Digital Control System to control the Electronically-Steered Phased Array Antenna described in [1]. The controllable fields for the RF front-end system include the active antenna face, two communication modes (transmit or receive), and control voltages for a phase shifter that sets the main beam direction. The digital control board components include:

RF Power Detector

The RF power detector measures the power received from the RF system. The received power is interpreted by the microcontroller using an ADC, which is further explained in Chapter 8.

Microcontroller

A microcontroller provides a communication interface between the computer and RF system; see Chapter 7 for additional details. The microcontroller also executes adaptive communication algorithms, as explained in

Digital Peripherals

The digital peripherals include a digital-to-analog converter (DAC), a comparator, and an analog-to-digital converter (ADC). The ADC is an internal peripheral of the microcontroller. The DAC output voltages control the phase shifters (via an SPI bus) to steer the antenna beam. The ADC measures received power by sampling the RF power detector output voltage. The comparator checks the receive power level against a reference level set by the DAC; this level is the previously received maximum power and is discussed further in Chapter 4. A feedback loop is implemented using an ADC, DAC and a comparator. The feedback loop improves the time required to find the receive direction with maximum power. The feedback loop is explained in Chapter 4.

CHAPTER 2

SYSTEM DESIGN

An AVR-based microcontroller serves as the system controller. The AVR model is an 8-bit Reduced Instruction Set Computer (RISC) single-chip microcontroller developed by Atmel. Figure 2.1 shows the system basic block diagram.

Figure 2.1: System Block Diagram

The adaptive antenna system is a tetrahedron shaped structure (Figure 2.2) with 2X2 patch arrays on each of the three faces. Only one face is active at a time. The system is half duplex in that it can both transmit and receive, but not simultaneously.

Figure 2.2: Tetrahedron Antenna Model

Figure 2.3 is the level-1 block diagram for the system. The block diagram shows the main system blocks and the associated data flow. The yellow blocks correspond to the RF components on the board. The purple blocks correspond to the analog system on the board. The pink blocks are the USART support components.

Figure 2.3: Digital Control Board Block Diagram

Table 2.1: 16-Pin IDC Pin-out Between Digital Control Board and RF Board

PIN #	Control Line	Function
1	GND	Ground Connection
2	GND	Ground Connection
3	CTRL1	Unused
4	CTRL0	Unused
5	SPDT0	Control line for Single pole double throw
6	PS1	Control Voltage Phase Shifter 1
7	SPDT1	Control line for Single pole double throw
8	PS2	Control Voltage Phase Shifter 2
9	SP3T0	Control line for Single pole triple throw
10	PS3	Control Voltage Phase Shifter 3
11	SP3T1	Control line for Single pole triple throw
12	PS4	Control Voltage Phase Shifter 4
13	GND	Ground Connection
14	VCO	Control Voltage for the Voltage Control oscillator
15	GND	Ground Connection
16	GND	Ground Connection

Figure 2.4: IDC connector Pin Positions

The control board and RF system communicate via a 16-pin insulation displacement connector (IDC). The IDC pinout is defined in Table 2.1 and pin positions are shown in Figure 2.4. System requirements for the digital control board include:

1. Graphical User Interface (GUI) Controlled System

A MATLAB-based GUI tests the system's beam steering. The GUI communicates with the digital control board via a Universal Asynchronous Receiver/Transmitter (USART) using a RS-232 protocol. All antenna system variables are defined through the GUI; see Chapter 7.

2. Adaptive RX

An adaptive receive station directs the system's radiation pattern in the maximum receive power direction. The scan algorithm for finding this direction is explained in Chapter 8.

2.1 System Requirements

2.1.1 GUI Control

The first project goal is to interface the system with the MATLAB GUI that defines phase shifter voltages, mode, and face; see Figure 2.5.

Figure 2.5: Screen shot of MATLAB GUI

Phase Shifter Voltages

Voltage controlled phase shifters in the RF front-end are used to direct the radiation pattern's main beam [1].

Mode

The system has two modes: transmit and receive. Single pole double throw (SPDT) switches control the modes; see Section 5.2.

Face

The tetrahedral antenna structure has three faces. The active face is controlled using single pole triple throw (SP3T) switches; see Section 5.3.

A USART is used for MATLAB GUI and system communications. The Voltage Controlled Oscillator (VCO) output frequency is controlled by an external potentiometer for fine adjustments. Detailed GUI information is provided in Chapter 7.

2.1.2 Adaptive Receive Mode

The second system goal is to operate as an adaptive receive station, which tracks a transmitting signal's location. A scan algorithm determines the maximum power direction and is described in Chapter 8. Figure 2.6 shows two 'RX antenna' placements and how the radiation patterns adapt to the optimum direction. Additional information appears in Chapter 8.

Figure 2.6: Adaptive RX, Example System Configuration

2.2 System Sub-blocks

2.2.1 RF Power Detector

The RF power detector converts the received RF power to a DC voltage. Most RF power detectors are Schottky diode-based topologies; they exhibit an exponential relation between input power and output voltage, $V_{out}(V) \propto e^{P_{in}(W)}$. Another common implementation is a log-amp based topology, which exhibits a linear relationship between input power and output voltage, $V_{out}(V) \propto P_{in}(W)$. RF power detector information appears in Chapter 3.

2.2.2 Interrupt Feedback Loop

The block diagram of the Interrupt Feedback Loop is shown in Figure 2.7. The Interrupt Feedback Loop improves system efficiency by reducing the number of required ADC samples at every step. The ADC samples only when hardware interrupts are triggered; i.e.: when a power level that exceeds the previous maximum is detected. When an interrupt is triggered, the received power is saved in memory as the new maximum value. The feedback loop includes a comparator, the RF power detector and the microcontroller. The microcontroller uses a DAC to set the comparator's reference level, which represents the previous maximum received power. Interrupt feedback loop information is provided in Chapter 4.

Figure 2.7: Inner Feedback Loop Block Diagram

CHAPTER 3

RF POWER DETECTOR

An RF power detector monitors the RF circuit's output and develops a DC voltage proportional to the received power in Watts [2]. Equation 3.1 shows power in decibels relative to 1mW (dBm), commonly used by RF and wireless engineers.

$$P(dBm) = 10\log P(mW) \quad (3.1)$$

An operational amplifier (op-amp) with a PN junction diode as negative feedback is a classical implementation for a log-amp [3]. The logarithmic relationship between diode voltage and current yields a linear relationship between input power (dB scale) and output voltage (linear voltage scale). A bipolar junction transistor (BJT) generates the logarithmic I vs V relation in place of a diode. Figure 3.1 shows implementation examples for the single stage NPN and PNP log-amp. Equation 3.2 defines RF power detector output voltage (V_{out}) as a function of the input power (I_{in}).

$$V_{out} = \frac{kT}{q} \ln \frac{I_C}{I_S} \approx \frac{kT}{q} \ln \frac{I_{In}}{I_S} \quad (3.2)$$

Figure 3.1: DC log-amp BJT implementation

Two Linear Technology Corp. (LTC) log-amps were compared to maximize dynamic range and output voltage slope. Log-amp datasheet characteristics include:

1. LT 5534

- RF Frequency Range: 50MHz to 3GHz
- Linear Dynamic Range: 60dB
- Supply Voltage: 2.70V to 5.25V
- Low Supply Current: 7mA [4]

2. LT 5538

- RF Frequency Range: 40MHz to 3.8GHz
- Linear Dynamic Range: 75dB
- Supply Voltage: 3.00V to 5.25V
- Low Supply Current: 29mA [5]

The log-amps were compared to the required dynamic range, 60dB, and the output slope of the linear $V_{out}(V)$ vs input power(dBm) relationship, $> 20mV/dB$. Comparison results are shown in Section 3.3.

3.1 LT-5534

The **LT-5534** is a monolithic RF power detector capable of measuring RF signals over a dynamic range of -63dBm to 3dBm at 2.5GHz [6]. A Linear Technology Corp log-amp demo board DC748A enabled LT-5534 characterization, as shown in Figure 3.2 The demo board's schematic is shown in Appendix C [7].

Figure 3.2: Demo Board DC748A

The log-amp, LT-5534, output characteristics were compared to datasheet values. Figure 3.3a shows measured output voltage $V_{out}(V)$ vs Input Power (dBm) at 2.4GHz, Figure 3.3b shows the same plot provided by the datasheet. The measured output slope is $0.0373V/dB$ compared to $0.0366V/dB$ in the datasheet [6]. The minimum detectable signal power is -60dBm.

(a) Measured

(b) Datasheet

Figure 3.3: LT-5534 log-amp Characteristics

3.2 LT-5538

The **LT-5538** is a monolithic RF power detector capable of measuring RF signals over a dynamic range of -72dBm to 10dBm at 2.7GHz [8]. The demo board DC1120A, Figure 3.4 schematic can be found in Appendix D [9].

Figure 3.4: Demo Board DC1120A

The LT-5538 log-amp's output characteristics are compared to datasheet values. Figure 3.5a shows the measured output voltage $V_{out}(V)$ vs. Input Power (dBm) at 2.4GHz. Figure 3.5b shows the same plot provided by the datasheet. The measured output slope is $0.0180V/dB$ compared to the datasheet value of $0.0176V/dB$ [8]. The minimum detectable signal power is -68dBm.

(a) Measured

(b) Datasheet

Figure 3.5: LT-5538 Output characteristics

3.3 Log-Amp Power Detector Analysis

From the previous sub-sections, the LT-5534 and LT-5538 have output slopes of $37.3mV/dB$ and $18.0mV/dB$, respectively. For an 8-bit ADC with reference voltage of $5V$, a quantum is $19.6mV$, as shown in Equation 3.3.

$$quanta = \frac{5V}{2^8 - 1} = 19.6mV \quad (3.3)$$

Thus the LT-5534 is the best option, since the dynamic range satisfies the required range ($-60dBm$ to $-30dBm$) and the output slope is greater than one quanta ($19.6mV/dB$).

CHAPTER 4

INTERRUPT FEEDBACK LOOP

Microcontrollers are widely used in communication applications. The AT-mega2560 AVR architecture [12], microcontroller is the main system controller for the system. Key features include:

- Flash : 256 Kbytes (kB)
- Static Random Access Memory (SRAM): 8 kB
- Maximum Operating Frequency: 16 MHz
- Serial Peripheral Interface (SPI): 5 channels
- Analog-to-Digital Converter: 16 channels, 10-Bit Resolution
- Real Time Clock (RTC)

Flash memory stores the boot loader and firmware. The boot loader is a program that loads the firmware, or runtime environment, for the processor following self-test completion. SRAM microcontroller memory used for system variable declaration and firmware operation. An algorithm with multiple subroutines requires an extensive ($>128\text{kB}$) flash memory (see Section 8.1 for algorithm). Status variables are required for each algorithm branch; thus, greater than 2kB of SRAM must be available. Many current digital peripherals use a communication protocol (SPI, CAN, I2C, USART, etc.) for intercommunication. SPI and

USART are the two communication buses used in this system. ADC converts the RF peak detector DC output voltage into a digital value. A 2% output accuracy and resolution greater than eight bits is required to capture a 0.25dBm change in received power level. Real time clock (RTC) compatibility is preferred for systems synchronization. Figure I.2 (Appendix I) shows the microcontroller's block diagram.

The inner feedback loop (Figure 2.7) consists of an ADC, DAC, and a comparator. The DAC sets the reference input to the comparator. The peak detector output is connected to both the positive input terminal of the comparator and the microcontroller's ADC input.

When the peak detector output is greater than the comparator's reference voltage, the comparator output changes to logic high, triggering a microcontroller interrupt. The microcontroller is notified that a new maximum power has been received and is sampled by the microcontroller's ADC. In this case, a new reference value is set by the DAC, and microcontroller stores the face and phase counters (see Section 8.1). This loop eliminates redundant power detector output voltage sampling in each algorithm step. Only voltage levels greater than the previously received maximum power are sampled. Lock time is defined as the time required to find the optimal receive direction.

4.1 ADC

The microcontroller's ADC samples the power detector's output voltage. Figure I.3 (Appendix I) shows the microcontroller's ADC block schematic. Key features include:

- 10-bit resolution

- $13\mu s$ - $260\mu s$ conversion time
- $0V - V_{CC}$ ADC input voltage range, $V_{CC} = 5V$
- Free running or single conversion mode

The ATmega2560 uses a 10-bit successive approximation ADC that can be configured as either a single-ended or a differential input. A single-ended ADC is preferable since negative voltages are not sampled. Equation 4.1 defines the digital output for a single-ended conversion, where V_{IN} is the voltage at the selected input and V_{REF} is the selected voltage reference.

$$ADC_{out} = floor\left(\frac{V_{IN} \cdot 1024}{V_{REF}}\right) \quad (4.1)$$

The 10-bit ADC resolution results in a quanta of ($V_{CC} = 5V$):

$$quanta = \frac{V_{CC}}{2^n - 1} = \frac{5V}{2^{10} - 1} = 4.9mV \quad (4.2)$$

The ADC is configured in single conversion mode since samples are recorded only upon interrupt triggers. As specified in Table 4.1, the first conversion requires 25 clock cycles, while subsequent conversions require 13 clock cycles.

Table 4.1: ADC Conversion Time

Condition	Sample & Hold (Cycles from Start of Conversion)	Conversion Time (Cycles)
First conversion	13.5	25
Subsequent conversions, single end	1.5	13

The ADC conversion timing diagram is shown in Figure 4.1. Table 4.2 shows ADC register definitions and functions. The Application Programming Interface (API) for the ADC is listed in Appendix E.

Figure 4.1: Analog to Digital Converter Timing Diagram for Single Conversion Mode

Table 4.2: ADC Configuration

ADC Parameter	Microcontroller Register and Bit(s)	Value	Value Interpretation
Reference Value	ADMUX(REFS1:0)	b01	AVCC with external capacitor at AREF pin, 5V
ADC Clock	ADCSRA(ADPS2:0)	b010	XTAL/4
ADC Trigger	ADCSRA(ADATE)	b0	ADC auto trigger disable
ADC Input Pin	ADCSRB(MUX5) + ADMUX(MUX4:0)	b000000	ADC0
ADV value justification	ADMUX(ADLAR)	b1	ADC left adjust result
ADC Interrupt	ADCSRA(ADIE)	b0	ADC interrupt disables

4.2 Interrupt

An external microcontroller interrupt triggers the Interrupt Service Routine (ISR) (see Chapter 8). The interrupt configuration for the microcontroller is shown in Table 4.3.

Table 4.3: Interrupt Configuration

Interrupt Parameter	Microcontroller Register and Bit(s)	Value	Value Interpretation
Active Interrupt pin	EIMSK(INT0)	b1	Enable INT0
Interrupt trigger edge	EICRA(ISC10:00)	b011	Rising edge triggered

4.3 DAC

The **LTC2565** is an Octal 12-bit rail-to-rail DAC. The DAC block diagram is shown in Figure I.4 (Appendix I). Key features include:

- 8 individually configurable DAC units
- Synchronous or asynchronous update on each DAC
- Precision 10ppm/°C Max Deviation from Reference Voltage
- Selectable Internal or External Reference
- Power-On-Reset to Zero-Scale (0V)/Mid-scale (half of reference voltage)

In the internal feedback loop, one DAC output channel is set to the comparator reference input. The other four output channels are used to set the four phase shifter's control voltages, which are further described in Section 5.1. The DAC has a resolution defined in Equation 4.3

$$DAC_{resl} = \frac{2 * V_{ref}}{2^{bits}} = \frac{2 * 2.5}{2^{12}} = 1.2mV/quanta \quad (4.3)$$

The comparator has an internal error of 6mV, or 5 quanta. The RF Power Detector's output slope is 37.3 mV/dBm, thus the DAC resolution with respect to power is provided by Equation 4.4:

$$\frac{37.3mV}{1dB} \times \frac{1quanta}{1.2mV} \approx 31quanta/dB \quad (4.4)$$

The DAC uses an SPI bus to communicate with the microcontroller. The LTC2656

can operate with clock speeds up to 50MHz; however, the DAC operates at a clock speed of 4MHz. The maximum clock frequency for the SPI is one quarter the microcontroller's clock frequency, $\frac{f_{osc}}{4}$. The microcontroller's operating frequency is 16MHz.

The load sequence timing diagram is shown in Figure 4.2. The data word is 16-bits in length since the DAC is available in both 12 and 16 bits. The system only uses a 12 bit DAC: thus, the four Least Significant Bits (LSB) are not used.

Figure 4.2: LTC2656 DAC Load Sequence

The DAC has a 24-bit input word, but the ATmega2560 is an 8-bit microcontroller (Figure 4.2). Each time a load sequence is sent to the DAC, the SPI Data Register (SPDR) is loaded sequentially three times. Tables 4.4 and 4.5 show the DAC command and address codes, respectively. For DAC and ADC API, refer to files: *SPI_API.h*, *SPI_API.c* and *DAC_SPI.h* in Appendix E.

Table 4.4: DAC Command Codes

Command				Operation
C3	C2	C1	C0	
0	0	0	0	Write to Input Register n
0	0	0	1	Update (Power Up) DAC Register n
0	0	1	0	Write to Input Register n, Update (Power Up) All
0	0	1	1	Write to and Update (Power Up) n
0	1	0	0	Power Down n
0	1	0	1	Power Down Chip (All DACs and Reference)
0	1	1	0	Select Internal Reference (Power-Up Reference)
0	1	1	1	Select External Reference (Power-Down Reference)
1	1	1	1	No Operation

Table 4.5: DAC Address Codes

Address 'n'				Operation
A3	A2	A1	A0	
0	0	0	0	DAC A
0	0	0	1	DAC B
0	0	1	0	DAC C
0	0	1	1	DAC D
0	1	0	0	DAC E
0	1	0	1	DAC F
0	1	1	0	DAC G
0	1	1	1	DAC H
1	1	1	1	All DAC's

4.4 Comparator

A high-precision comparator enables voltage comparison between two signals with difference in mV range; the voltages used in the system are $\approx 20\text{mV}$ apart. The **LM339** is a *Low Power Low Offset Voltage Quad Comparator*. Key features include:

- Supply voltage 2 to 36 V_{DC}
- Low input biasing current: 25nA
- Low supply current drain (0.8mA) independent of supply voltage
- Output voltage compatible with TTL, DTL, ECL, MOS and CMOS logic systems
- Response time of $1.3\mu\text{s}$

The simplified schematic of a single LM339 comparator is shown in Figure 4.3. The open collector comparator output requires a pull-up resistor to the 5V rail; a $3.3k\Omega$ resistor is used.

Figure 4.3: LM339 Schematic Diagram

A $0.1\mu\text{F}$ capacitor is used at the comparator output to remove high frequency glitching caused when inputs are within 20mV of each other. Although a capacitor delays the comparator output rise time, it is required to avoid output glitching. The comparator output triggers the microcontroller interrupt. A context switch is the process of storing and restoring the state (context) of a process so that execution can be resumed from the same point at a later time. If an interrupt triggers multiple times within a single context switch, the microcontroller keeps track of the trigger counts, and causes the microcontroller to go in multiple nested context switches. These multiple context switching cause the system to become unstable. The system unsuitability is due to the unknown and unstable state of the system variables. If the microcontroller enters an unstable state, a power cycle is executed.

CHAPTER 5

RF SYSTEM INTEGRATION

This chapter describes the microcontroller control lines for the RF system. A 16-pin IDC interfaces the RF board to the digital board. The connector pinout (Table 2.1) and control lines are described in the following subsections.

5.1 Phase Shifters

Phase shifters control the four-patch inter-element phase shift to steer the radiation beam. The **JSPHS-2484+** (MiniCircuits) is a 50Ω matched, 0° to 180° voltage-controlled phase shifter operating in the frequency range 2150MHz to 2484MHz. The datasheet provides voltage-to-phase data at 2150MHz, 2300MHz and 2484MHz. Linear interpolation between 2300MHz and 2484MHz yields voltage-to-phase data at 2400MHz as shown in Figure 5.1.

Figure 5.1: JSPHS-2484+ Phase Shifter, Interpolated Data

Individual phase shifters control the relative signal phase with respect to each path. The DAC was initially intended to set control voltages for the phase shifters directly. This requires DAC analog output voltages from 0V to 15V. DACs with 15V output capability are limited, thus a 5V rail DAC was chosen. The LTC2656 DAC was selected to set phase shifter control voltages. An op-amp is required to increase the DAC output voltage range from 0 – 5V to 0 – 15V; thus a gain of +3 is required. Figure 5.2 shows an op-amp in a non-inverting gain configuration. Equation 5.1 shows the input and output voltage relationship.

Figure 5.2: Operational Amplifier in Non-Inverting Configuration

$$V_{out} = V_{in} \left(1 + \frac{R_f}{R_g} \right) \quad (5.1)$$

For improved system performance a stable rail-to-rail op-amp was used. Each of the phase shifters require a voltage control line and an op-amp. To reduce component count, a quad pack op-amp (**LT6005**) was selected. Key Features of the LT6005 include:

- Wide supply range 1.6V to 16.0V
- Low supply current, 1 μ A
- Low input bias current, 90pA

Figure 5.3: LTSpice Simulation Schematic, LT6005 Non-Inverting Gain Op-Amp Circuit

Figure 5.3 shows an LT6005 op-amp LTSpice simulation. The simulation in Figure 5.3 assumes ideal resistors and capacitors. To model a practical circuit, a Monte Carlo Analysis was completed using variable resistor and capacitors values. Variations in resistor values cause control voltage deviations and phase offset errors, which will affect the beam direction.

Analyses with resistor tolerances ranging from 5% to 0.01% were completed. The 0.01% tolerance had the best performance; the most cost effective option utilizes 0.5% tolerance resistors. The Monte Carlo analysis schematic and results are displayed in Figure 5.4. The response is expanded to highlight the area of maximum error, which occurs when input voltages are close to the 5.0V rail. Figure 5.5 shows results from 4.95V to 5.00V. The measured output saturation voltage for the op-amp is 14.97V for a 15.00V rail. The extreme cases are:

- $V_{out} = 14.97\text{V}$ at $V_{in} = 4.95\text{V}$
- $V_{in} = 5.00\text{V}$ outputs $V_{out} = 14.92\text{V}$

This Monte Carlo Analysis was iterated 50 times, which constitutes 85% of the Gaussian distribution at 0.5% tolerance. [10]

(a) Schematic

Figure 5.4: LTSpice Simulation results, LT6005 Op-amp Non-Inverting Gain Circuit

(b) Result

Figure 5.4: LTSpice Simulation results, LT6005 Op-amp Non-Inverting Gain Circuit

Figure 5.5: Monte Carlo Analysis for Amplification Circuit, Expanded View

5.2 RF Single Pole Double Throw (SPDT) Switch

SPDT switches determine the Antenna and RF system modes: transmit or receive. Two control lines control the SPDT switch position. The **AS179-92LF** is a 20MHz to 3.0GHz GaAs SPDT switch. The AS179-92LF's pinout and block diagram is shown are Figure 5.6.

Figure 5.6: AS179-92LF, SPDT, Pin-out and Block Diagram

Table 5.1 shows the SPDT truth table. As defined in Figure 5.6b, V1 and V2 are control lines while J1, J2, and J3 are RF lines. J1 is the common line while J2 and J3 are selectable. Table 5.2 shows the system truth table for the receive (RX) and transmit (TX) modes. For the transmit (TX) mode, J1 is connected to J3; for receive (RX) mode, J1 is connected to J2.

Table 5.1: Truth Table for SPDT, $V_{HIGH} = 2V$ to $5V$, $V_{LOW} = 0V$ Insertion Loss = 0.5dB, and Isolation = 22dB

V1	V2	J1 to J2 connection	J1 to J3 connection
V_{HIGH}	0	Isolation	Insertion Loss
0	V_{HIGH}	Insertion Loss	Isolation

Table 5.2: SPDT, Antenna Mode Truth Table

SPDT1(V1)	SPDT0(V2)	Mode
1	0	TX
0	1	RX

5.3 RF Single Pole Triple Throw (SP3T) Switch

The SP3T switches determine the tetrahedral structure's active face. The **HMC245QS16** is a SP3T RF switch is a GaAs-based monolithic microwave integrated circuit (MMIC) operating in the frequency range DC to 3.5 GHz. The SP3T switch's pinout and functional diagram is shown in Figure 5.7.

Figure 5.7: HMC245QS16 SP3T RF Switch Pin-out and Functional Diagram

Table 5.3 shows a truth table for the HMC245QS16 SP3T RF switch. Control lines A and B are compatible with both TTL (Transistor-Transistor Logic) and CMOS (Complementary Metal-Oxide Semiconductor) logic levels. Voltage ranges are defined as 0 to 0.8V for *LOW* and 2.0V to 5.0V for *HIGH*. The MMIC exhibits an insertion loss of 0.6dB and isolation of 35dB between RF ports at 2.4GHz.

Table 5.3: Truth Table for HMC245QS16 and the Active Antenna Face

Control Input		Signal Path State	
A	B	RF COM to:	Active Face
Low	Low	RF1	1
High	Low	RF2	2
Low	High	RF3	3
High	High	All Off	All Off

5.4 Voltage Control Oscillator (VCO) Control Line

The **JTOS-2700V** is a linearly tunable voltage controlled oscillator (VCO) for the frequency range 2050 to 2700 MHz. VCO Frequency Tuning and output power data are shown in Figure 5.8.

(a) Frequency Tuning

(b) Output Power

Figure 5.8: JTOS-2700V, VCO, datasheet characteristic

Figure 5.8a shows that a control voltage of 9.18V is required to produce a 2.4GHz signal, the RF system's operating frequency. The antenna resonance frequency has an engineering tolerance of 5% at 2.4GHz [1], which requires a tunable VCO control line. Figure 5.9 shows the VCO tuning circuit with output voltages from 7.5V to 10V. Table 5.4 shows output voltages when the tunable potentiometer is in the range 1Ω to $5k\Omega$. A 14-turn tunable $5k\Omega$ potentiometer

ter provides fine adjustment for the VCO output frequency. High tolerance 1% resistors are used for $R1$ through $R4$.

Figure 5.9: VCO tuning Schematic, R5 is the tunable resistor

Table 5.4: VCO Tuning Circuit Result

Potentiometer resistance (Ω)	VCO control voltage (V)
1	7.50
1k	8.18
2k	8.75
3k	9.23
4k	9.64
5k	10

CHAPTER 6

PRINTED CIRCUIT BOARD DESIGN

CadSoft EAGLE PCB Design Software was used to design the printed circuit board (PCB) schematic and layout. PCB schematic and layout can be found in Appendices F and G, respectively.

6.1 Schematic

The schematic was created to add the maximum testability in the PCB. The following are some of the key testability features added to the PCB design:

- Zero ohm resistors to isolate power supplies and ICs
- Zero ohm resistors to isolate outputs and inputs for testability
- DIP switch and header pins to set SPDT and SP3T control signal manually and LEDs to show the status
- Test points at most microcontroller input/outputs (I/Os)
- LED Display Driver(LM3914) to show the received power RF power detector.
- LEDs to check the power statuses
- On board ISP programmer pinout

The ICs used required 5V and 15V power rails. To avoid the need for two power supplies, a 20V AC to DC wall transformer was used with power regulators. A barrel connector was used to connect the 20V power supply to the board. ON Semi's NCP1117ST50T3G was used to achieve 5V rail and Texas Instrument part LM3480 was used to achieve 15V rail. Linear Technology LT1761 was used to set the 2.5V DAC reference voltage.

6.2 Layout

A two-layer PCB was chosen for the layout. A full copper pour on the top and bottom layers was used as the ground. The advantage of large group plane is its low inductance and resistance. Routing the signals and power lines in the group pour helps maintain a good signal value by creating capacitance between the signal or power and the ground signal. A section of copper pour was cut out from the full copper pour to act as analog ground. The full ground plane and analog ground plane were connected via 22nH inductor, which prevents the high frequency switching ground plane currents from affecting the analog voltages. The analog plane was used under the DAC and the Amplifier. The layout was designed so that traces would have a minimal number of vias.

Figure 6.1: PCB layout

Figure 6.1 shows the layout of the subsequent PCB. All the main components are marked in the Figure with accompanying text. All connectors were placed so that they are as close to their mates as possible.

CHAPTER 7

GRAPHICAL USER INTERFACE (GUI) CONTROL SYSTEM

The MATLAB GUI is designed to test system functionality. The GUI configures all system variables for beam steering and can be set to transmit or receive mode. MATLAB uses *RS-232*, a serial protocol, to communicate between the computer and control board. A 9-pin D-subminiature (D-sub) connector is used for RS-232 communication; the pinout is shown in Figure 7.1.

Figure 7.1: RS-232, 9-pin D-sub connector pinout

MATLAB has a built-in serial communication library. Data is sent from the MATLAB GUI to the microcontroller via a one-way data link. The microcontroller interprets the RS-232 data and sets the system variables accordingly. The GUI screen is shown in Figure 7.2.

Figure 7.2: MATLAB GUI main screen

7.1 GUI Inputs and Features

MATLAB GUI has four user interface fields.

1. Drop down menus: Face, Mode and COM
2. Edit Text: Theta and Phi
3. Push Buttons: Reset, Close, Phase Shifter Data, Send and Update
4. Checkbox: Radiation Pattern, Element Pattern, Array Factor and E and H Planes

7.1.1 Drop Down Menus

The three drop down menus are Face, Mode and COM port. The *Face* drop-down menu has three options: 1, 2, or 3. Figure 7.3 shows the GUI screen-shot with

user options. The selection controls the adaptive antenna face. The antenna face is controlled using SP3T switches. The antenna faces 1, 2, and 3 are labeled on the tetrahedral antenna structure.

Figure 7.3: MATLAB GUI screen with Face drop down menu

The *Mode* drop down menu has two options; TX (transmit) or RX (receive), which are controlled by SPDT switches. Figure 7.4 shows the GUI screen-shot with the *Mode* drop down menu open.

Figure 7.4: MATLAB GUI Screen with Mode Drop-Down Menu

RS-232 uses the COM port set by the *COM* drop down menu. A TRENDnet TU-S9 (Figure 7.5) USB to RS-232 converter cable connects the PC to the Control Board. On Microsoft Windows, the Device Manager shows the COM port that the converter cable is connected to on the computer. As shown by the red highlighted box in Figure 7.6.

Figure 7.5: TRENDnet TU-S9, USB to RS-232 Converter Cable

Figure 7.6: Device Manager screen shot with COM port highlighted

Once the COM port is known, the COM drop-down menu sets the COM port value. The blue highlighted box in Figure 7.7 shows the default range of COM port values, while the red highlighted box shows the serial connection details. The BAUD rate (pulses per second) of 57600, eight data bits, and one stop bit is used.

Figure 7.7: MATLAB GUI screen with COM drop down menu

7.1.2 Edit Text

Theta (θ) and *Phi* (ϕ) are two editable text fields. Figure 7.8 shows theta and phi in the spherical coordinate system. The limits on θ are 0° to 90° or 0 to $\frac{\pi}{2}$ radians because it is impractical to direct radiation below the antenna plane. The limits on ϕ are 0 to 360° or 0 to 2π radians.

Figure 7.8: Antenna Radiation Pattern Coordinate system

θ and ϕ set the antenna beam direction, or its radiation pattern's main lobe. The calculated control angles and phase shifter voltages from the θ and ϕ fields are shown in the green highlighted box in Figure 7.9. The antenna radiation pattern is displayed in the GUI right panel, highlighted with a red box. The blue highlighted box shows the achievable main beam direction in θ and ϕ coordinates. The offset between theoretical and achievable is due to phase shifter limitations [1].

Figure 7.9: MATLAB GUI Screen Shot, θ and ϕ Control Variables

7.1.3 Push Buttons

There are five GUI push buttons: Reset, Close, Phase Shifter Data, Send, and Update. The *Reset* button returns the GUI to its default state. The *Close* button closes the MATLAB GUI, but maintains all open figures defined in Section 7.1.4. The *Phase Shifter Data* button shows the Phase Shifter JSPHS-2484+ characteristic data interpolated from the associated datasheet, which is shown in Figure 7.10.

Figure 7.10: Phase Shifter JSPHS-2484+ Interpolated Data

The *Update* button initiates phase shifter control voltage and angle value calculations from theta and phi values. The *Update* button also refreshes the *Value* and *Radiation Pattern* panel, and creates the plots selected from the *Additional Figures* panel. In addition to *Update* button's function, the *Send* Button also transmits the data packet to the microcontroller. Transmit data packet structure is described in Section 7.2.

7.1.4 Additional Figure Checkboxes

The four checkboxes that create additional information plots for antenna radiation pattern are *Radiation Pattern*, *Element Pattern*, *Array Factor* and *E and H Planes*. Figure 7.11 shows all the additional plots for $\theta = 30^\circ$ and $\phi = 45^\circ$. The *E and H planes* checkbox creates an addition plot for all previously selected options in the *Additional Figures* panel.

Figure 7.11: Checkbox Selected Images, with $\theta = 30^\circ$ and $\phi = 45^\circ$

7.2 Communication Protocol

Figure 7.12 shows a single RS-232 physical frame. The protocol consists of a start bit, eight data bits, and one stop bit. The start bit is usually HIGH. Data bits are in order of least significant bit (LSB) to most significant bit (MSB). The stop bit is usually LOW.

Figure 7.12: RS-232 Frame

The protocol data packet for communication between the microcontroller and MATLAB GUI include mode value, face value and four phase shifter control voltages. Figure 7.13 shows the timing diagram for a data packet. RS-232 data bits are transmitted as an 8-bit American Standard Code for Information Interchange (ASCII) character. Therefore, conversion is performed from decimal ASCII characters to 8-bit integer values, conversion chart is shown in Table 7.1.

Figure 7.13: Communication Packet Frame

Table 7.1: Hexadecimal Notation for ASCII Decimal Characters to 8-bit Integers

Data in Hexadecimal	ASCII Character	8-bit integer value
0x30	0	0x00
0x31	1	0x01
0x32	2	0x02
0x33	3	0x03
0x34	4	0x04
0x35	5	0x05
0x36	6	0x06
0x37	7	0x07
0x38	8	0x08
0x39	9	0x09

The flowchart in Figure 7.14 shows microcontroller received data packet processing methods. The C code implementing the algorithm is provided in Appendix E.

Figure 7.14: Microcontroller, MATLAB GUI Mode Flowchart

7.3 Test and Results

The board was initially tested with the RF system disconnected. Status LEDs were checked for SPDT and SP3T control lines. Set line or logic high is indicated by an illuminated LED; clear line or logic low is shown by a dark LED. The highlighted box in Figure 7.15 shows status LED locations. The phase shifter control voltages were measured using a digital multimeter. Table 7.2 shows the

measured control voltages for three test cases:

1. $\theta = -30^\circ$ $\phi = 0^\circ$
2. $\theta = 0^\circ$ $\phi = 0^\circ$
3. $\theta = 15^\circ$ $\phi = 0^\circ$

Radiation patterns were collected for antenna Face-3 in transmit mode. The radiation pattern plots are shown in Figure 7.16. The offset angle in all the radiation patterns is explained in [1].

Table 7.2: GUI Test Result

Theta	Phi	Expected Phase Shifter Control Voltage(V)	Measured Phase Shifter Control Voltage (V)	Percent Error
-30	0	7.98	7.96	-0.25%
		7.98	7.94	-0.50%
		0	0.01	NA
		0	0.01	NA
0	0	0	0.01	NA
		0	0.01	NA
		0	0.01	NA
		0	0.01	NA
15	0	0	0.01	NA
		0	0.01	NA
		5.64	5.62	-0.35%
		5.64	5.61	-0.53%

Figure 7.15: Status LED's for Mode and Face value

(a) Radiation Pattern, $\theta = -30^\circ$ $\phi = 0^\circ$

(b) Radiation Pattern, $\theta = 0^\circ$ $\phi = 0^\circ$

Figure 7.16: GUI Test Measured Radiation Patterns

(c) Radiation Pattern, $\theta = 15^\circ$ $\phi = 0^\circ$

Figure 7.16: GUI Test Measured Radiation Patterns

CHAPTER 8

ADAPTIVE RECEIVE MODE

In receive mode, an adaptive antenna performs a scan to determine the maximum receive power direction. This mode is used to maintain a lock on a receiving signal from a transmitting antenna.

8.1 Adaptive Receive Algorithm

For the search algorithm, a 58-point scan on each antenna face is performed. Figure 8.1 shows the location of the points used in the adaptive receive scan. The points are scanned using a raster scan technique, which is a line-by-line rectangular sweep as shown in Figure 8.2. Power is received for each scan point. If the received power at the current point is greater than the power received at any previous point, the new maximum is stored. This continues until the scanning is complete. Following scan completion, the beam is reset to the maximum power direction. The scan direction is maintained until the receive power level decreases below -50dBm. This level is chosen because the RF system has a noise floor of -60dBm.

Figure 8.1: Adaptive Receive scan plot

Figure 8.2: Raster Scan Pattern

The flowchart in Figure 8.3 shows the scan algorithm in the adaptive receive mode. Upon scan completion, if the *lock flag* is set, the maximum beam direction is initialized. If the flag was not set in the previous scan, the scan repeats itself. The *lock flag* is initially set when the receive power is greater than -50dBm, or subsequently if the received power is greater than the previously received maximum power. The interrupt service routine (ISR) flowchart for the microcontroller is shown in Figure 8.4. Figure 8.4 shows the flowchart for the interrupt service routine (ISR), which is triggered when the comparator output changes to logic high.

Figure 8.3: Adaptive Receive Flowchart

Figure 8.4: ISR Flowchart

8.2 Testing

The system was tested without the RF board and antenna connected to the digital control board. A Wiltron (Model 68147A) RF source was used to simulate the received power. A delay of 100ms was set between scan points to facilitate observation of the working algorithm. Table 8.1 shows adaptive receive mode test procedure data. The following test procedure was performed:

1. Apply -60dBm power to the receive port
2. Change the power to -30dBm at a single scan point and then back to

$-60dBm$, to set the trigger

3. Observe when *Lock LED* status turns on
4. Revert back to $-30dBm$ power
5. Reduce the power from $-30dBm$ in $2dB$ steps and observe lock LED turn off once $-50dBm$ is reached

Table 8.1: Test Data for Adaptive Receive Mode Test Procedure

Receive Power (dBm)	Lock LED status
-30	ON
-32	ON
-34	ON
-36	ON
-38	ON
-40	ON
-42	ON
-44	ON
-46	ON
-48	ON
-50	OFF
-52	OFF
-54	OFF
-56	OFF
-58	OFF
-60	OFF

The data in Table 8.1 proves that system operates in the specification, maintaining lock for power level greater than -50dBm. The complete system test was not performed due to RF PCB manufacturing problems [1].

CHAPTER 9

CONCLUSIONS AND FUTURE WORK

The system shows a successful implementation of the digital control board for beam steering and adaptive communications. The digital control board controls the antenna face and mode as described in [1]. Each sub-block of the digital controlled board was tested in order to verify that specifications were met. The MATLAB graphical user interface successfully controlled the digital control board. An adaptive communication system was implemented to demonstrate a working example. The system autonomously locked to the maximum receive power using the 58-point scan, for the power levels above -50dBm.

The RF power detector used a logarithmic amplifier-based design, which provides a linear relation between input power and output voltage. The RF power detector has a slope of $37.3mV/dB$ with a minimum detectable power of $-60dBm$ and maximum detectable power of $0dBm$.

An ATmega2560 is used as the microcontroller for the system. The built-in ADC was used to measure the receive power. The microcontroller is also used to communicate with MATLAB, which allows it to set the output voltages for the phase shifters as well as the control signals that set the antenna face and the mode. The microcontroller can be configured in MATLAB GUI mode or the adaptive receive mode.

The system successfully controls the SP3T and SPDT switches, which control

active antenna face and mode selection, respectively. The system also successfully sends control voltages to the phase shifter within 0.53% of expected values. The control board demonstrates a working bench test for an adaptive receive station.

The PCB design shows improved performance with a separate analog and digital plane and reduces the noise on the analog signal. The digital control board was designed for in system test and debugging. The digital control board has features for future expandability.

Future work:

- Re-test the digital control board with a fully operational RF board
- Develop a half duplex adaptive receive and transmit communication system
- Digital communication (16-QAM, APSK, LTE, etc.) implementation on the control board

BIBLIOGRAPHY

- [1] S. Brockhoff, “Electronically-Steered Tetrahedral-Structured Phased Array 2.4 GHz Transceiver Design Applied to Adaptive Communications,” Master’s thesis, California Polytechnic State University, 2013.
- [2] Louis E. Frenzel, “Design FAQ: RF Detector for Wireless Devices.” *http : //www.analog.com/static/imported_files/faqs/201551981DetectorFAQ.pdf*.
- [3] “Integrated DC Logarithmic Amplifiers,” *Dallas Semiconductor, Maxim Engineering Journal*, vol. 56, 2005.
- [4] “LT5534 - 50MHz to 3GHz RF Power Detector with 60dB Dynamic Range.” *http : //www.linear.com/product/LT5534*.
- [5] “LT5538 - 40MHz to 3.8GHz RF Power Detector with 75dB Dynamic Range.” *http://www.linear.com/product/LT5538*.
- [6] “LT5534 Datasheet.” *http : //cds.linear.com/docs/en/datasheet/5534fc.pdf*.
- [7] “LT5534 Demo Board.” *http : //www.linear.com/demo?demo_board = part_number = 5534category_id = 0companion_board = software_id =*.
- [8] “LT5538 Datasheet.” *http : //cds.linear.com/docs/en/datasheet/5538f.pdf*.
- [9] “LT5538 Demo Board.” *http : //www.linear.com/demo?demo_board = part_number = 5538category_id = 0companion_board = software_id =*.

- [10] Morris R. Driels and Young S. Shin, “DETERMINING THE NUMBER OF ITERATIONS FOR MONTE CARLO SIMULATIONS OF WEAPON EFFECTIVENESS,” Tech. Rep. NPS-MAE-04-005, Naval Postgraduate School, MONTEREY, CALIFORNIA, April 2004.

APPENDICES

A 2013 IEEE APS Student Design Challenge: Reconfigurable Antennas

2013 IEEE AP-S Student Design Challenge: Reconfigurable Antennas

Travel to the 2013 IEEE Antennas and Propagation Symposium
Win \$1500, \$750, \$250

Join the 4th IEEE AP-S Antenna Design Challenge! Build an antenna system with reconfigurable antenna elements that can adapt to different propagation conditions (e.g. line-of-sight versus non-line-of-sight). The top three teams will receive up to \$2,500 (US dollars) in travel funds to attend the IEEE Antennas and Propagation Symposium in Orlando, FL, USA, July 7-13, 2013 to demonstrate their working systems. From these top teams, first, second, and third place winners will be announced at the 2013 IEEE AP-S Awards Banquet and will receive cash awards of \$1500, \$750, and \$250, respectively.

Important deadlines are **November 30, 2012** and **April 26, 2013**. See below for details.

Goals and Specifications:

1. Design an antenna system with reconfigurable antenna elements that can adapt to different propagation conditions in order to achieve the best link performance. The performance can be shown in terms of received power or higher level system metric such as symbol error rate.
2. The antenna system should be used to teach how antennas work. Such a system might be used in college undergraduate or graduate courses, and in pre-college ('High School') physics courses.
3. The system must be safe and durable, easily reproducible by others, inexpensive, and portable so that it can be demonstrated at the Symposium.
4. The system must operate at 2.4 GHz, have its own source (i.e. no commercial signal generator can be used), and fit on a table top (roughly 24"x 40") or two closely spaced tables. Readily available software (e.g., student versions of C, Matlab, Visual Basic, LabView) or free software packages may be used. All software must be included in the budget.
5. The total cost for reproduction of the system must be **less than \$1,500**. The use of a laptop computer is allowed and does not have to be included in the \$1,500 limit.

Eligibility:

The team should consist of 2 to 5 persons, with a majority of undergraduate students. Each team should be advised by a professional mentor who is a member of the AP Society. No student or mentor should be involved in more than one team.

The Application and Review Process:

1. All applicants must submit a preliminary design by **November 16, 2012**. It must include:
  - a. A proposal limited to two pages and in 12-pt Times New Roman font that includes
  - i. A detailed description of the system to be built.

- ii. The steps that will be taken to ensure the accuracy of the system.
  - iii. A bill of materials (up to \$1,500).
  - b. A letter from a professional mentor such as a professor or engineer in industry indicating agreement to supervise the project. The mentor must be an IEEE AP-S member and must verify that all members of the team are graduate and/or undergraduate students at a university, college, or technical school. The proposal and letter must be integrated into a single pdf file named TeamName.pdf. The proposal should precede the letter.
2. The Design Contest Committee will assess each preliminary design based on creativity, likelihood of achieving the design goals, educational value, and quality of written materials. Six semi-finalist teams will be selected by **November 30, 2012** and will receive \$1,500 each to build and test their designs.
  3. Each of the six semi-finalist teams must submit its final design by **April 26, 2013**. It must be accompanied by a video demonstration of its working system, and a final report in pdf format using the template available at the AP-S web-site. Submission instructions for the video demonstration will be provided later. The report must be limited to 10 pages and include:
    - a. A detailed description of the system (including schematic and other diagrams).
    - b. A list of parts and materials required, including where to obtain them and costs.
    - c. Photos of the final system (including a scale to show how large it is).
    - d. Assembly and operating instructions for the system.
    - e. A set of measurements obtained using the system with an example test antenna.
    - f. Biographies (100 words or less each) and photos of all design team members.
    - g. All software necessary to build and/or operate the system in a separate file(s).
  4. The Design Contest Committee will assess each semi-finalist's design based on creativity, completeness of the description, functionality of the system as determined by the video, educational value, and quality of written materials. Three finalist teams will be selected by **May 10, 2013** and will receive stipends of up to \$2,500 per team to travel to and attend the IEEE AP-S Symposium. The stipend is intended to cover equipment shipping costs and all of the expenses for one team representative; however, it may be divided among multiple team members.
  5. The finalists will be expected to demonstrate their working systems during the Symposium and attend the Awards Ceremony at the banquet. Power supplies will be made available at the Symposium. Each team is responsible for bringing all other necessary equipment for a successful demonstration.
  6. The Design Contest Committee will judge the final demonstrations and select the first, second, and third prize winners to receive \$1,500, \$750 and \$250, respectively. The prize winners will be announced at the AP Awards Banquet.
  7. After the Symposium, the finalists will be required to revise the final report for publication in the IEEE AP Magazine under the Education Column.

How to Submit Materials:

Send all materials to designcontest@ieeeaps.org with the subject line "2013 IEEE AP-S Design Contest Submission." Questions may be sent to the same address. All submitted materials must be in pdf format according to the guidelines above.

B Contest Proposal

IEEE Antenna Design Contest
By: Steve Brockhoff, Mayur Bansal

Objective

We plan to build an electrically reconfigurable antenna system to demonstrate line-of-sight and non-line-of-sight transmission. The physical structures of both transmit and receive antenna systems will be a triangular-based pyramidal structure. Each face of the structure has three probe-fed triangular microstrip patch antennas. See Figure 1 for the general structure.

Figure 1: Triangular-based pyramidal structure.

This structure has two levels of precision. The face and patch antenna arrangement creates a three dimensional phased array in which array elements are phase-controlled to direct a beam to three-dimensional sectors. Two elements on one face could be activated and one on another to optimize beam-steering to maximize signal reception.

Transmit and receive antenna systems are completely isolated and are identical, both capable of transmitting and receiving. Two-way communication enables transmission beam directing to maximize receive antenna reception.

Preliminary Design

The 2.4 GHz signal is generated using an Analog Devices integrated synthesizer (CC2500). Three 2.4GHz amplifiers amplify signals for transmission and after reception. Three 2.4 GHz bandpass filters suppress out-of-band power by at least 10dB. Each bandpass filter will be a cascaded combination of Chebyshev low-pass and high-pass filters with cutoff frequencies of 2.35GHz and 2.45GHz, respectively. Amplifier placement before the filters minimizes noise-figure.

The signal is applied to a distribution network, which includes four phase-shifters controlled by an Arduino microcontroller, see Fig. 2. The Arduino controls the antenna and active face by controlling RF switches in order coarsely scan for the optimal transmit direction. Multiple faces can be active at one time. The design utilizes three phase-shifters to control three patch antennas on three

Figure 2: System Block Diagram

different structure faces. Three of the nine patch antennas will be active at any one time.

To maximize received signal strength, the microcontroller selects combinations of faces and active patches to direct the transmit signal. Concurrently, the receive antenna scans in a similar fashion in a two-step process. First, all phase-shifters are set to zero and the signal is applied to different three-element combinations of the TX patch antennas. The system then waits for an acknowledgement (ACK) signal from the RX antenna. The TX system measures the ACK signal power and saves it in the Arduino memory and associates the recorded power level with the specific three-element combination. Second, the Arduino recalls each three-element combination, then controls the phase-shifters to change the beam direction to finely scan for the optimal transmit direction. The TX antenna waits for an ACK signal, as before, but will now store the phase-shift values in memory as well, in order to recall the coarse and fine directions for optimal transmission.

The first scan determines the general direction to establish a link (both the TX and RX directions) Then, the phase-shifters are adjusted to finely scan in each direction that received an ACK message, starting with the strongest sector direction. After all antenna combinations and fine scanning is completed, the three-element array and phase-shift values that correspond to the maximum signal strength is chosen as the optimum transmission direction.

Figure 3: Algorithm Flow Chart

Component	Part	Unit Price	Qty	Cost	Notes
Antenna	PCB	\$ 45.00	6	\$ 270.00	PCBExpress
	SMA Connector	\$ 2.50	9	\$ 22.50	DigiKey
Motherboard	PCB	\$ 75.00	2	\$ 150.00	PCBExpress
	Microcontroller	\$ 30.00	2	\$ 60.00	Arduino
	Crystal	\$ 0.35	2	\$ 0.70	Analog Device
	Transreciever	\$ 4.76	2	\$ 9.52	Texas Instruments
	Power detector	\$ 19.42	2	\$ 38.84	Analog Device
	RF Amp	\$ 1.50	20	\$ 30.00	Analog Device
	Active Phase Shifter	\$ 5.35	8	\$ 42.80	Mini Circuits
	RF Switch (SP3T)	\$ 8.36	42	\$ 351.12	HMC245QS16
	RF Switch (SP2T)	\$ 0.52	18	\$ 9.36	AS179
	R,L,C,D			\$ 50.00	DigiKey
	LCD 16X2 character	\$ 13.95	2	\$ 27.90	Sparkfun
	SMA Connector	\$ 2.00	18	\$ 36.00	DigiKey
Accessories	SMA male to male cable	\$ 12.96	18	\$ 233.28	DigiKey
	MATLAB Student Version	\$ 100.00	1	\$ 100.00	
Total				\$ 1,432.02	

C LT 5534 Demo Board Schematic

CUSTOMER NOTICE

LINEAR TECHNOLOGY HAS MADE A BEST EFFORT TO DESIGN A CIRCUIT THAT MEETS CUSTOMER-SUPPLIED SPECIFICATIONS; HOWEVER, IT REMAINS THE CUSTOMER'S RESPONSIBILITY TO VERIFY PROPER AND RELIABLE OPERATION IN THE ACTUAL APPLICATION. COMPONENT SUBSTITUTION AND PRINTED CIRCUIT BOARD LAYOUT MAY SIGNIFICANTLY AFFECT CIRCUIT PERFORMANCE OR RELIABILITY. CONTACT LINEAR TECHNOLOGY APPLICATIONS ENGINEERING FOR ASSISTANCE.

THIS CIRCUIT IS PROPRIETARY TO LINEAR TECHNOLOGY AND SUPPLIED FOR USE WITH LINEAR TECHNOLOGY PARTS.

CONTRACT NO.

APPROVALS		DATE
DRAWN	June Wu	12/17/03
CHECKED		
APPROVED		
ENGINEER	V. Dvorkin	12/17/03
DESIGNER		

Thursday, December 18, 2003

1630 McCarthy Blvd.
Milpitas, CA 95035
Phone: (408)432-1900
Fax: (408)434-0507

TITLE

LT5534ESC6, RF Power Detector w/60dB Range

SIZE	CAGE CODE	DWG NO	REV
		DC748A	A
SCALE:		FILENAME:	SHEET 1 OF 1

D LT 5538 Demo Board Schematic

CUSTOMER NOTICE

LINEAR TECHNOLOGY HAS MADE A BEST EFFORT TO DESIGN A CIRCUIT THAT MEETS CUSTOMER-SUPPLIED SPECIFICATIONS; HOWEVER, IT REMAINS THE CUSTOMER'S RESPONSIBILITY TO VERIFY PROPER AND RELIABLE OPERATION IN THE ACTUAL APPLICATION. COMPONENT SUBSTITUTION AND PRINTED CIRCUIT BOARD LAYOUT MAY SIGNIFICANTLY AFFECT CIRCUIT PERFORMANCE OR RELIABILITY. CONTACT LINEAR TECHNOLOGY APPLICATIONS ENGINEERING FOR ASSISTANCE.

THIS CIRCUIT IS PROPRIETARY TO LINEAR TECHNOLOGY AND SUPPLIED FOR USE WITH LINEAR TECHNOLOGY PARTS.

CONTRACT NO.

APPROVALS		DATE
DRAWN	A. Karpova	6/12/06
CHECKED		
APPROVED		
ENGINEER	D. Stuetzle	6/12/06
DESIGNER		

Thursday, November 15, 2007

1630 McCarthy Blvd.
Milpitas, CA 95035
Phone: (408) 432-1900
Fax: (408) 434-0507

TITLE
LT5538EDD
50MHz to 3.8GHz DETECTOR

SIZE	CAGE CODE	DWG NO	REV
		DC1120A	3

SCALE:	FILENAME:	SHEET 1 OF 1

E Microcontroller Code

```

/*****
* File      : Thesis_Spring_STK_600.c
*
* Description : brief description of file purpose
*
* Author     : Mayur Bansal (mb)
*
* Revisions  : 1.00 6/27/2013 (mb) First release
*
* "THE BEER-WARE LICENSE" (Revision 42):
* <mbansal@calpoly.edu> wrote this file. As long as you
* retain this notice you can do whatever you want with
* this stuff. If we meet some day, and you think this
* stuff is worth it, you can buy me a beer in return
* Mayur Bansal
*
*****/

/*****#define Declarations*****/

#define F_CPU      16000000UL

#define SET        1
#define CLEAR      0

#define PDOUT      PF0
#define LOCK       PA7
#define SP3TUC0    PC0
#define SP3TUC1    PC1
#define SPDTUC0    PC2
#define SPDTUC1    PC3
#define TESTDIP0   PC6
#define TESTDIP1   PC7
#define CMPOUT     PD0
#define CTRL0      PD6
#define CTRL1      PD7

#define TESTMODEMASK      0xC0
#define TESDTMODEMATLAB   0x00
#define TESTMODEADAPTIVERX 0x40
#define TESTMODEADAPTIVETXRX 0x80

#define MATLABGUI         0
#define ADAPTIVERX        1
#define ADAPTIVETXRX      2
#define ERRORTTESTMODE    3

/*****#include Declarations*****/

#include <avr/io.h>
#include <util/delay.h>
#include <avr/interrupt.h>
#include "ADC_API.h"
#include "SPI_API.h"
#include "interrupt_API.h"
#include "Master_algorithm.h"
#include "USART_API.h"
#include "DAC_API.h"

/*****Global Variable Declarations*****/

volatile uint16_t g_ADC_value = 0x00;
volatile int g_ADC_math = 0x0000;

volatile uint8_t g_collect = 0;
volatile uint8_t g_testmode = 0;
volatile uint8_t g_mode = 0;
volatile uint8_t g_face = 0;
volatile uint8_t g_phase = 0;
volatile uint8_t g_lock = 0;

volatile uint8_t g_facevalue = 0;
volatile uint8_t g_phasevalue = 0;

```

```

volatile uint8_t g_modevalue = 0;

uint16_t g_phs1v = 0;
uint16_t g_phs2v = 0;
uint16_t g_phs3v = 0;
uint16_t g_phs4v = 0;

uint8_t g_phs1_v[] = {0,0,0,0};
uint8_t g_phs2_v[] = {0,0,0,0};
uint8_t g_phs3_v[] = {0,0,0,0};
uint8_t g_phs4_v[] = {0,0,0,0};

volatile uint16_t g_phs1_v_rx[] =
{0xFFFF, 0xFFFF, 0xCBC0, 0xB740, 0xF6C0,
 0x0000, 0x9990, 0xCBC0, 0x2E10, 0x9680,
 0xFFFF, 0xED80, 0xD1E0, 0xA8F0, 0x8830,
 0x51E0, 0x76C0, 0x76C0, 0x72B0, 0x51E0,
 0x0000, 0x0000, 0x0000, 0xA8F0, 0x8830,
 0x6040, 0x0000, 0x0000, 0x0000, 0x0000,
 0x0000, 0x0000, 0x0000, 0x51E0, 0x0000,
 0xB220, 0x9680, 0x70A0, 0x0000, 0x0000,
 0x0000, 0x0000, 0xB740, 0x76C0, 0x0000,
 0x0000, 0x9BA0, 0x9990, 0x76C0, 0x0000,
 0x0000, 0x0000, 0xFFFF, 0x0000, 0x9BA0,
 0xFFFF, 0x0000, 0xFFFF,
};

volatile uint16_t g_phs2_v_rx[] =
{0x9EB0, 0x9470, 0x0000, 0x0000, 0x9990,
 0xE970, 0x0000, 0x5A10, 0x2E10, 0x0000,
 0x9260, 0xB220, 0x9680, 0x70A0, 0x0000,
 0x0000, 0x0000, 0x0000, 0x51E0, 0x0000,
 0x0000, 0x0000, 0x0000, 0xA8F0, 0x8830,
 0x6040, 0x0000, 0x0000, 0x0000, 0x0000,
 0x0000, 0x0000, 0x0000, 0x72B0, 0x51E0,
 0xED80, 0xD1E0, 0xA8F0, 0x8830, 0x70A0,
 0x76C0, 0x76C0, 0xFFFF, 0xD1E0, 0xA8F0,
 0x9680, 0xFFFF, 0xF6C0, 0xED80, 0xC070,
 0xB220, 0x9990, 0x000, 0xCFD0, 0xFFFF,
 0x0000, 0xD4F0, 0x0000
};

volatile uint16_t g_phs3_v_rx[] =
{0x9EB0, 0x0000, 0x5A10, 0xFFFF, 0x9990,
 0x0000, 0xF6C0, 0x0000, 0x2E10, 0xD1E0,
 0x0000, 0x76C0, 0x76C0, 0x70A0, 0x8830,
 0xA8F0, 0xD1E0, 0xED80, 0x51E0, 0x72B0,
 0xD4F0, 0xDA10, 0xE970, 0x0000, 0x0000,
 0x0000, 0x0000, 0x6040, 0x8830, 0xA8F0,
 0xC070, 0xCFD0, 0xD4F0, 0x0000, 0x51E0,
 0x0000, 0x0000, 0x0000, 0x0000, 0x70A0,
 0x9680, 0xB220, 0x0000, 0x0000, 0x0000,
 0x76C0, 0xFFFF, 0x0000, 0x0000, 0x0000,
 0x76C0, 0x9990, 0x9260, 0x0000, 0xFFFF,
 0x9470, 0x0000, 0x0000
};

volatile uint16_t g_phs4_v_rx[] =
{0x0000, 0xFFFF, 0xFFFF, 0x8410, 0x0000,
 0xE970, 0x9990, 0xFFFF, 0x0000, 0x76C0,
 0xFFFF, 0x0000, 0x0000, 0x0000, 0x0000,
 0x70A0, 0x9680, 0xB220, 0x0000, 0x51E0,
 0xD4F0, 0xDA10, 0xE970, 0x0000, 0x0000,
 0x0000, 0x0000, 0x6040, 0x8830, 0xA8F0,
 0xC070, 0xCFD0, 0xD4F0, 0x51E0, 0x72B0,
 0x76C0, 0x76C0, 0x70A0, 0x8830, 0xA8F0,
 0xD1E0, 0xED80, 0x8410, 0x9680, 0xA8F0,
 0xD1E0, 0x0000, 0x9990, 0xB220, 0xC070,
 0xED80, 0xF6C0, 0xFFFF, 0xCFD0, 0x0000,
 0xFFFF, 0xD4F0, 0xA7E0
};

int main(void)
{

```



```

// Set the different I/O's

// set Lock as Output
DDRA |= (1 << LOCK);
// set peak detector output as input to ADC0
DDRA &= ~(1 << PDOUT);
// set the SPDT as outputs
DDRC |= ( 1 << SPDTUC0) | ( 1 << SPDTUC1);
// set the SP3T as outputs
DDRC |= ( 1 << SP3TUC0) | ( 1 << SP3TUC1);
// set the TESTDIP as inputs
DDRC &= ~(1 << TESTDIP0) & ~( 1 << TESTDIP1);
// set Comparator out as input
DDRD &= ~(1 << CMPOUT);
// set CTRL line as GPIO for RF board for future use.
//DDRD |= (1 << CTRL0 ) | (1 << CTRL1);

/* test CODE */

// Initialize all the Peripherals required

// Initialize ADC
initialize_ADC_single_conv();
set_ADC_clock();
enable_ADC();
set_ADC_trigger_source();

// Initialize SPI
SPI_MasterInit();

// Initialize USART
USART_init();

// disable the Semaphore
g_collect = 0;

// Check to see what test mode the uC should be on

// MATLAB GUI mode
if ( (PINC & TESTMODEMASK) == TESDTMODEMATLAB )
{
    SPI_MasterTransmit_DAC(set_pwrDACA,0xff,0xff);

    while(1)
    {
        // receive the mode
        g_mode = USART_rx();
        // receive the face
        g_face = USART_rx();

        // receive the phase 1 value
        g_phs1_v[1] = USART_rx();
        g_phs1_v[2] = USART_rx();
        g_phs1_v[3] = USART_rx();
        g_phs1_v[4] = USART_rx();

        // receive the phase 2 value
        g_phs2_v[1] = USART_rx();
        g_phs2_v[2] = USART_rx();
        g_phs2_v[3] = USART_rx();
        g_phs2_v[4] = USART_rx();

        // receive the phase 3 value
        g_phs3_v[1] = USART_rx();
        g_phs3_v[2] = USART_rx();
        g_phs3_v[3] = USART_rx();
        g_phs3_v[4] = USART_rx();

        // receive the phase 4 value
        g_phs4_v[1] = USART_rx();
        g_phs4_v[2] = USART_rx();
        g_phs4_v[3] = USART_rx();
        g_phs4_v[4] = USART_rx();
    }
}

```

```

// convert the recive characters to number value
g_mode = char_to_num(g_mode);
g_face = char_to_num(g_face);

// convert the recieve character phase value to voltage
value
g_phs1v = convert_data_voltage(g_phs1_v);
g_phs2v = convert_data_voltage(g_phs2_v);
g_phs3v = convert_data_voltage(g_phs3_v);
g_phs4v = convert_data_voltage(g_phs4_v);

g_phs1v = (g_phs1v << 4);
g_phs2v = (g_phs2v << 4);
g_phs3v = (g_phs3v << 4);
g_phs4v = (g_phs4v << 4);

// set the system variables
set_face(g_face);
set_mode(g_mode);
SPI_MasterTransmit_DAC(setDACE,(g_phs1v >> 8),
g_phs1v);
SPI_MasterTransmit_DAC(setDACF,(g_phs2v >> 8),
g_phs2v);
SPI_MasterTransmit_DAC(setDACG,(g_phs3v >> 8),
g_phs3v);
SPI_MasterTransmit_DAC(setDACHpwrALL,(g_phs4v >> 8),
g_phs4v);
}

// Adaptive RX
else if ( (PINC & TESTMODEMASK) ==
TESTMODEADAPTIVERX )
{
    // set the mode to receive
    set_mode(RX);

    // clear the semaphore
    g_collect = CLEAR;

    // set the comparater reference to -50dBm
    SPI_MasterTransmit_DAC(set_pwrDACA,(MINPWRLVL
>> 8), MINPWRLVL);

    // Initialize Interrupts
    enable_interrupts();
    enable_int0_rising_edge();

    while (1)
    {
        // semaphore check
        if(g_collect == CLEAR)
        {
            // clear lock semaphore
            g_lock = CLEAR;
            clr_lock();

            // start the face loop
            for (g_facevalue = 0; g_facevalue <
NUMBEROFFACES; g_facevalue++)
            {
                set_face(g_facevalue+1);

                // start the phase loop
                for (g_phasevalue = 0; g_phasevalue <
NUMBEROFPOINTSRX; g_phasevalue++)
                {
                    SPI_MasterTransmit_DAC(setDACE,(g_phs1_v_rx[g_phasevalue
] >> 8), g_phs1_v_rx[g_phasevalue] );
                }
            }
        }
    }
}

```

```

    SPI_MasterTransmit_DAC(setDACF,(g_phs2_v_rx[g_phasevalue]
>> 8), g_phs2_v_rx[g_phasevalue] );

    SPI_MasterTransmit_DAC(setDACG,(g_phs3_v_rx[g_phasevalue]
] >> 8), g_phs3_v_rx[g_phasevalue] );

    SPI_MasterTransmit_DAC(setDACHpwrALL,(g_phs4_v_rx[g_ph
asevalue] >> 8), g_phs4_v_rx[g_phasevalue] );
        _delay_ms(DELAYTIME*20);
    }
}

if ( g_collect == SET)
{
    // set the lock semaphore
    g_lock = SET;
    set_lock();

    // clear semaphore
    g_collect = CLEAR;

    // set the face and phase count
    g_facevalue = g_face;
    g_phasevalue = g_phase;

    // set the beam direction
    set_face(g_face+1);

    SPI_MasterTransmit_DAC(setDACE,(g_phs1_v_rx[g_phase] >>
8), g_phs1_v_rx[g_phase] );

    SPI_MasterTransmit_DAC(setDACF,(g_phs2_v_rx[g_phase] >>
8), g_phs2_v_rx[g_phase] );

    SPI_MasterTransmit_DAC(setDACG,(g_phs3_v_rx[g_phase] >>
8), g_phs3_v_rx[g_phase] );

    SPI_MasterTransmit_DAC(setDACHpwrALL,(g_phs4_v_rx[g_ph
ase] >> 8), g_phs4_v_rx[g_phase] );

        //delay
        _delay_ms(DELAYTIME*20*5);
    }
}

// Future work
else if ( (PINC & TESTMODEMASK) ==
TESTMODEADAPTIVETXRX )
{
    g_testmode = ERRORTESTMODE;
}

else
{
    g_testmode = ERRORTESTMODE;
}
}

/*-----
* Function: ISR
*
* Description: Interrupt service routine for a external
*              hardware interrupt. This interrupt is
*              triggered on a rising edge. The trigger
*              is output of the comparator.
*
* param vector address : interrupt 0 vector address
*-----*/
ISR (INT0_vect)
{
    // Set the Semaphore

```

```

    g_collect = SET;

    // Save the Important values
    g_face = g_facevalue;    // The face of Antenna used
    g_phase = g_phasevalue;  // The Phase index

    if ( g_lock == CLEAR)
    {
        start_conversion_ADC();
        while(!(ADCSRA & 0x10));
        ADCSRA|=(1<<ADIF);
        g_ADC_value = ADC;
        SPI_MasterTransmit_DAC(set_pwrDACA,(g_ADC_value
>> 8) , g_ADC_value);
    }
    else
    {
        SPI_MasterTransmit_DAC(set_pwrDACA, (MINPWRLVL
>> 8) , MINPWRLVL);
    }
}

```

```

/*****
* File      : ADC_API.h
*
* Description : brief description of file purpose
*
* Author     : Mayur Bansal (mb)
*
* Revisions  : 1.00 6/27/2013 (mb) First release
*
* "THE BEER-WARE LICENSE" (Revision 42):
* <mbansal@calpoly.edu> wrote this file. As long as you
* retain this notice you can do whatever you want with
* this stuff. If we meet some day, and you think this
* stuff is worth it, you can buy me a beer in return
* Mayur Bansal
*
*****/

#ifndef ADC_API_H_
#define ADC_API_H_

/*****Function Prototypes*****/

/*-----
* Function: initialize_ADC_single_conv
*
* Description: Initialize the ADC
*-----*/
void initialize_ADC_single_conv();

/*-----
* Function: enable_ADC
*
* Description: enable the ADC
*-----*/
void enable_ADC();

/*-----
* Function: start_conversion_ADC
*
* Description: start a single conversation of the ADC
*-----*/
void start_conversion_ADC();

/*-----
* Function: set_ADC_clock
*
* Description: set the ADC clock to OSC/4
*-----*/
void set_ADC_clock();

/*-----

```

```

* Function: set_ADC_trigger_source
*
* Description: set the ADC trigger to free running
*-----*/
void set_ADC_trigger_source();
#endif /* ADC_API_H_ */

/*****
* File      : ADC_API.c
*
* Description : brief description of file purpose
*
* Author     : Mayur Bansal (mb)
*
* Revisions  : 1.00 6/27/2013 (mb) First release
*
* "THE BEER-WARE LICENSE" (Revision 42):
* <mbansal@calpoly.edu> wrote this file. As long as you
* retain this notice you can do whatever you want with
* this stuff. If we meet some day, and you think this
* stuff is worth it, you can buy me a beer in return
* Mayur Bansal
*
*****/

#include <avr/io.h>
#include "ADC_API.h"

/*-----
* Function: initialize_ADC_single_conv
*
* Description: Initialize the ADC
*-----*/
void initialize_ADC_single_conv()
{
    // Reference to AREF, Internal VREF turned off
    ADMUX &= ~(1 << REFS1);
    ADMUX |= (1 << REFS0);

    // // Left justified on result
    ADMUX |= (1 << ADLAR);

    // // Single ended input to ADC0 located PORTA0
    ADMUX &= ~(1 << MUX5);
    ADMUX &= ~(1 << MUX4);
    ADMUX &= ~(1 << MUX3);
    ADMUX &= ~(1 << MUX2);
    ADMUX &= ~(1 << MUX0);
}

/*-----
* Function: enable_ADC
*
* Description: enable the ADC
*-----*/
void enable_ADC()
{
    // set the ADC enable bit
    ADCSRA |= (1 << ADEN);
    //Auto Trigger based in ADCSRB
    ADCSRA |= (1 << ADSC);
}

/*-----
* Function: start_conversion_ADC
*
* Description: start a single conversation of the ADC
*-----*/
void start_conversion_ADC()
{
    // set the conversion bit of ADC
    ADCSRA |= (1 << ADSC);

```

```

}

/*-----
* Function: set_ADC_clock
*
* Description: set the ADC clock to OSC/4
*-----*/
void set_ADC_clock()
{
    // Setting a division factor of 4
    ADCSRA &= (0 << ADPS2);
    ADCSRA |= (1 << ADPS1);
    ADCSRA &= (0 << ADPS0);
}

/*-----
* Function: set_ADC_trigger_source
*
* Description: set the ADC trigger to free running
*-----*/
void set_ADC_trigger_source()
{
    // Free Running mode
    ADCSRB &= (0 << ADTS2);
    ADCSRB &= (0 << ADTS1);
    ADCSRB &= (0 << ADTS0);
}

/*****
* File      : DAC_API.h
*
* Description : brief description of file purpose
*
* Author     : Mayur Bansal (mb)
*
* Revisions  : 1.00 6/27/2013 (mb) First release
*
* "THE BEER-WARE LICENSE" (Revision 42):
* <mbansal@calpoly.edu> wrote this file. As long as you
* retain this notice you can do whatever you want with
* this stuff. If we meet some day, and you think this
* stuff is worth it, you can buy me a beer in return
* Mayur Bansal
*
*****/

#ifndef DAC_API_H_
#define DAC_API_H_

/*
DAC Command and Address Codes

C3 | C2 | C1 | C0 |
0 | 0 | 0 | 0 | Write to Input Register n
0 | 0 | 0 | 1 | Update(Power up ) DAC Register n
0 | 0 | 1 | 0 | Write to Input Register n, Update ( Power up) All
0 | 0 | 1 | 1 | Write to and Update (power up) n
0 | 1 | 0 | 0 | Power Down n
0 | 1 | 0 | 1 | Power Down Chip ( All DACs and References)
0 | 1 | 1 | 0 | Select Internal Reference ( Power-up Reference)
0 | 1 | 1 | 1 | Select External Reference ( Power-Down Reference)
1 | 1 | 1 | 1 | No Operation

A3 | A2 | A1 | A0 |
0 | 0 | 0 | 0 | DAC A
0 | 0 | 0 | 1 | DAC B
0 | 0 | 1 | 0 | DAC C
0 | 0 | 1 | 1 | DAC D
0 | 1 | 0 | 0 | DAC E
0 | 1 | 0 | 1 | DAC F
0 | 1 | 1 | 0 | DAC G
0 | 1 | 1 | 1 | DAC H
1 | 1 | 1 | 1 | All DACs

```

```

*/

/*
24-Bit input Protocol

    C3-C2-C1-C0-A3-A2-A1-A0-D15-D14-D13-D12-D11-D10-D9-D8-
    D7-D6-D5-D4-D3-D2-D1-D0
    Command  Address  Data

DAC_API_H_

*/

/*****#define Declarations*****/

#define setDACA    0x00
#define setDACB    0x01
#define setDACC    0x02
#define setDACD    0x03
#define setDACE    0x04
#define setDACF    0x05
#define setDACG    0x06
#define setDACH    0x07

#define pwrDACA    0x10
#define pwrDACB    0x11
#define pwrDACC    0x12
#define pwrDACD    0x13
#define pwrDACE    0x14
#define pwrDACF    0x15
#define pwrDACG    0x16
#define pwrDACH    0x17

#define pwrALL     0x1F
#define setREF     0x74

#define setDACApwrALL 0x20
#define setDACBpwrALL 0x21
#define setDACCpwrALL 0x22
#define setDACDpwrALL 0x23
#define setDACEpwrALL 0x24
#define setDACFpwrALL 0x25
#define setDACGpwrALL 0x26
#define setDACHpwrALL 0x27

#define set_pwrDACA 0x30
#define set_pwrDACB 0x31
#define set_pwrDACC 0x32
#define set_pwrDACD 0x33
#define set_pwrDACE 0x34
#define set_pwrDACF 0x35
#define set_pwrDACG 0x36
#define set_pwrDACH 0x37

#endif

/*****
* File      : interrupt_API.h
*
* Description : brief description of file purpose
*
* Author     : Mayur Bansal (mb)
*
* Revisions  : 1.00 6/27/2013 (mb) First release
*
* "THE BEER-WARE LICENSE" (Revision 42):
* <mbansal@calpoly.edu> wrote this file. As long as you
* retain this notice you can do whatever you want with
* this stuff. If we meet some day, and you think this
* stuff is worth it, you can buy me a beer in return
* Mayur Bansal
*
*****/

```

```

#ifndef INTERRUPT_API_H_
#define INTERRUPT_API_H_

/*****Function Prototypes*****/

/*-----
* Function: enable_interrupts
*
* Description: Enable all interrupts
*-----*/
void enable_interrupts ();

/*-----
* Function: enable_int0_rising_edge
*
* Description: sets the interrupt on the rising edge
*              for INTO
*-----*/
void enable_int0_rising_edge();

#endif /* INTERRUPT_API_H_ */

/*****
* File      : interrupt_API.c
*
* Description : brief description of file purpose
*
* Author     : Mayur Bansal (mb)
*
* Revisions  : 1.00 6/27/2013 (mb) First release
*
* "THE BEER-WARE LICENSE" (Revision 42):
* <mbansal@calpoly.edu> wrote this file. As long as you
* retain this notice you can do whatever you want with
* this stuff. If we meet some day, and you think this
* stuff is worth it, you can buy me a beer in return
* Mayur Bansal
*
*****/

/*****#include Declarations*****/

#include <avr/io.h>
#include "interrupt_API.h"
#include <avr/interrupt.h>

/*-----
* Function: enable_interrupts
*
* Description: Enable all interrupts
*-----*/
void enable_interrupts()
{
    sei();
}

/*-----
* Function: enable_int0_rising_edge
*
* Description: sets the interrupt on the rising edge
*              for INTO
*-----*/
void enable_int0_rising_edge()
{
    //Trigger on rising edge of INTO
    EICRA |= (1 << ISC00) | (1 << ISC01);
    //Enable INTO
    EIMSK |= (1 << INT0);
}

/*****
*****/

```

```

* File      : Master_algorithm.h
*
* Description : brief description of file purpose
*
* Author     : Mayur Bansal (mb)
*
* Revisions  : 1.00 6/27/2013 (mb) First release
*
* "THE BEER-WARE LICENSE" (Revision 42):
* <mbansal@calpoly.edu> wrote this file. As long as you
* retain this notice you can do whatever you want with
* this stuff. If we meet some day, and you think this
* stuff is worth it, you can buy me a beer in return
* Mayur Bansal
*
*****/

#ifndef MASTER_ALGORITHM_H_
#define MASTER_ALGORITHM_H_

/*****#define Declarations*****/

#define TX_FC1 0x04
#define TX_FC2 0x05
#define TX_FC3 0x06
#define RX_FC1 0x08
#define RX_FC2 0x09
#define RX_FC3 0x0A

#define TX    0x01
#define RX    0x02

#define FC1   0x01
#define FC2   0x02
#define FC3   0x03

#define NUMBEROFMODES    2
#define NUMBEROFFACES    3
#define NUMBEROFPOINTS    50
#define DELAYTIME        50

#define MINPWRLVL 0x1410 // set the DAC to 0.392V appx -50dBm
power

/*****Function Prototypes*****/

/*-----
* Function: set_phases
*
* Description: Set the control voltage for the phase
*             shifters. The voltage is set as 1/3 the
*             value using DACs.
*
* param phase1: uint16_t: phase 1 control voltage
* param phase2: uint16_t: phase 2 control voltage
* param phase3: uint16_t: phase 3 control voltage
* param phase4: uint16_t: phase 4 control voltage
*-----*/

/*-----
* Function: set_phases
*
* Description: Set the control voltage for the phase
*             shifters. The voltage is set as 1/3 the
*             value using DACs.
*
* param phase1: uint16_t: phase 1 control voltage
* param phase2: uint16_t: phase 2 control voltage
* param phase3: uint16_t: phase 3 control voltage
* param phase4: uint16_t: phase 4 control voltage
*-----*/
void set_phases(uint16_t phase1, uint16_t phase2, uint16_t phase3,
uint16_t phase4);

```

```

/*-----
* Function: set_face
*
* Description: Sets the Single pole triple throw switch
*             control voltages. PORTC0:1
*
* param face: uint8_t: the face value FC1, FC2, or FC3
*-----*/
void set_face(uint8_t face);

/*-----
* Function: set_mode
*
* Description: Sets the Single pole double throw switch
*             control voltages. PORTC2:3
*
* param face: uint8_t: the face value FTX, or RX
*-----*/
void set_mode(uint8_t mode);

/*-----
* Function: set_lock
*
* Description: Turn on the lock LED when adaptive mode is
*             in lock. PORT7
*-----*/
void set_lock();

/*-----
* Function: clr_lock
*
* Description: Turn off the lock LED when adaptive mode is
*             in lock. PORT7
*-----*/
void clr_lock();

/*-----
* Function: char_to_num
*
* Description: convert a ASCII decimal character to a
*             integer number in uint8_t
*
* param character: uint8_t: ASCII character
*
* return uint8_t: the actual decimal value number
*-----*/
uint8_t char_to_num(uint8_t character);

/*-----
* Function: convert_data_voltage
*
* Description: converts a 4 character decimal value to
*             integer value in uint16_t
*
* param v[]: uint8_t: array of ASCII character
*
* return uint16_t: the actual decimal voltage value
*-----*/
uint16_t convert_data_voltage(uint8_t v[]);

#endif /* MASTER_ALGORITHM_H_ */

```

```

/*****
* File      : Master_algorithm.c
*
* Description : brief description of file purpose
*
* Author     : Mayur Bansal (mb)
*
* Revisions  : 1.00 6/27/2013 (mb) First release
*
* "THE BEER-WARE LICENSE" (Revision 42):
* <mbansal@calpoly.edu> wrote this file. As long as you
* retain this notice you can do whatever you want with

```

```

* this stuff. If we meet some day, and you think this
* stuff is worth it, you can buy me a beer in return
* Mayur Bansal
*
*****/

/*****#define Declarations*****/

# define F_CPU 16000000UL

/*****#include Declarations*****/

#include <avr/io.h>
#include <util/delay.h>
#include "Master_algorithm.h"
#include "SPI_API.h"
#include "DAC_API.h"

/*-----
* Function: set_phases
*
* Description: Set the control voltage for the phase
* shifters. The voltage is set as 1/3 the
* value using DACs.
*
* param phase1: uint16_t: phase 1 control voltage
* param phase2: uint16_t: phase 2 control voltage
* param phase3: uint16_t: phase 3 control voltage
* param phase4: uint16_t: phase 4 control voltage
*-----*/
void set_phases(uint16_t phase1, uint16_t phase2, uint16_t phase3,
uint16_t phase4)
{
    SPI_MasterTransmit_DAC(setDACE,(phase1 >> 8), phase1);
    SPI_MasterTransmit_DAC(setDAFC,(phase2 >> 8), phase2);
    SPI_MasterTransmit_DAC(setDACG,(phase3 >> 8), phase3);
    SPI_MasterTransmit_DAC(setDACHpwrALL,(phase4 >> 8),
phase4);
}

/*-----
* Function: set_face
*
* Description: Sets the Single pole triple throw switch
* control voltages. PORTC0:1
*
* param face: uint8_t: the face value FC1, FC2, or FC3
*-----*/
void set_face (uint8_t face)
{
    if( face == FC1)
    {
        PORTC &= ~(1 << PC0);
        PORTC &= ~(1 << PC1);
    }
    else if (face == FC2)
    {
        PORTC &= ~(1 << PC1);
        PORTC |= (1 << PC0);
    }
    else if (face == FC3)
    {
        PORTC &= ~(1 << PC0);
        PORTC |= (1 << PC1);
    }
    // error mode
    else
    {
        PORTC |= (1 << PC0);
        PORTC |= (1 << PC1);
    }
}

```

```

/*-----
* Function: set_mode
*
* Description: Sets the Single pole double throw switch
* control voltages. PORTC2:3
*
* param face: uint8_t: the face value FTX, or RX
*-----*/
void set_mode (uint8_t mode)
{
    if( mode == TX)
    {
        PORTC &= ~(1 << PC2);
        PORTC |= (1 << PC3);
    }
    else if (mode == RX)
    {
        PORTC &= ~(1 << PC3);
        PORTC |= (1 << PC2);
    }
    //error mode
    else
    {
        PORTC |= (1 << PC2);
        PORTC |= (1 << PC3);
    }
}

/*-----
* Function: set_lock
*
* Description: Turn on the lock LED when adaptive mode is
* in lock. PORT7
*-----*/
void set_lock()
{
    PORTA |= (1 << PA7);
}

/*-----
* Function: clr_lock
*
* Description: Turn off the lock LED when adaptive mode is
* in lock. PORT7
*-----*/
void clr_lock()
{
    PORTA &= (0 << PA7);
}

/*-----
* Function: char_to_num
*
* Description: convert a ASCII decimal character to a
* integer number in uint8_t
*
* param character: uint8_t: ASCII character
*
* return uint8_t: the actual decimal value number
*-----*/
uint8_t char_to_num (uint8_t character)
{
    uint8_t value = 0;

    if(character == 0x20) // Decimal 0
        return value;
    else if (character == 0x31) // Decimal 1
        return value = 0x01;
    else if (character == 0x32) // Decimal 2
        return value = 0x02;
    else if (character == 0x33) // Decimal 3
        return value = 0x03;
    else if (character == 0x34) // Decimal 4
        return value = 0x04;
}

```

```

else if (character == 0x35) // Decimal 5
    return value = 0x05;
else if (character == 0x36) // Decimal 6
    return value = 0x06;
else if (character == 0x37) // Decimal 7
    return value = 0x07;
else if (character == 0x38) // Decimal 8
    return value = 0x08;
else if (character == 0x39) // Decimal 9
    return value = 0x09;
else
    return value;
}

/*-----
* Function: convert_data_voltage
*
* Description: converts a 4 character decimal value to
*              integer value in uint16_t
*
* param v[]: uint8_t: array of ASCII character
*
* return uint16_t: the actual decimal voltage value
*-----*/
uint16_t convert_data_voltage(uint8_t v[])
{
    // 4 temp var
    uint8_t t_1, t_2, t_3, t_4;

    t_1 = char_to_num(v[1]);
    t_2 = char_to_num(v[2]);
    t_3 = char_to_num(v[3]);
    t_4 = char_to_num(v[4]);

    uint16_t value = 0;

    // convert to voltage value
    value = (t_1*1000)+(t_2*100)+(t_3*10)+t_4;

    return value;
}

```

```

/*-----
* File      : SPI_API.h
*
* Description : brief description of file purpose
*
* Author     : Mayur Bansal (mb)
*
* Revisions  : 1.00 6/27/2013 (mb) First release
*
* "THE BEER-WARE LICENSE" (Revision 42):
* <mbansal@calpoly.edu> wrote this file. As long as you
* retain this notice you can do whatever you want with
* this stuff. If we meet some day, and you think this
* stuff is worth it, you can buy me a beer in return
* Mayur Bansal
*
*-----*/

#ifndef SPI_API_H_
#define SPI_API_H_

// PB0 -- ~SS
// PB1 -- SCK
// PB2 -- MOSI
// PB3 -- MISO

/*-----#define Declarations-----*/

#define SETTLING_TIME 0x05

/*-----Function Prototypes-----*/

```

```

/*-----
* Function: SPI_MasterInit
*
* Description: Initialize the SPI in the master mode.
*              with clock speed OSC/4
*-----*/
void SPI_MasterInit(void);

/*-----
* Function: SPI_MasterTransmit_DAC
*
* Description: Send the voltage set command to DAC.
*              send the packet in the protocol stated
*              DAC_API.h
*
* param cDataH: char: upper 8bits
* param cDataM: char: middle 8bits
* param cDataL: char: lower 8bits
*
* return: uint8_t
*-----*/
void SPI_MasterTransmit_DAC(char cDataH, char cDataM, char
cDataL);

#endif /* SPI_API_H_ */

```

```

/*-----
* File      : SPI_API.c
*
* Description : brief description of file purpose
*
* Author     : Mayur Bansal (mb)
*
* Revisions  : 1.00 6/27/2013 (mb) First release
*
* "THE BEER-WARE LICENSE" (Revision 42):
* <mbansal@calpoly.edu> wrote this file. As long as you
* retain this notice you can do whatever you want with
* this stuff. If we meet some day, and you think this
* stuff is worth it, you can buy me a beer in return
* Mayur Bansal
*
*-----*/

#define F_CPU 16000000UL

#include <avr/io.h>
#include <util/delay.h>
#include "SPI_API.h"

// PB0 -- ~SS
// PB1 -- SCK
// PB2 -- MOSI
// PB3 -- MISO

/*-----
* Function: SPI_MasterInit
*
* Description: Initialize the SPI in the master mode.
*              with clock speed OSC/4
*-----*/
void SPI_MasterInit(void)
{
    /* Set ~SS, MOSI and SCK output, all others input */
    DDRB = (1<<DDB0)|(1<<DDB1)|(1<<DDB2);
    /* Enable SPI, Master, set clock rate fck/4 */
    SPCR = (1<<SPE)|(1<<MSTR);
    // MSB first
}

/*-----
* Function: SPI_MasterTransmit_DAC
*
* Description: Send the voltage set command to DAC.
*              send the packet in the protocol stated

```



```

*          DAC_API.h
*
* param cDataH: char: upper 8bits
* param cDataM: char: middle 8bits
* param cDataL: char: lower 8bits
*
* return: uint8_t
*-----*/
void SPI_MasterTransmit_DAC(char cDataH, char cDataM, char
cDataL)
{
    PORTB &= (0 << PB0);

    /* Start transmission */
    SPDR = cDataH;
    /* Wait for transmission complete */
    while(!(SPSR & (1<<SPIF)))
    ;
    SPDR = cDataM;
    /* Wait for transmission complete */
    while(!(SPSR & (1<<SPIF)))
    ;
    SPDR = cDataL;
    /* Wait for transmission complete */
    while(!(SPSR & (1<<SPIF)))
    ;
    PORTB |= (1 << PB0);

    // wait 5mS for the DAC settling time
    _delay_ms(SETTLING_TIME);
}

```

```

/*****
* File      : USART_API.h
*
* Description : brief description of file purpose
*
* Author     : Mayur Bansal (mb)
*
* Revisions  : 1.00 6/27/2013 (mb) First release
*
* "THE BEER-WARE LICENSE" (Revision 42):
* <mbansal@calpoly.edu> wrote this file. As long as you
* retain this notice you can do whatever you want with
* this stuff. If we meet some day, and you think this
* stuff is worth it, you can buy me a beer in return
* Mayur Bansal
*
*****/

#ifndef USART_API_H_
#define USART_API_H_

/*****#define Declarations*****/

#define F_CPU 16000000UL
#define BAUD 57600
#define MYUBRR (F_CPU/16/BAUD-1)

/*****Function Prototypes*****/

/*-----
* Function: USART_init
*
* Description: Initializer the USART
*             BAUD 57600
*             Data bits: 8
*             Stop bits: 1
*-----*/
void USART_init( void);

/*-----
* Function: USART_tx

```

```

*
* Description: send the data on the transmit line
*
* param data: uint8_t: data to be sent
*-----*/
void USART_tx( uint8_t data);

/*-----
* Function: USART_rx
*
* Description: receive the data on the receive line
*
* return uint8_t: data to be sent
*-----*/
uint16_t USART_rx( void);

#endif /* USART_API_H_ */

/*****
* File      : USART_API.c
*
* Description : brief description of file purpose
*
* Author     : Mayur Bansal (mb)
*
* Revisions  : 1.00 6/27/2013 (mb) First release
*
* "THE BEER-WARE LICENSE" (Revision 42):
* <mbansal@calpoly.edu> wrote this file. As long as you
* retain this notice you can do whatever you want with
* this stuff. If we meet some day, and you think this
* stuff is worth it, you can buy me a beer in return
* Mayur Bansal
*
*****/

/*****#include Declarations*****/

#include <avr/io.h>
#include "USART_API.h"

/*-----
* Function: USART_init
*
* Description: Initializer the USART
*             BAUD 57600
*             Data bits: 8
*             Stop bits: 1
*-----*/
void USART_init( void)
{
    /* Set baud rate */
    UBRR0H = (unsigned char)((unsigned int)(MYUBRR)>>8);
    UBRR0L = (unsigned char)(unsigned int)(MYUBRR);

    /* Enable receiver and transmitter */
    UCSR0B = (1<<RXEN0)|(1<<TXEN0);

    /* Set frame format: 8data, 1stop bit, parity Disable, Asynchronous
Mode */
    UCSR0C = (3<<UCSZ00);

    // USART_Init
}

/*-----
* Function: USART_tx
*
* Description: send the data on the transmit line
*
* param data: uint8_t: data to be sent
*-----*/
void USART_tx(uint8_t data)
{

```



```

    /* Wait for empty transmit buffer */
    while ( !(UCSR0A & (1<<UDRE0)) )
    ;
    /* Put data into buffer, sends the data */
    UDR0 = data;
}

/*-----
* Function: USART_rx
*
* Description: receive the data on the receive line
*
* return uint8_t: data to be sent
*-----*/
uint16_t USART_rx( void)
{
    /* Wait for data to be received */
    while ( !(UCSR0A & (1<<RXC0)) )
    ;
    /* Get and return received data from buffer */
    return UDR0;
}

```

F PCB Schematic

Mounting Holes

Reset Circuit

ISP Header

Microcontroller

TITLE: Thesis_Digital

Document Number:

REV:
B

Date: 7/15/2013 1:00:26 AM

Sheet: 1/5

Ocal DAC

Comparator

Phase Shifter Control line Amplifier

Peak Detector

Peripherals

TITLE: Thesis_Digital

Document Number:

REV:
B

Date: 7/15/2013 1:00:26 AM

Sheet: 2/5

Input Voltage

5V System

2.5V DAC Reference

15 Volt Amplifier Rails

Connecting Grounds

Power

TITLE: Thesis_Digital

Document Number:

REV:
B

Date: 7/15/2013 1:00:26 AM

Sheet: 3/5

Control Lines

Status LED

Signal Strength Display

VCO Tuning

RF Interface

TITLE: Thesis_Digital

Document Number:

REV:
B

Date: 7/15/2013 1:00:26 AM

Sheet: 4/5

RS-232 DRIVER

ANT MODE

SPDT[1]	SPDT[0]	MODE
0	1	RX
1	0	TX

ANT FACE

SP3T[1]	SP3T[0]	FACE
0	0	1
0	1	3
1	0	2

TEST MODE

TEST[1]	TEST[0]	MODE
0	0	MATLAB GUI
0	1	ADAPTIVE RX
1	0	ADAPTIVE TX/RX
1	1	UNUSED

DIP Pins

TEST MODE

TITLE: Thesis_Digital

Document Number:

REV:
B

Date: 7/15/2013 1:00:26 AM

Sheet: 5/5

G PCB Layout

H Bill Of Materials

The complete electrical bill of materials (BOM) is presented below for the Digital Control Board.

Part	Manufacturer	Distributor	Model Number	Unit Price (\$)	Qty/Board	Total
Crystal	ECS Inc	Digikey	ECS-160-20-5PXDU-TR	\$1.46	1	\$1.46
Microcontroller (ATmega2560)	Atmel	Digikey	ATMEGA2560-16AU	\$18.19	1	\$18.19
LT1761(2.5V)	Linear Technology	Digikey	LT1761IS5-2.5#TRMPBF	\$2.62	1	\$2.62
NCP1117ST50T3G	ON Semi	Digikey	NCP1117ST50T3G	\$0.49	1	\$0.49
LM3480(+15V)	Texas Instruments	Digikey	LM3480IM3-15/NOPB	\$0.97	1	\$0.97
LTC2656	Linear Technology	http://www.linear.com	LTC2656IFE-L12#PBF	\$14.37	1	\$14.37
LT5534	Linear Technology	http://www.linear.com	LT5534ESC6#TRMPBF	\$6.50	1	\$6.50
LT6005	Linear Technology	http://www.linear.com	LT6005CGN#PBF	\$2.06	1	\$2.06
LM339	Texas Instruments	Digikey	LM339ADR	\$0.41	1	\$0.41
LM3914	Texas Instruments	Digikey	LM3914VX/NOPB	\$3.66	1	\$3.66
MAX232	Texas Instruments	Digikey	MAX232ECPW	\$1.34	1	\$1.34
16 Pin Conn (16 POS)	FCI	Digikey	67996-216HLF	\$4.90	2	\$9.80
AVR-ISP-header (6POS)	FCI	Digikey	67996-206HLF	\$0.29	6	\$1.74
SPI Jumpers (2POS)	FCI	Digikey	67996-104HLF	\$0.27	1	\$0.27
DB-9	TE Connectivity	Digikey	1734351-1	\$1.18	1	\$1.18
DIP- 2 POS	CTS Electrocomponents	Digikey	219-2LPST	\$0.60	3	\$1.80
Jumper	TE Connectivity	Digikey	2-382811-1	\$0.09	4	\$0.36
SMA	TE Connectivity	Digikey	2081233-1	\$1.65	1	\$1.65
16 PIN IDC Cable	TE Connectivity	Digikey	A3DDH-1606G	\$7.19	1	\$7.19
PWR70Q2S	C & K Components	Digikey	PWR70Q2S	\$3.89	1	\$3.89
LED Green	OSRAM Opto Semiconductors Inc	Digikey	LG Q971-KN-1	\$0.07	16	\$1.09
LED Red	OSRAM Opto Semiconductors Inc	Digikey	LS Q976-NR-1	\$0.09	8	\$0.72
LED Yellow	OSRAM Opto Semiconductors Inc	Digikey	LY Q976-P1S2-36	\$0.09	3	\$0.27
0 Ohm	Yageo	Digikey	RC0402JR-070RL	\$0.01	20	\$0.24
49.9 ohm	Rohm Semiconductor	Digikey	MCR01MRTF49R9	\$0.10	1	\$0.10
7.5k	Panasonic Electronic Components	Digikey	ERJ-2GEJ752X	\$0.10	2	\$0.20
3.3k	Panasonic Electronic Components	Digikey	ERJ-2GEJ332X	\$0.10	4	\$0.40
470 ohm	Stackpole Electronics Inc	Digikey	RMCF0402JT470R	\$0.02	10	\$0.17
20k (0.5%)	Vishay Dale	Digikey	CRCW040220K0DHEDP	\$0.28	4	\$1.10
10k (0.5%)	Vishay Dale	Digikey	CRCW040210K0DHEDP	\$0.28	4	\$1.10
10K	Panasonic Electronic Components	Digikey	ERJ-2RKF1002X	\$0.10	11	\$1.10
5K POT	Bourns Inc.	Digikey	3224W-1-502E	\$3.64	1	\$3.64
CER 0.1uF	Kemet	Digikey	C0402C104K8PACTU	\$0.10	9	\$0.90
CER 20pF	Yageo	Digikey	CC0402JRNPO9BN200	\$0.10	2	\$0.20
CER 100pF 16V	Kemet	Digikey	C0402C101K4GACTU	\$0.10	4	\$0.40
CER 1uF 16V	TDK Corporation	Digikey	C1005X5R1C105K050BC	\$0.12	7	\$0.84
TANT 0.1uF 35V	Kemet	Digikey	T491A104M035AT	\$0.38	2	\$0.76
TANT 1uF 16V	Kemet	Digikey	T491A105K016AT	\$0.34	1	\$0.34
TANT 10uF 20V	Kemet	Digikey	T494A106M020AT	\$1.02	3	\$3.06
Fuse	TE Connectivity	Digikey	0603SFF050F/32-2	\$0.35	1	\$0.35
RFC	TDK Corporation	Digikey	MLK1005S22NJ	\$0.10	2	\$0.20
Diode	Micro Commercial Co	Digikey	1N4148X-TP	\$0.20	1	\$0.20
20V	CUI Inc	Digikey	ETSA200200UDC-P5P-SZ	\$24.23		\$0.00
Power Jack	CUI Inc	Digikey	PJ-002AH-SMT-TR	\$1.89	1	\$1.89

I Block Diagrams

(a) Electrical Model

```

|*SPICE model for HSMS-286x
|*The parameters are for a single diode (HSMS-2860). Parameters also apply
|*to the individual diodes within multiple diode configurations.
|*
|.subckt hsms286x Anode Cathode

D1 Anode Cathode DMOD

.MODEL DMOD D(IS=5E-8 CJO=0.18E-12 UJ=.65 BV=7 IBV=10E-5 EG=0.69 N=1.08 RS=5 XTI=2 M=0.5)

.ends hsms286x

```

(b) Spice Netlist

Figure I.1: Schottky Diode Chip Model

Figure I.2: ATmega2560 Block Diagram

Figure I.3: Analog to Digital Converter Block Schematic

Figure I.4: LTC2656 Block Diagram