4/20/2021

EEL 4911C & EEL 4915 C

Team 311: Digital Beamsteering Phased Array

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Abstract

A technique called beamsteering is the process of rotating the direction of the signal through a series of signal delays. This changes the radiation direction without physically moving the transmitting antennas. The market for beamsteering antenna arrays is extremely vast and can be used across multiple industries. For military applications, it is useful for improving the speed and range of radar systems. For civilian applications, it can be useful in communication systems, allowing for the technological progression of 5G systems and satellite to ground communications.

This project aims to develop a setup that allows the ease of implementation of beamsteering. It is software-based and uses digital techniques for flexibility. The setup contains commercially available parts, such as the four transmitting antennas, to reduce the cost of the system. The system will be controlled through the FPGA development board, which is essentially the brain of the project. The setup supports a high-intensity signal of 2.4 GHz and has the ability to transmit the signal in any given direction with a range comparable to an average household router.

This project tasks the team with creating a transmitting antenna array, which is multiple antennas arranged in a line, to implement beamsteering. When thoroughly reviewing the datasheets, the team studies the propagation of the input/output signals for each component and how it connects to one another for hardware assembly. After confirming these I/O ports, the team can write the software necessary for the project. The goal of the software design is to create an unmodified signal and control the direction the signal is transmitting.

This project transmits a focused high-intensity signal that can change the radiation direction. When testing the final project, the team will use the assisting professor's antenna lab to check if the signal was properly transmitted. Overall, this project aims to develop a setup that allows beamsteering implementations.

Disclaimer

Team 311s project: Digital Beamsteering Phased Array is an independent project not sponsored by the FAMU-FSU College of Engineering. Team 311 is not responsible for any damage that may occur when implementing the project. Please use project at your own risk.

Acknowledgement

Thank you to our Sponsor L3Harris!

Thank you Dr. Uwe Meyer-Baese for advising our project! We appreciate you your constructive feedback and guidance throughout the year

Thank you Dr. Jerris Hooker for being our acting customer!

Thank you Dr. Bayanar Arigong for acting as an assisting instructor for our team! We appreciate the help you and your PhD students have given our team.

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Notation

5G	5th Generation Cellular Network Technology
AC	Alternating Current
Cm	Centimeter
Coax	Coaxial
DAC	Digital to Analog Converter
dB	Decibel
dBm	Decibel Milliwatt
DC	Direct Current
DDS	Direct Digital Synthesis
FPGA	Field Programmable Gate Array
GHz	Gigahertz
GUI	Graphics User Interface
HDL	HDL
HDMI	High-Definition Multimedia Interface
Hz	Hertz
I/O	Input/ Output
IEEE	Institute of Electrical and Electronics Engineers
IPC	Institute of Printed Circuits
ISM	Industrial, Scientific, Medical
ITU	International Telecommunication Union

LCD	Liquid Crystal Display
LED	Light Emitting Diode
LO	Local Oscillator
MCU	Microcontroller Unit
MHz	Mega-Hertz
Micro-USB	Micro-Universal Serial Bus
NSPE	National Society of Professional Engineers
OLED	OLED
PC	Personal Computer
PCB	Printed Circuit Board
PSD	Phase Synchronizing Device
RF	Radio Frequency
SMA	Subminiature Version A
SPI	Serial Peripheral Interface
USB-A	Universal Serial Bus Type A
USB-C	Universal Serial Bus Type C
V	Volts
VCO	Voltage Controlled Oscillator
VGA	Video Graphics Array
VHDL	Very High-Speed Integrated Circuit Hardware Description Language
Wi-Fi	Wireless Fidelity

1.1 Project Scope

An array of antennas will be used to create a transmitter and receiver that utilizes beamsteering within the ISM band. The beamsteered transmitter should be able to focus radio waves at a specified direction done through an algorithm that controls the phase shifting of a transmitted signal. This would be done by having a microcontroller that allows the user to pick the direction of the beam by using phase shifters and communicates with the Voltage-controlled Oscillator (VCO) to determine the signal it should send. The VCO will connect to an up converter to change the band of frequencies to a higher one. This signal will then be sent to the transmitter.

The receiver that our team will develop should be able to sweep all directions and figure out where the signal is coming from and steer the beam to that direction using phase shifters. It will take in the signal and down convert it, so it is at a lower frequency for the computer to be able to read. Then, the signal is taken to the analog to digital converter.

1.2 Customer Needs

Although senior design encourages students to have a strong relationship with their sponsor, Team 311's sponsor, L3Harris, has allowed the team a more open-ended approach. Therefore, we have no clear customer statement to present. Based on the project description and specifications we were able to develop needs and requirements.

Needs:

Needs	**Ref #**
Control radiation direction	1
Transmitting device	3
Digital to analog signal conversion	4
FPGA/MCU controlled	5

Table 1 *Customer Needs*

The two most important needs are:

- FPGA/MCU controlled
  - The FPGA/MCU controller will allow the user to control the system. This is an important need because you will not be able to steer the beam without a main controller.
- Control radiation direction
  - This is an important need because it is one of the main aspects of beam steering. You must be able to control the direction in which the transmitted signals will be directed.

Requirements:

Requirements	**Need Ref #**
Operating Frequency is with in ISM Bandwidth < 30 dB	2
4 Channel DDS	3
Measurement of Phase Difference	1
Optimum radiation beam control algorithm	4
Manipulate digital baseband signal	4

Table 2 *Customer Requirements*

Materials:

- Antenna array
- RF up-conversation channel
- DAC (Digital to Analog Converter)
- MCU/FPGA

Explanation of Results:

Since we do not have any clear customer statements, we are able to develop our own explanation of the results. The final result will be a FPGA based beam steered away, which the user will be able to control the phase delay and direction of the system.

1.3 Functional Decomposition

<u>Introduction:</u>

The system's function is to steer the radiation pattern of a beam steered array by manual control or automated algorithmic processes. The system subdivides into five different modules, each with their own inputs and outputs. The entire system is controlled digitally, with the up-converters and antennas being the only analog parts.

<u>Function Tree:</u>

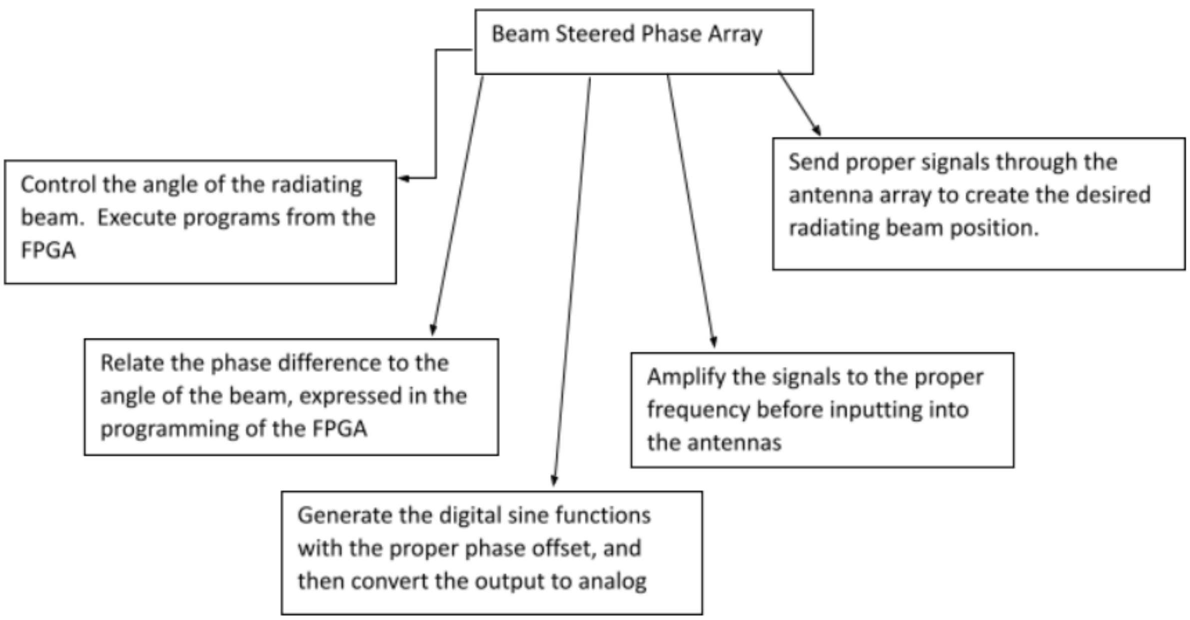


Figure 1. Function Tree

Decomposition Levels:

Level 0:

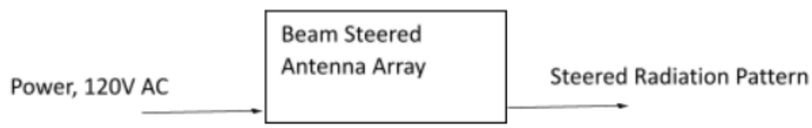


Figure 2. Level 0 of Functional Decomposition

Module	Beam Steering Antenna Array
Inputs	120V AC power
Outputs	Steered Radiation Pattern
Functionality	Transmits a radiation beam pattern that can be steered using a computer interface.

Table 3 *Beam Steered Antenna Array Properties*

Level 1:

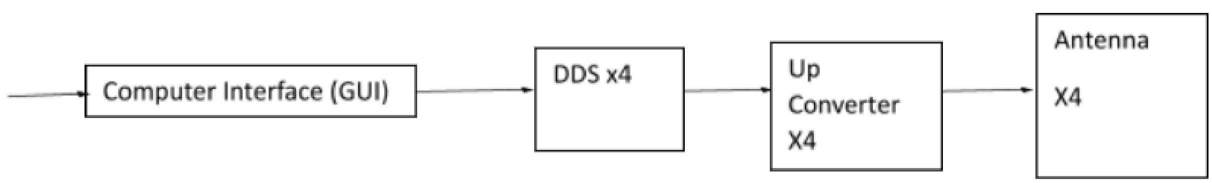


Figure 3. Level 1 of Functional Decomposition

Module	Computer Interface GUI
Inputs	120V AC power
Outputs	USB interface with FPGA
Functionality	Control the operating function and angle of the radiation pattern by communicating with the FPGA.

Table 4 *Computer Interface GUI Properties*

Module	DDS X4
Inputs	1.8V, 3.3V dc
Outputs	4 analog sine wave patterns with phase offset, 200.3 MHz (Highest the DDS can output)
Functionality	Generates four different analog sign wave patterns each with an equal phase offset that will be input into the up-converter.

Table 5 *DDS Properties*

Module	Up-Converter
Inputs	4 analog sine wave patterns at 200.3MHz a piece
Outputs	4 analog sine wave patterns at 2.4GHz
Functionality	Amplifies the sine waves from the DDS to the correct frequency for the antenna array.

Table 6 *Up-Converter Properties*

Module	Antenna X4
Inputs	4 analog sine wave patterns at 2.4GHz and equal phase difference
Outputs	Radiation pattern with angle relative to the phase difference of the input signals.
Functionality	Amplifies the input signals into a radiating beam in which signals can be transmitted wirelessly to a receiver.

Table 7 *Antenna Properties*

<u>Summary:</u>

The beam steered phase array will consist of five sub modules that work together in series. The system starts with a PC that sends instructions to the DDS evaluation software. The DDS evaluation software will control the four DDS modules that generate the sine waves and their phase offsets. These waves are output from the DDS as analog signals and are input into the up-converters to amplify them to the desired frequency, 2.4GHz. The antennas are the final stage of the system, where the signals from the upconverters are input and the radiation pattern is generated.

1.4 Target Summary

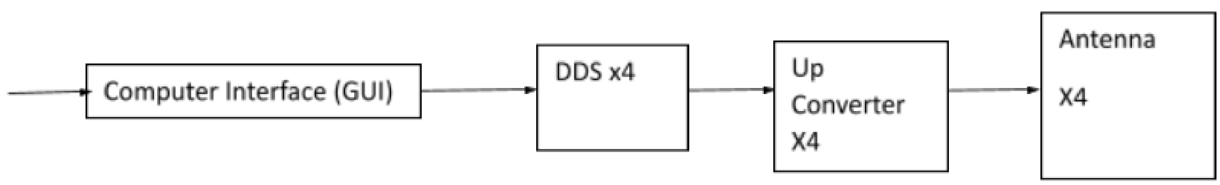


Figure 4. System Propagation

Module	Computer Interface GUI
Inputs	120V AC power
Outputs	USB interface with FPGA

Table 8 *Computer GUI I/O Properties*

Module	DDS X4
Inputs	1.8V, 3.3V dc
Outputs	4 analog sine wave patterns with phase offset, 200.3 MHz (Highest the DDS can output)

Table 9 *DDS I/O Properties*

Module	Up-Converter
Inputs	4 analog sine wave patterns at 200.3MHz a piece
Outputs	4 analog sine wave patterns at 2.4GHz

Table 10 *Up Converter I/O Properties*

Module	Antenna X4
Inputs	4 analog sine wave patterns at 2.4GHz and equal phase difference
Outputs	Radiation pattern with angle relative to the phase difference of the input signals.

Table 11 *Antenna I/O Properties*

Method of Validation & Discussion of Measurements:

Graphical User Interface (GUI):

Make sure that there are no errors in the code and that the elements in the code align for example they are compatible in size, position, and width.

Direct Digital Synthesizer (DDS):

We can test the DDS by using an oscilloscope and test whether the sinusoidal waves that it is outputting is around 200 MHz which is the input that is required for the up converter to up convert to 2.4 GHz.

Up Converter:

We can also test the Up Converter by using the oscilloscope, but instead of looking for 200 MHz we will test to make sure that the signal is at a frequency of 2.4 GHz.

Antenna:

Dr. Arigong is going to have an RF lab available to students by next semester. We can test the transmitter through a receiver in the lab. To successfully have a beamsteered array of antennas, the gain needs to be controlled through the GUI. There were no specifications for gain or angle width of the beam. Those two variables depend on the quality of the antenna. The graph on the next page shows what the GUI should display when pointing the beam at around -35 degrees. The gain is significantly better at where the beam is steered.

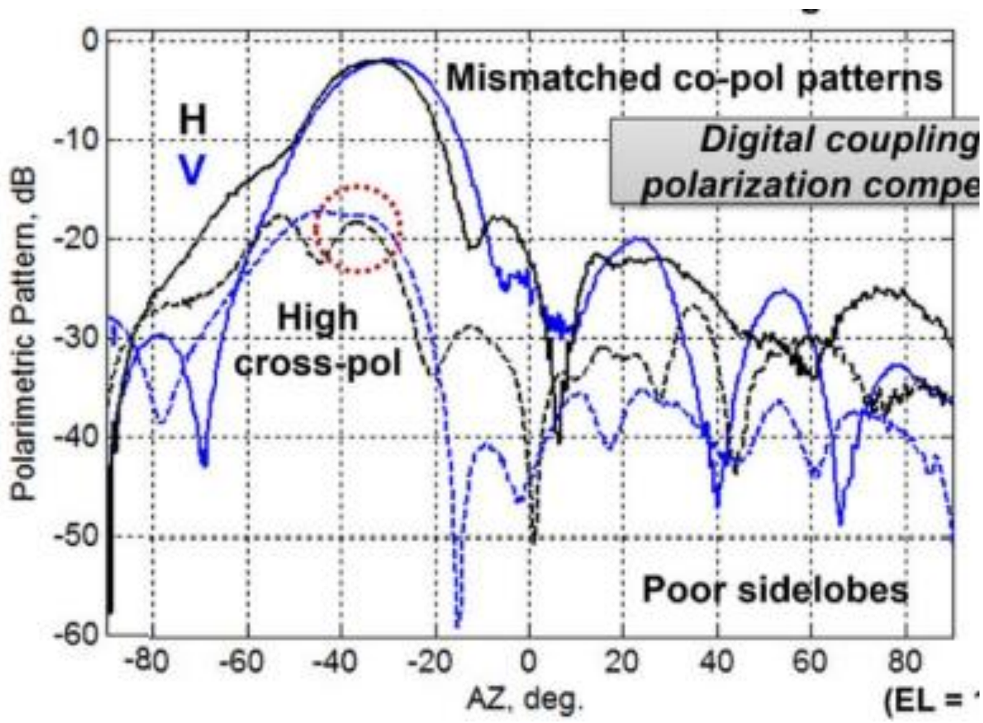


Figure 5. Radiation Polarization Patterns

Critical Target and Derivation of Targets and Metrics:

We need to achieve a transmitting frequency within the ISM band. Dr. Arigong recommended 2.4 GHz. To do this that means we need an upconverter that can take our output from the DDS up to 2.4 GHz. The DDS operates at around 200 MHz, which is why we need to upconvert to get the frequency within the ISM band.

1.5 Concept Generation

Given the generated Collective Concept List, Concept Classification, and Conceptual Function Application charts below, we were able to narrow down the high and medium fidelity concepts which are most applicable and realistic for our design.

3 High Fidelity Concepts:

1. Pre-built 4-Channel DDS (no PCB required)
2. FPGA and MCU based
3. Operation Frequency Band is 2.4 - 2.5 GHz

5 Medium Fidelity Concepts:

1. 7-segment Display and LCD Display
2. Handheld Size (can fit into shoe box)
3. Series Antenna Array
4. Pre-built DAC/DDS for signal generator
5. 120V 60Hz Power Supply

FPGA	MCU	Arduino	Raspberry Pi	MSP	OLED	Touch screen display	Smart Phone App	Head-mounted display	Development Boards I/O	Coax Cables
Development Board LCD	Monitor (PC)	LED array	7-segment	HDMI	USB-A	VGA	Ethernet	Bluetooth	Wi-Fi	USB-C
VHDL	Verilog	C	Python	C++	Java	C#	Linux	Javascript	Lab View	HDL
Development Board LCD	Monitor (PC)	LED array	7-segment	Quantum dot	OLED	Touch screen display	Smart Phone App	Head-mounted display	Micro-USB	Soldering
Buttons	Switches	Dials	Keyboard	Mouse	Command Line	Form Based	Menu Driven	Voice Control	Gesture Control	Touchscreen
Development Boards I/O	Coax Cables	HDMI	USB-A	VGA	Ethernet	Bluetooth	Wi-Fi	USB-C	Micro-USB	Soldering
Analog Waveform Generator	Pre-built DAC/DDS	Custom PCB with DDS	Analog Phase Shifter	Digital Phase Delay	Analog Beamformer	Time Delay	Distance between antennas	Pre-built Upconverter	Custom PCB with Upconverter chip	Analog Signal Amplifier
Transmitter	Receiver	Transceiver	Directional Antenna	Patch Antenna	Series	Matrix	Signal Amplifier	Fabricated Metal	Plastic	Carbon Fiber
40.66 - 40.7 MHz	902 - 928 MHz	2.4 – 2.5 GHz	5.725 – 5.875 GHz	24 - 24.250 GHz	ISM	Military	Aviation	Cellular	3D Printed	Easy Maintenance
Portable	Handheld	Semi portable	"Shoebox" Sized	Permanent installation	Tabular size	120V 60Hz	DC Power Supply	Lithium-Ion Battery	12V Solar cell with battery	5V Battery

Table 12 *Collective Concept List*

Options/ Subfunction	1	2	3	4	5	6	7	8	9	10	11
System Control	FPGA	MCU	Arduino	Raspberry Pi	MSP						
Development Language	VHDL	Verilog	C	Python	C++	Java	C#	Linux	Javascript	Lab View	HDL
Display	Development Board LCD	Monitor (PC)	LED array	7-segment	Quantum dot	OLED	Touch screen display	Smart Phone App	Head-mounted display		
User Interface	Buttons	Switches	Dials	Keyboard	Mouse	Command Line	Form Based	Menu Driven	Voice Control	Gesture Control	Touchscreen
Connectivity & Expansion	Development Boards I/O	Coax Cables	HDMI	USB-A	VGA	Ethernet	Bluetooth	Wi-Fi	USB-C	Micro-USB	Soldering
Power	120V 60Hz	DC Power Supply	Lithium-Ion Battery	12V Solar cell with battery	5V Battery	9V Battery	USB From Computer	Crank Generator	Wind Turbine	Wind Mill	Water mill
Signal Generation	Analog Waveform Generator	Pre-built DAC/DDS	Custom PCB with DDS								
Signal Phase Shift	Analog Phase Shifter	Digital Phase Delay	Analog Beamformer	Time Delay	Distance between antennas						
Up Conversion	Pre-built Upconvert	Custom PCB	Analog Signal	Signal Amplifier							

Table 13 *Concept Classifications*

User Interface	**Display**	**Connectivity & Expansion**	**Power**	**Size**	**Architecture**
graphical user interface	Liquid crystal display	Coax Cables	5V Battery	6.25cm	Waveform/Function Generator
graphical user interface	7-segment	HDMI	USB from Computer	12.5cm	RF Phase Shifter
graphical user interface	Liquid Emitting Diode	USB	Outlet	18.75cm	Beam Forming
graphical user interface	Quantum dot	VGA	Lithium Ion Battery	25cm	Beam steering
graphical user interface	Computer Monitor	Ethernet	Solar Cell	31.25cm	FPGA/MCU
command line	Liquid crystal display	Coax Cables	5V Battery	6.25cm	Waveform/Function Generator
command line	7-segment	HDMI	USB from Computer	12.5cm	RF Phase Shifter
command line	Liquid Emitting Diode	USB	Outlet	18.75cm	Beam Forming
command line	Quantum dot	VGA	Lithium Ion Battery	25cm	Beam steering
command line	Computer Monitor	Ethernet	Solar Cell	31.25cm	FPGA/MCU
menu driven	liquid crystal display	Coax Cables	5V Battery	6.25cm	Waveform/Function Generator
menu driven	7-segment	HDMI	USB from Computer	12.5cm	RF Phase Shifter

menu driven	Liquid Emitting Diode	USB	Outlet	18.75cm	Beam Forming
menu driven	Quantum dot	VGA	Lithium Ion Battery	25cm	Beam steering
menu driven	Computer Monitor	Ethernet	Solar Cell	31.25cm	FPGA/MCU
form based	liquid crystal display	Coax Cables	5V Battery	6.25cm	Waveform/Function Generator
form based	7-segment	HDMI	USB from Computer	12.5cm	RF Phase Shifter
form based	Liquid Emitting Diode	USB	Outlet	18.75cm	Beam Forming
form based	Quantum dot	VGA	Lithium Ion Battery	25cm	Beam steering
form based	Computer Monitor	Ethernet	Solar Cell	31.25cm	FPGA/MCU
Interactive user control	Touchscreen display	wireless	Lithium-ion battery	20cm	Phase shift status
Frequency Classification	Frequency PSD graphs show on LCD	Booster pack extension	Booster connected to MCU	3cm	Frequency detection
Frequency measurement	Frequency value displays on fpga seven segment display	Seven segment display on DoC-1 board	Through fpga power source	1cm	receiver
Phase measurement	Phase shift displays on fpga	Seven segment	Through fpga	1cm	receiver

	seven segment display	display on DoC-1 board	power source		
Signal detection	Light up LED when signal is detected	LED on fpga	Through fpga power source	1cm	receiver
Phase range	Show phasor diagram on LCD	Booster pack extension	Booster connected to MCU	3cm	receiver
Voice Control steered beam	Display voice recognized phase value on LCD on MCU	Booster pack extension	Booster connected to MCU	3cm	transmitter
Voice Control signal range detection	Display voice recognized frequency range on LCD	Booster pack extension	Booster connected to MCU	3cm	Receiver, looks for signal within the given range

Table 14 *Conceptual Function Application*

1.6 Concept Selection

House of Quality:

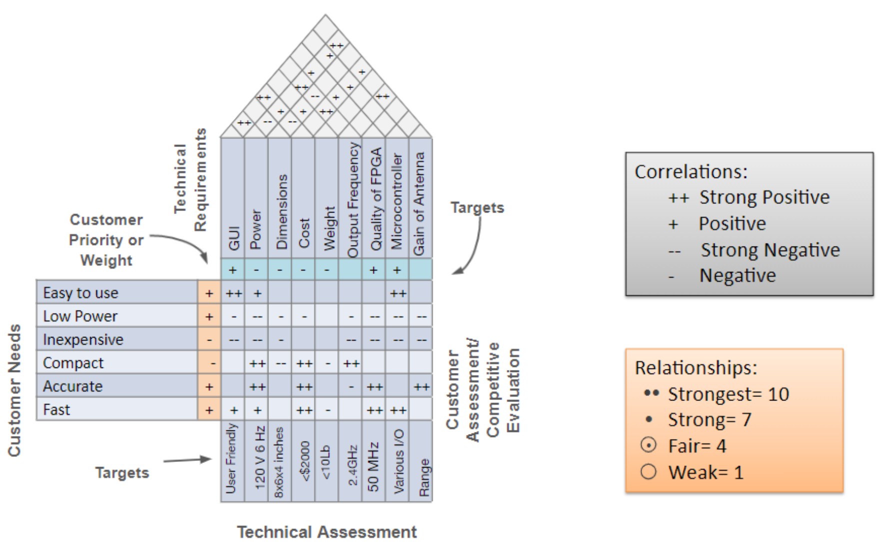


Figure 6. House of Quality Chart

- **Easy to use** - Strong positive correlation with the GUI and the microcontroller because the GUI will be how users input values into the system and the microcontroller will offer input options like joystick or voice-control.
- **Low Power** - Overall had very low priority will all technical requirements as power supply will not be a big problem.
- **Inexpensive** - Strong negative correlation with GUI, input power, output frequency, quality of FPGA, microcontroller and the gain of the antenna. These devices are more expensive for a higher quality product that is reliable.
- **Compact** - Strong positive correlation with power, cost, and output frequency because with the frequency being at 2.4 GHz, the size of the spacing of the antennas will be relatively small.
- **Accurate** - Strong positive correlation with power, cost, quality of FPGA, and quality of antenna. Over almost everything, accuracy is extremely important as without accuracy, the whole project would be a complete waste of time and money.
- **Fast** - Strong positive correlation between GUI, power, cost, quality of FPGA, and Microcontroller. Overall, speed will be key here as the faster the FPGA and MCU, the quicker that the project can function.

Analytical Hierarchy Process (AHP):

	Ease of Use	Compactness	Weight	Accuracy	Speed	Mean $\sqrt[n]{\prod a_i}$	Weights
Ease of Use	1	3	5	1/7	1/5	0.844	0.103
Compactness	1/3	1	3	1/7	1/7	0.46	0.056
Weight	1/5	1/3	1	1/9	1/7	0.254	0.031
Accuracy	7	7	9	1	3	4.21	0.515
Speed	5	7	7	1/3	1	2.412	0.295

Table 15 *Analytical Hierarchy Process*

- **Accuracy** - The most heavily weighted criteria. Thus, maximizing all other criteria's leads to a functionally accurate system. For the design to be functional, it must accurately detect frequencies within in the beams range. Otherwise if we are detecting false signal, the functionality of our system is compromised.
- **Speed** - Apart from accuracy, this is an extremely important criteria, for the faster the FPGA and MCU, the faster the beam can shift and therefore the faster the experiment will be able to advance. Compactness and weight efficiency are direct improvements to speed.
- **Ease of Use** - A simple design with minimum controls allows for advancement in compactness and weight. Minimal controls leads to a compact design and lighter weight. A lighter weight will not require as much processing power whereas a compact design leads to enhanced overall efficiency.

- **Compactness** - Although compactness is not weighted heavily, its impacts should not be underestimated. A compact design leads to a simpler ease of use and becomes more efficient when considering accuracy and speed.
- **Weight** - The least heavily weighted criteria. The design is aimed to be a size that can fit into a shoe box. The weight of the design is not significant; however, the design will ensure to not be above a weight where the design requires more processing power.

Pugh Chart:

		Digital Antenna Array	Digitized Antenna Array	Analog Antenna Array
Ease of Use	0.103	-	0	-1
Compactness	0.056	-	0	-1
Weight	0.031	-	-1	-1
Speed	0.295	-	0	0
Accuracy	0.515	-	-1	-1
Score		0	-0.546	-0.705

Table 16 *Pugh Chart*

- **Ease of Use** - The digital antenna array and digitized antenna array is going to be the easiest to use because you can use a GUI instead of using variable electronic components that the analog antenna array would require.
- **Accuracy** - The digital and digitized systems are going to be more accurate because analog systems can be finicky due to the generation of the signals being physically created.
- **Speed** - The speed throughout all systems will be around the same.

- **Compactness -** Using the digital and digitized systems require a lot less hardware, so it will be more compact than the analog antenna array.
- **Weight -** The weight of the digital antenna array is going to be the lightest because there are the least number of physical components.

After multiplying by the weights we see that the digital antenna array is the best choice.

1.8 Spring Project Plan

<u>Important Dates:</u>

- Spring Semester Begins…………………………………………..…………01/05/2022
- Graduation……………………………………………………...…………04/30/2022
- Engineering Design Day…………………………………………………….04/07/2022
- Spring Break………………………..…………………………03/14/2022 - 03/14/2022
- Finals Week…………………………...…..…………………….. .04/25/2022 - 04/29/2022

<u>Spring Project Plan:</u>

Task Name	Duration	Start	End	Tiernen Pan	Christian Balos	William Snyder	Katheryn Potemken	Andrew Cayson
Order All Necessary Parts	1 week	12/02/2021	12/09/2021					
Ensure all parts work	3 days	01/05/2022	01/07/2022					
FPGA	0.33 day							
MCU/Boosterpack	0.33 day							
AD9959 Development Board	0.33 day							
Mixer Upconverters	0.5 day							
Local Oscillators	0.5 day							
Amplifiers	0.5 day							
Antennas	0.5 day							
Configure I/O Ports for MCU to FPGA	1 week	01/07/2022	01/14/2022					
Write FPGA Software	3 & 1/2 weeks	01/14/2022	02/09/2022					
Clocks to feed into DDS signal generator	1/2 week							
Slave Antenna Phase Shift algorithm	2 weeks							
AD9959 Register/Pin Control	1 week							
Configure boosterpack and MCU	2 weeks	01/14/2022	01/28/2022					
Configure LCD Display								
Configure Analog Joystick								
Configure I/O ports for FPGA and DDS	2 weeks	01/21/2022	01/28/2022					
Write MCU Software that relate the controller to an angle change	3 weeks	01/28/2022	02/18/2022					
Connect Components	2 weeks	02/18/2022	03/04/2022					
AD9959 to Upconverter	1 week							
LO to Upconverter	1 week							
Upconverter to Amplifier	1 week							
Amplifier to Antenna	1 week							
Test Software	2 weeks	03/04/2022 - 03/11/2022	03/20/2022 - 03/26/2022					
FPGA to AD9959	1 week							
MCU to FPGA	1 week							

Chapter Two: EEL 4915C

2.1 Restated Project Definition and Scope

An array of antennas will be used to create a transmitter that utilizes beamsteering within the ISM band. The ISM band is a designated frequency band that the Industrial, Scientific, and medical community are allowed to operate in. The beam steered transmitter should be able to focus radio waves at a specified direction done through an algorithm that controls the phase for each of the signals. This would be done by having a microcontroller that allows the user to pick the direction of the beam. The microcontroller will then feed its outputs into the FPGA which will do the calculations. It will calculate the special delay that is needed for each of the signals to direct the beam in a particular direction. The FPGA's output will be fed into the Direct Digital Synthesizer (DDS). The DDS will create the signals and apply the special delays that the FPGA calculated. The DDS has four output signals, one for each antenna. The output of the DDS will not be in the correct frequency band, so the output of the DDS will need to go into a mixer. The mixer's output will retain the same information that the DDS is trying to output but bump the frequency up to the required ISM band. The four signals will then be sent to the array of antennas.

Key Goals:

- Convert four digital signals to four analog signals
- Control phase shift of each channel to adjust propagation direction
- Increase signal frequency to 2.4 GHz by mixing 200.3 MHz DDS output with 2.2 GHz oscillator output

- Increase gain of each signal to ensure a strong signal
- Create a four-antenna linear array to propagate signal in direction specified by changing the phase shift of each signal

2.2 Detailed Design

I. Introduction

Problem Statement: The team needs to develop a transmitting phased antenna array that can control the main lobe of radiation by controlling the digital baseband signal.

Motivation: The motivation for beamsteering is the need for higher data transmission rates. It allows for transmission of higher quality signals to receivers. This means that the Signal to Noise Ratio is significantly higher leading to fewer errors in the transmission of data. Another upside to using beamsteering is that there is no need to increase the transmitting power in order to achieve the higher quality signal. By focusing the main lobe of the transmission radiation, we are also able to decrease the amount of interference that we inflict on other receivers because of the large attenuation in the sidelobes that comes as a by-product of beamsteering.

Requirements: The system must include an antenna array, RF up-conversion channels, digital to analog converters, and a DDS. The operating frequency needs to be within the ISM band at 2.4 GHz, and the output power that leads into the antenna must be less than 30 dBm. The steering angle of the beam needs to be able to have a 180-degree range.

II. Selected Concept

1. When selecting final concepts, the first main decision was to select the type of system. Various types of systems are digitized, digital, and analog. The team has selected the digital route to implement the beam steering system. This will allow us to initially create and control the signal digitally, which later be converted to an analog signal.
2. We will take advantage of the evaluation software that comes with the DDS to control the phase offset of the design. The size of the system will be handheld size. That way it can be easily transported to areas of high signal density, which may also help us when testing our final design.
3. There will be various power supplies throughout our design. The DDS will be powered through a 3 V and a 1.8 V voltage supply. We will also use a DC power supply to power the PCB. We will take advantage of the USB connection of the DDS and connect it to our laptops, so our laptop will be the GUI. Power will be constantly supplied through our system. We can ensure this with impedance matching. Since the impedance is matched, it will create a channel which will allow a consistent amount of power to be supplied throughout the whole system.

III. Updated Preliminary Design

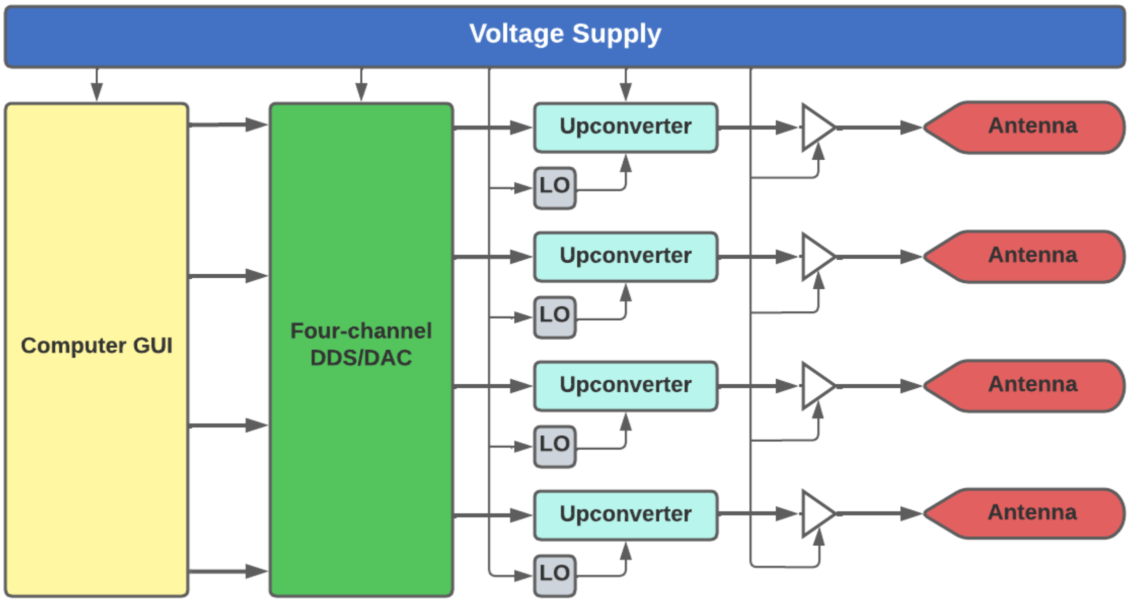


Figure 7. Project Block Diagram

Design Revisions: The team had to make the executive decision to eliminate the FPGA from our design. This is due to multiple reasons. The team had issues implementing the SPI and reference clock. This created issues that would have taken a lot of time to debug. The evaluation software that came with the DDS simplifies our design. There is no reason we need the FPGA in the first place, we were just implementing it because it was in the project description. Given our time constraints and the fact that we are trying to get our project to actually work, we decided to eliminate the FPGA from our design. We decided it was more important to have a working design than implement a subsystem that is not needed within our design.

Computer GUI: As previously mentioned, since we eliminated the FPGA from our design, we are now taking advantage of the evaluation software that came with the DDS. Using the software, you can control the reference clock and the initial pre-amplified signal. You can then enter the phase offset you want to achieve in the software. We are able to steer the transmitted signal through the evaluation software.

Voltage Supply: As previously stated, there will be various power supplies throughout our design. The DDS will be powered through a 3 V and a 1.8 V voltage supply. We will also use a DC power supply to power the PCB. We will take advantage of the USB connection of the DDS and connect it to our laptops, so our laptop will be the GUI. Power will be constantly supplied through our system. We can ensure this with impedance matching. Since the impedance is matched, it will create a channel which will allow a consistent amount of power to be supplied throughout the whole system.

Four-Channel DDS: The four channel DDS will be an AD9959 development board that consists of four direct digital synthesizers. The board will receive a reference clock signal from the DDS evaluation software that will dictate the amplitude of the base signal the four DDSs will use. Each DDS channel will have a separate input signal that will correspond with the required phase delay needed for each signal. The module will output four signals that will need to be amplified before being input into the antennas.

AD9959/PCBZ

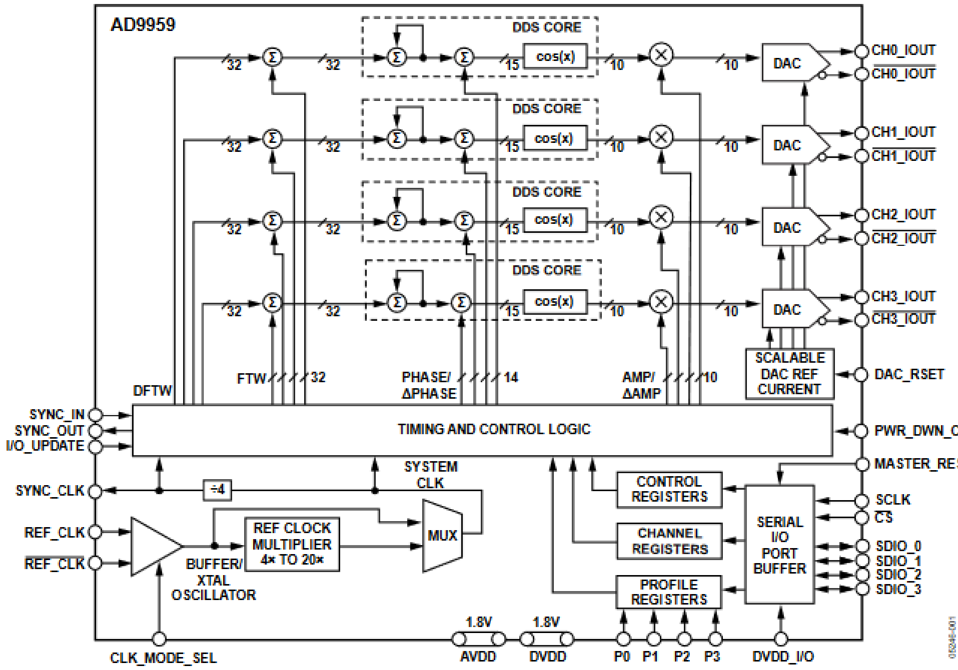


Figure 8. DDS Detailed Block Diagram

Up Converter: The upconverter will be a mixer that will combine the frequency of the signals from the DDSs with the frequency of a signal supplied by a local oscillator to reach the desired frequency.

Local Oscillator (LO): The local oscillator will be used to add the signal with the required frequency to the mixer/ upconverter. A voltage supply will supply the required input power.

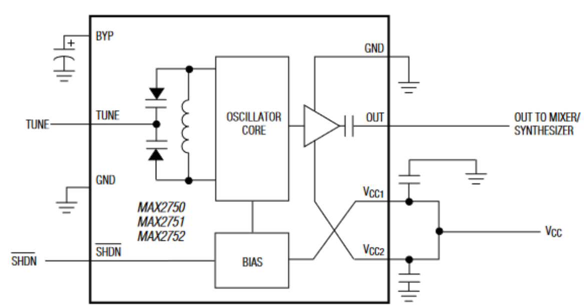


Figure 9. Local Oscillator Block Diagram

Amplifier Gain: A gain amplifier will be used to add power to the signal before inputting into the antenna. Power should be <30dBm.

Antenna: Four 2.4GHz patch antennas will be used. The antennas will be spaced 0.5 wavelength apart, which is about 2.46 inches from center at 2.4GHz. Since our functional decomposition we have decided to move away from using omnidirectional antennas to using directional patch antennas. Omnidirectional antennas would provide a second beam which is not needed for the purposes of this project. Directional patch antennas will be simpler to implement.

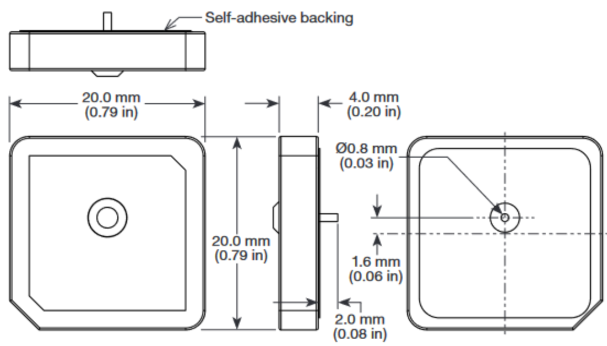
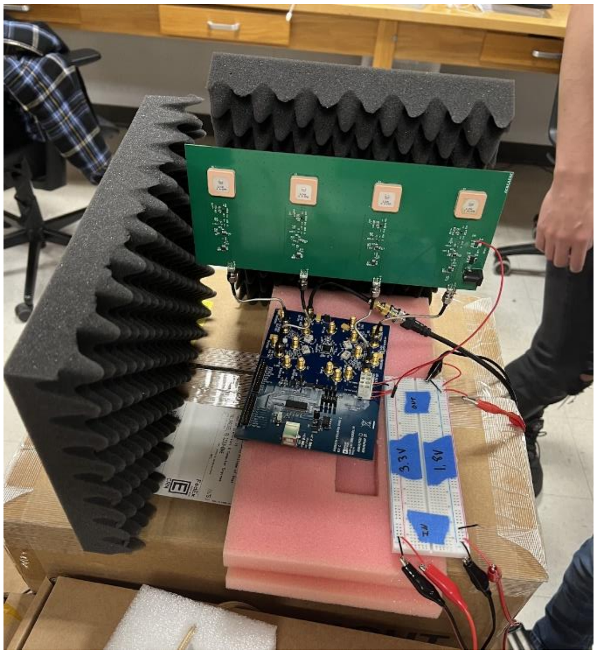


Figure 10. Antenna Block Diagram

PCB: A PCB designed by the team will be used to implement the mixing and amplification of the output signal from the DDS. The PCB will consist of upconverters, local oscillators, amplifiers, voltage regulators and antennas. One of each of these components will be arranged in four circuits, one for each of the four antennas. Between each of these components will be an impedance matching network that will regulate the impedance to the 50 Ohms required for RF signals.

V. Summary

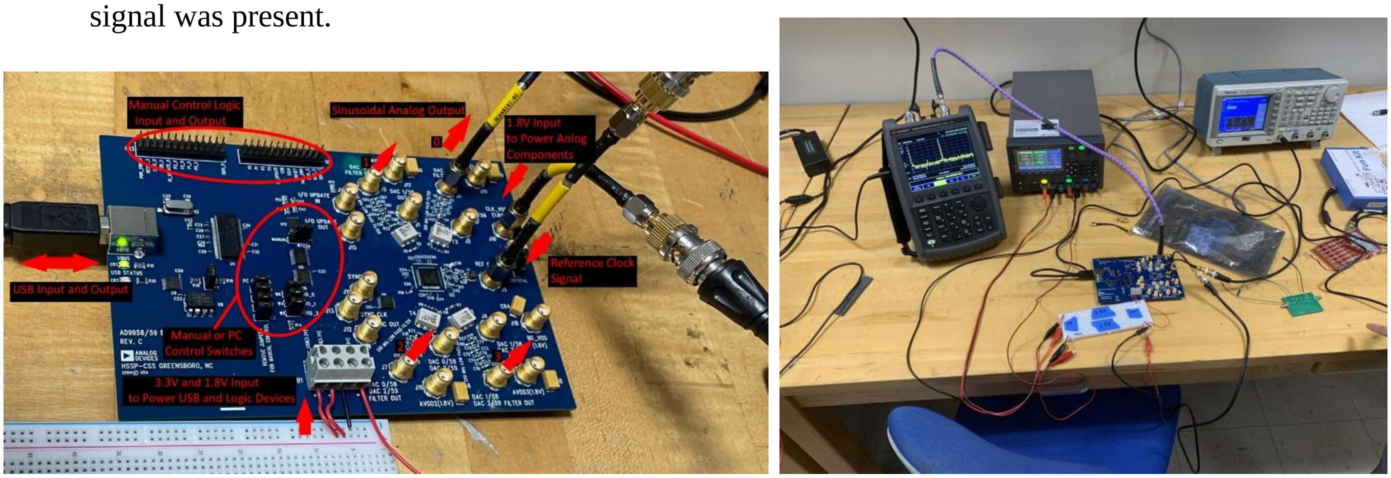
The team has selected a digital system for the project. A brief breakdown of the components for the system: The DDS evaluation software generates the clock cycles and the phase delays required for the DDS to correctly generate four signals that are offset in a way that the beam points in the direction the user intended. The upconverter takes the input from the software, generates the offset signals, and then converts them from digital signals to analog ones. The mixer takes the output from the DDS and the output of a local oscillator and combines them to create the designated frequency (around 2.4 GHz). The signal out of the DDS is then fed into an amplifier that adjusts the output power so that it is acceptable for the antenna. The antenna outputs the voltage-based signal into a radio signal.



Final Assembled Design

2.3 Results

<u>DDS Testing:</u> The goal of testing the DDS was to ensure that the 200 MHz signal was present. After testing the DDS through the evaluation software, the team could ensure the 200 MHz signal was present.



DDS Test Assembly

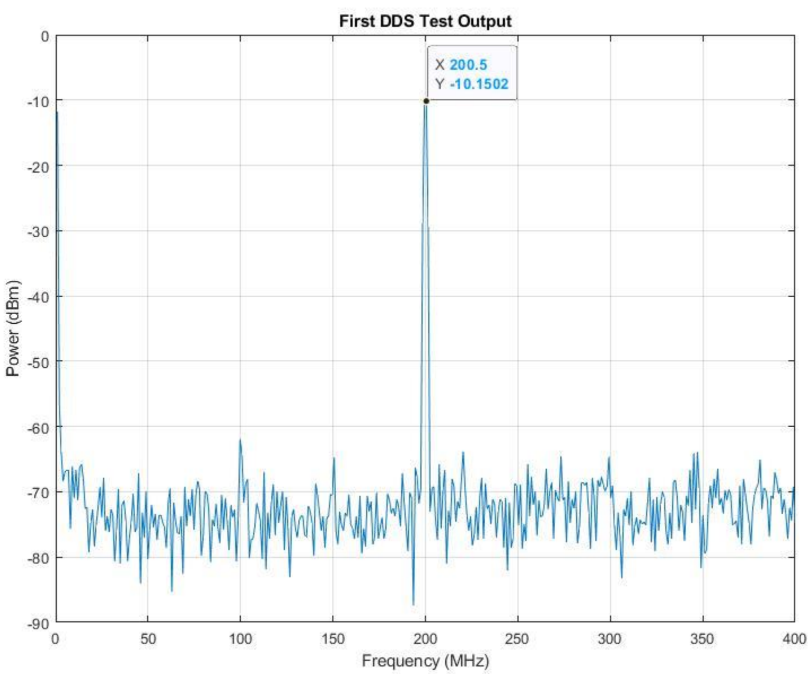
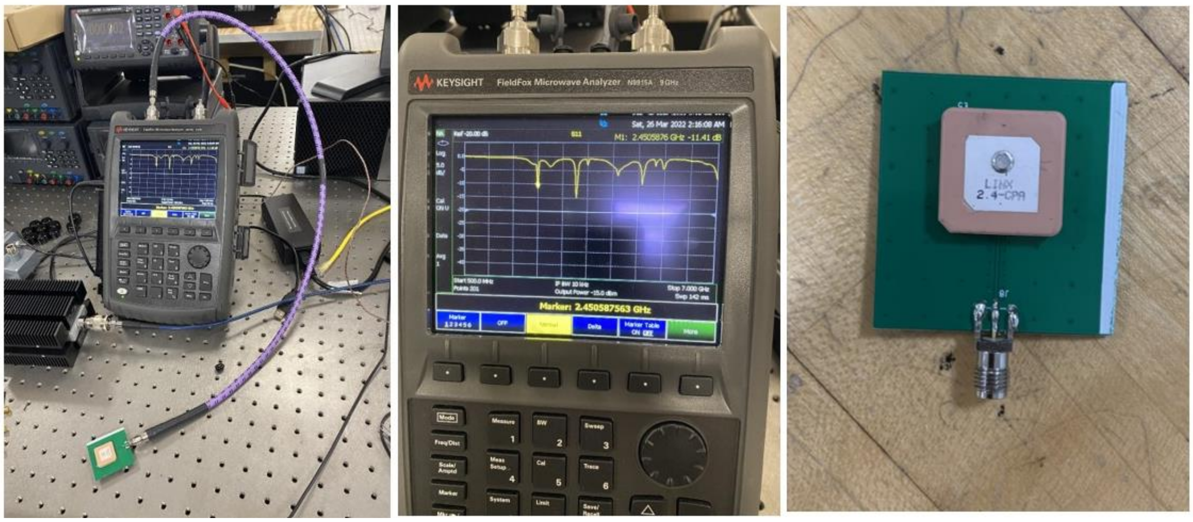


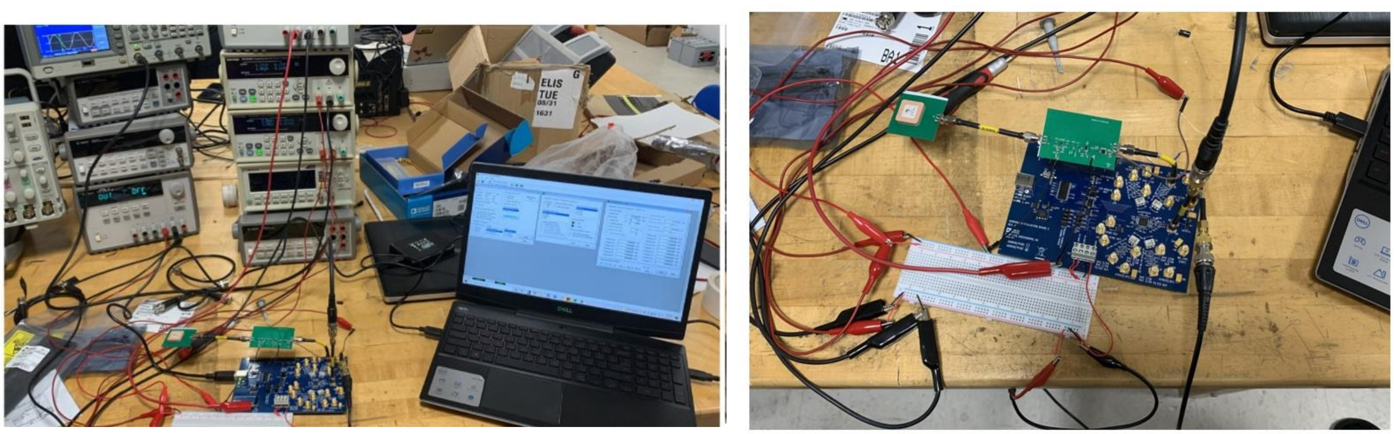
Figure 11. DDS Test Output Data

Antenna Testing: After separating the test cutout from the main PCB board. The team could then perform antenna testing. At the center frequency of 2.4 GHz, the return loss is -11.41 dB.

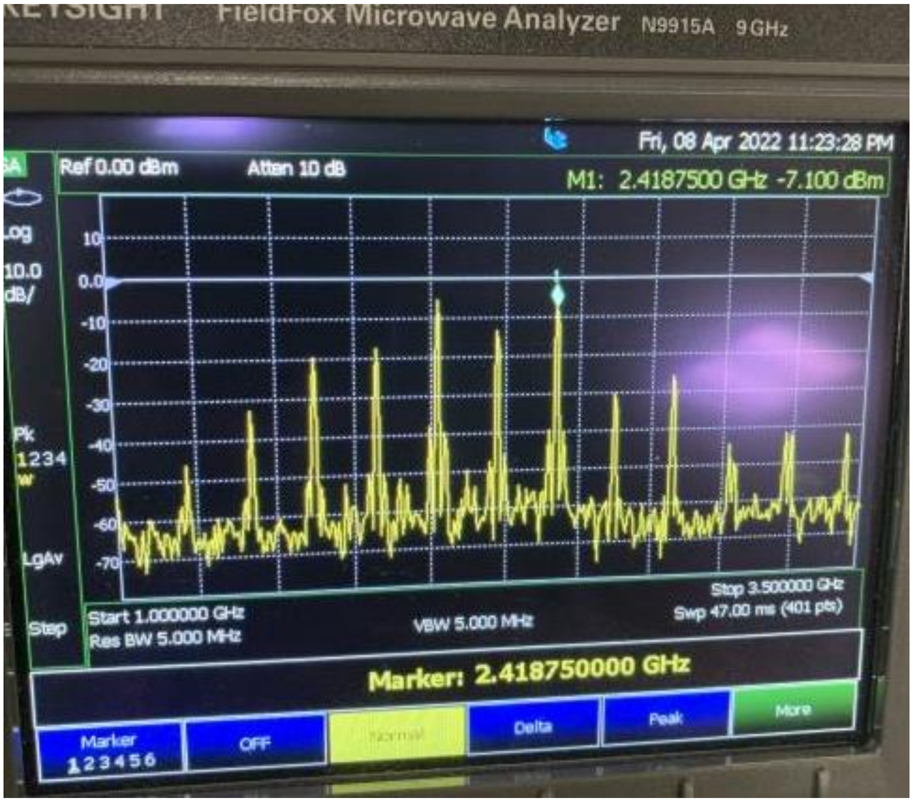


Antenna Testing Setup and Data

Cutout with all other components: The other components test cutout contained all tiny soldering components. After hooking it up to the DDS and testing the output signal power, we received 3 dBm, which is exactly what we were hoping for.

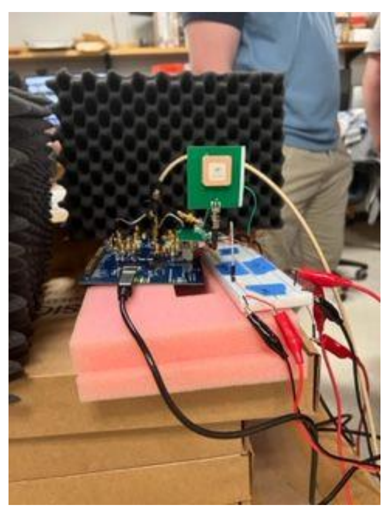


Component Test Cutout Test Setup



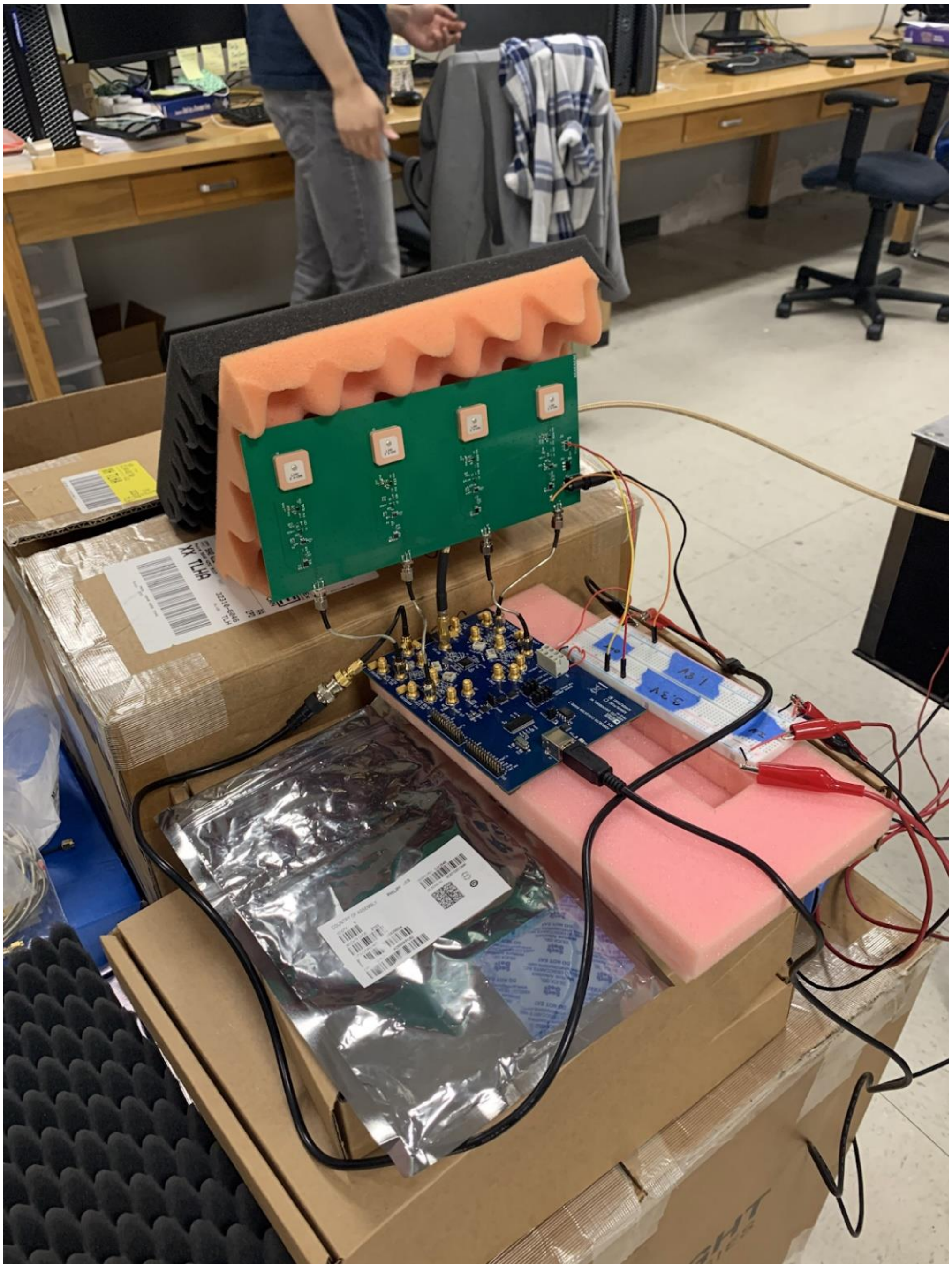
Data for Component Test Cutout

Single Channel Testing: The team next tested the test cutouts at a channel to make sure it is properly transmitting the 2.4 GHz signal. The single channel was indeed transmitting a 2.4 GHz signal at around -42 dBm.



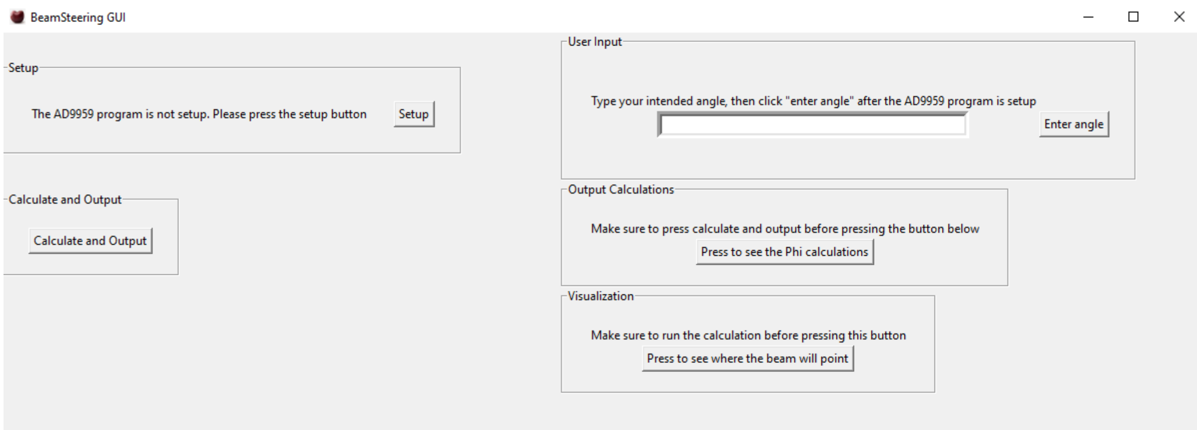
Single Channel Setup & Data

Final Testing:



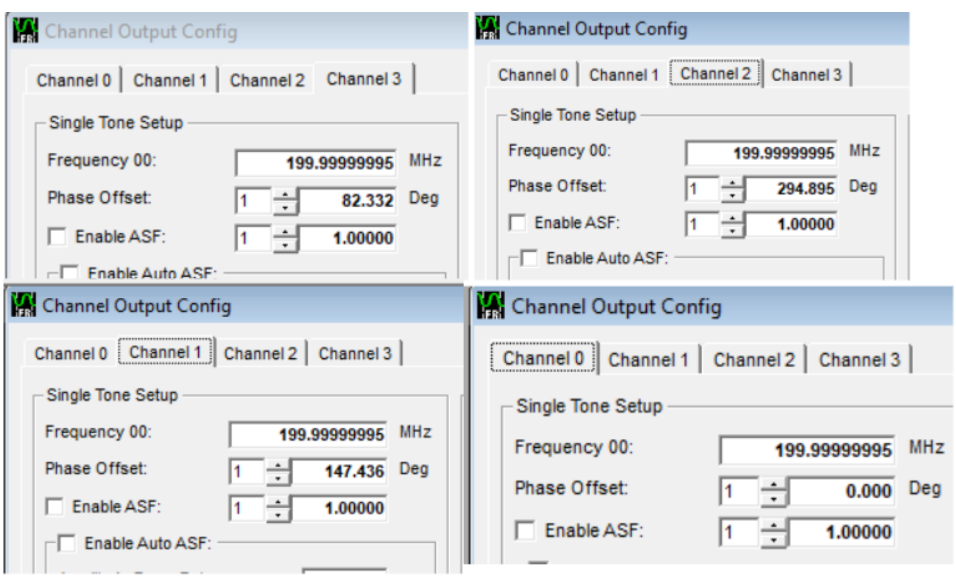
Final Testing Setup

Receiving Antenna

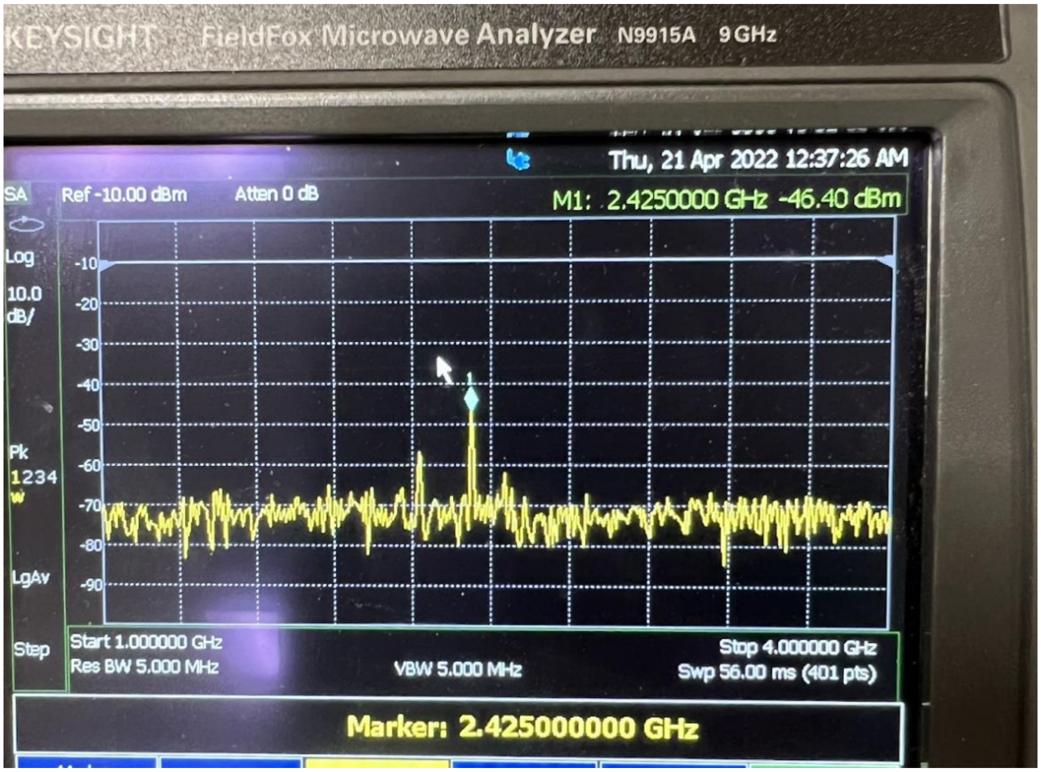


Final Design Beamsteering GUI

To start the testing, the AD9959 evaluation software needs to be setup. After the setup is complete you will receive a message The user is then able to enter the desired angle. If the desired angle is not within the given range, an error message will pop up. Once the appropriate angle is selected, clicking calculate will result in the output. The program calculates the phase offsets required for each of the channels and the program will automatically type them into the DDS GUI.



Phase Offset for Each Channel



Obtained Results for Antenna Array

Only two of the four channels were operational. This was enough to perform beamsteering, but the beam was not able to be steered because the device had not been calibrated due to time constraints. The receiving antenna was not directly in front of the transmitting antenna array when the phase offset for all the antennas were set to zero, meaning that at least two antennas were operational, but were not properly calibrated.

2.4 Discussion

The first component that was tested was the AD9959 Evaluation Board to ensure that the signal output matched the specifications needed for the MAX2260 Upconverter Mixer. Figure 11 shows the output power (P_{IFIN}) of the AD9959 to be -10 dBm at 200.5 MHz. With the -10 dBm input, the mixer experiences almost 0 dB conversion gain and an output power of -10 dBm. The mixer also utilizes the -3dBm 2.2GHz output from the MAX2751 VCO as an input for the mixer's required local oscillator (LO) input signal. The signals then mix to achieve a dual-banded output of -10 dBm at 2 GHz and 2.4 GHz. After the up conversion, the dual-banded signal is sent to the GRF2201 amplifier which increases the signal power by 20 dB. This means our -10 dBm output from the mixer should be increased to 10 dBm after the amplifier.

The data for the component test cutout shows the measured single-channel output. The signal at 2 GHz and 2.4 GHz have the highest power, with the 2.4 GHz signal being at -7 dBm with a 10 dB attenuator attached to the output. The attenuator was used to ensure the output did not damage the frequency analyzer. This means our actual output before the antenna is 3 dBm. This was lower than the expected result of 10 dBm. This loss is mostly caused by the inductors, capacitors, and resistors that are used for impedance matching but it is also possible that we were experiencing a gain less than 20 dB from the amplifier. The figure also shows signals at various unused frequencies due to signal reflections that were likely caused by the VCO, mixer, imperfect solder connections, and imperfect impedance matching.

The 3 dBm signal is then sent to the ANT-2.4-CPA antenna which then transmits the signal to an identical receiving antenna. The antenna also filters out the unneeded harmonics for it will only transmit the 2.4 GHz signal. It can be seen in single channel setup and data that the power received at the receiving antenna was -42.56 dBm.

After testing the output of the test circuit to ensure it was properly designed, the 4-channel array was soldered together and then tested. The final test of the 4-channel phased array is shown in the obtained results for the antenna array. This shows a received power of -46.40 dBm at 2.425 GHz. This is much lower than the expected result calculated using the Friis transmission equation of -31.92 dBm. Much of this error is the result of only getting two out of four channels on the circuit to work. The two inoperable channels are likely due to shorted or floating connections on the amplifiers. Other errors could be that the four signals are not in the proper phase to add constructively and create the stronger beam. If the signals are not in phase the beam could be pointing in an undesired direction or the signals could be adding deconstructivity and create a weaker signal.

2.5 Conclusions

Overall, the team has learned a great amount about RF throughout this experience. The team started with minimal knowledge on the subject of RF, PCB design and designing a circuit using commercial parts such as the voltage-controlled oscillator, amplifier and mixer. For the first time, the team had to make practical choices based on specification sheets and this would not have been possible without the help of Dr. Arigong and PHD students. However, throughout the design and overcoming a lack of knowledge, we were able to deliver a successful circuit that upconverted from 200 MHz to 2.4 GHz and had a strong signal of 3 dBm. The four-channel array, which would be the final product, would have been successful if the team had more time and experience on soldering. There were many lessons learned, especially on the PCB side, such as the need for more testing. One such play would be an SMA connector before it went into the antenna, as well as a switch to act as a breaker so that the team could test each individual channel. On the soldering side, it would have simplified the soldering experience massively had we ordered a PCB stencil with the PCB board. On the software side, we also learned that it would have been much easier to use SPI to feed the DDS values using a MCU instead of the FPGA, which we attempted for the majority of the year. This project was definitely a learning experience and served as a brief peek into the life of an engineer.

2.6 Future Work

This project should be operational without the use of a laptop or computer. Our team would recommend the use of a microcontroller over an FPGA because the FPGA is more difficult to work with. If in the future an FPGA is used please see the below diagram:

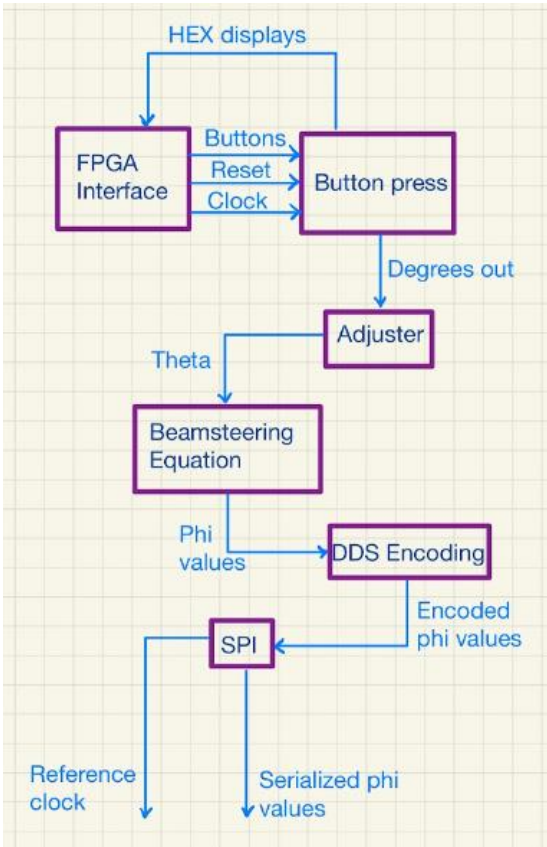


Figure 12. Software Block Diagram

This is a suggested component flow diagram for the FPGA. To make the design easier for the user do not make the user pick the theta value instead let them pick a user intended angle like shown below.

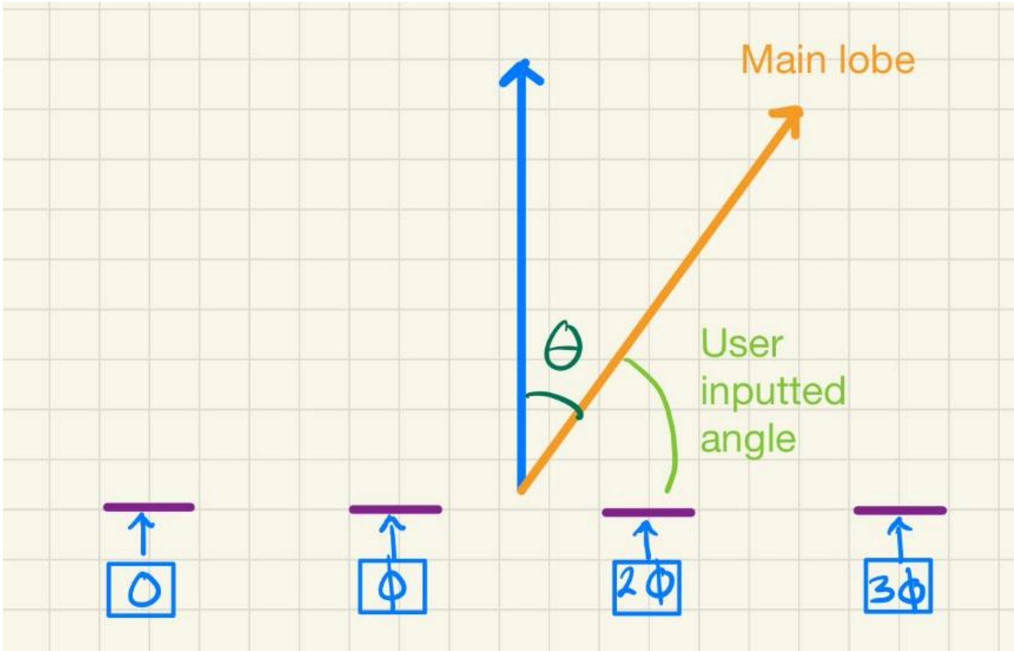


Figure 13. Beamsteering Phase Shift Representation

That means you are going to have to find the theta value. That is what the adjuster component is for. The theta value is then given to the beamsteering equation component. This component has been designed, although it is not optimized. The VHDL code can be found on this github:

https://github.com/NaniMoh/FSU-Team-311-BeamSteering

The DDS encoder changes the output of the beamsteering equation component into a format that the DDS can read. This will depend on the resolution of the DDS. The SPI block serializes the binary representation that the DDS can read and sends the inputs one by one (serially).

There is also the code for the master SPI communication provided by NANDLAND:

https://github.com/nandland/spi-master/blob/master/VHDL/source/SPI_Master.vhd

This code has an error where you have to buffer one of the signals. You will see the signal when you run the code. There is also a video where he explains how the code works.

After coding the microcontroller or VHDL, the next team needs to make sure how to configure the DDS. The information is given in the AD9959 data sheet. It is important to get help on this portion of the project because it is very difficult to figure out, debug, and test.

The next team should take the PCB designed by our group and try to create traces that allow for SMA connectors between circuits (upconverter and amplifier) to test the intermediate signals. The team had added test pads between circuits, but that is not testable for the frequency of 2.4 GHz range. The SMA connectors are vital for testing within RF. This frequency range also requires a 50-ohm matching impedance. Make sure that the traces follow this requirement.

Please check the zip file for the PCB design.

Appendix A: Codes and Standards

ISM Frequency Band:

The team will adhere to the ISM Frequency Band, specifically in the 2400 - 2500 MHz range, as defined by the ITU Radio Regulation (article 5) in footnotes 5.138, 5.150, and 5.280 of the Radio Regulations. The ISM frequency band is a set of RF frequencies set aside for any purpose outside of telecommunications. It is important to stay within our range of 2400 - 2500 MHz so as to not interfere with any telecommunications systems. To operate outside of the designated ISM bands would mean a license is required. The antennas we have are rated at 2.4Ghz, which is within the ISM band we are targeting.

Referencing: IEEE 1076-2019 - IEEE Standard for VHDL Language Reference Manual:

When programming the Altera FPGA, the team will closely adhere to the VHDL language standards set by the IEEE. These standards are not in place for safety reasons, but for readability of the code. The team will strive to adhere to these standards in case the code is to be read by other electrical or computer engineers in the future. The standards for VHDL are extensive, so the IEEE 1076-2019 - IEEE Standard for VHDL Language Reference Manual will be referred to periodically as the VHDL code is being written.

Soldering Standard IPC J-STD-001:

While soldering components to the PCB, the team will adhere to the soldering standards from IPC J-STD-001. The workspace will remain clean to prevent the contamination of materials, tools, and surfaces. The heating and cooling rates will be equivalent to the manufacturer's instructions for each component. Strands of wires will not be damaged or exposed. The solder will cover the entire tinned area of the wire. Soldering and cleanliness inspections will be conducted between each successful component soldering. If any defects may occur during soldering, the errors will be removed and re-soldered before moving on to the next component. The quality of the soldering job will meet the required specifications, shown in the images below.

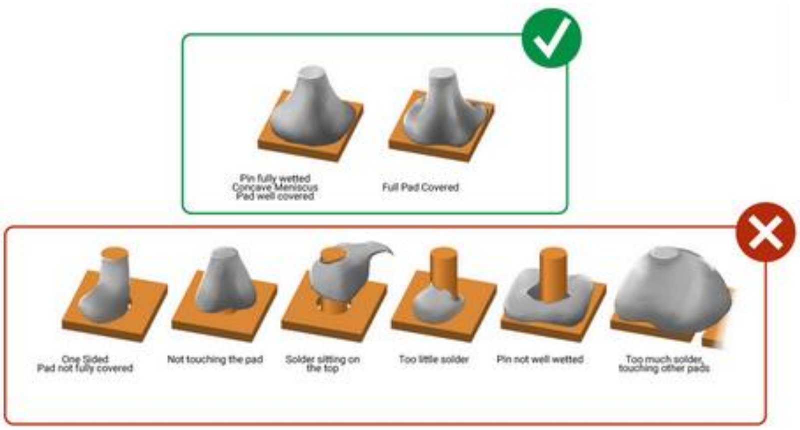


Figure 14. Proper Solder Surface Area

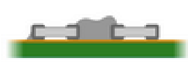
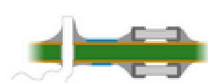
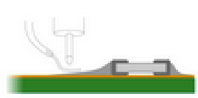
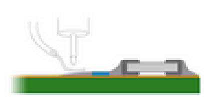
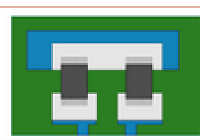
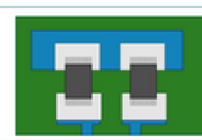
Item	Poor Example	Recommended example /Separated by solder resist
Multiple parts mount		
Mount with leaded parts		
Wire soldering after mounting		
Over view		

Table 17 *Solder Do's and Don'ts*

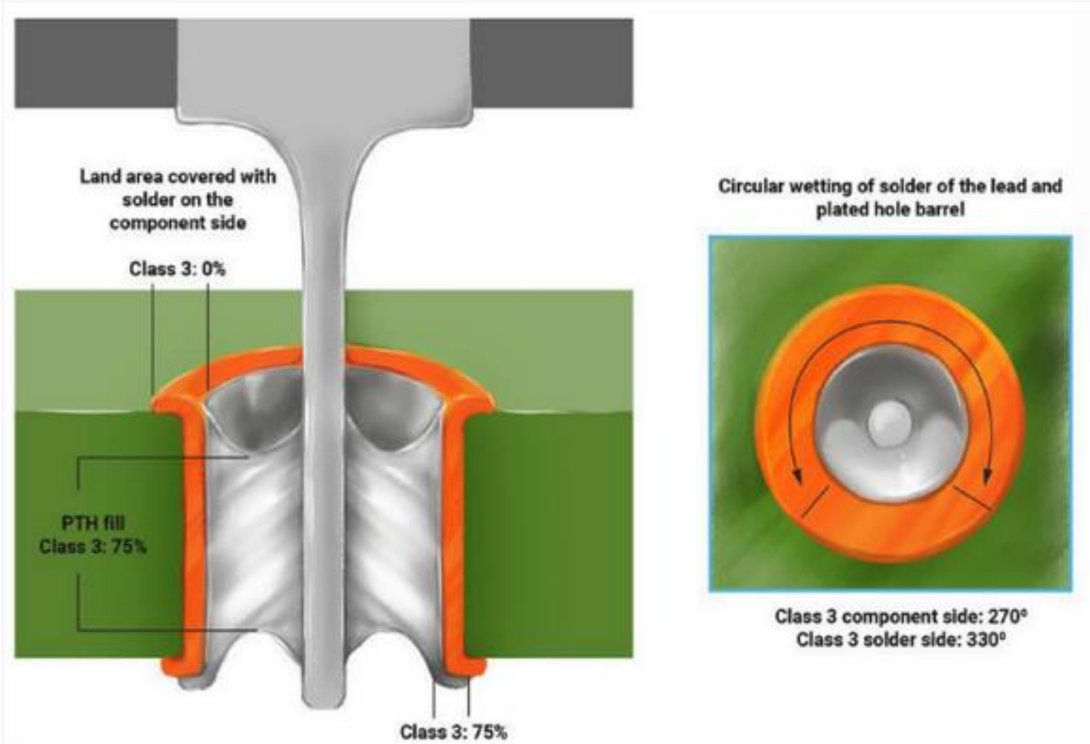


Figure 15. Thorough Soldering Job

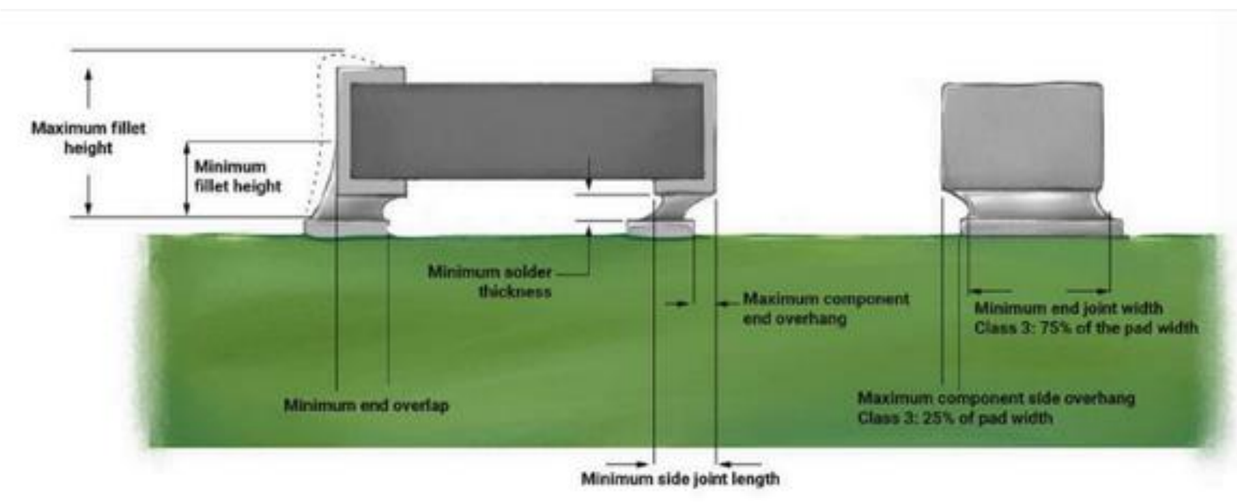


Figure 16. Finished Soldering Product

Appendix B: Code of Conduct

Mission Statement:

Team 311 is committed to ensuring a positive work environment that supports professionalism, integrity, respect, and trust. Every member of this team will contribute a full effort to the creation and maintenance of such an environment in order to bring out the best in all of us as well as this project.

Roles:

Each team member is delegated a specific role based on their experience and skill sets and is responsible for all here-within:

Team members:

Team Leader – Tiernen Pan

Manages the team as a whole; develops a plan and timeline for the project, delegates tasks among group member according to their skill sets; finalizes all documents and provides input on other positions where needed. Promotes synergy and increased teamwork. If a problem arises, Tiernen will act in the best interest of the project. He keeps the communication flowing, both between team members and Sponsor. Tiernen will take the lead in organizing, planning, and setting up meetings. In addition, he is responsible for keeping a record of all correspondence between the group and 'minutes' for the meetings. Finally he gives or facilitates presentations by individual team members and is responsible for overall project plans and progress.

Financial Advisor – Katheryn Potemken

Manages the budget and maintains a record of all credits and debits to project account. Any product or expenditure requests will be presented to the advisor, who is then responsible for reviewing and the analysis of equivalent/alternate solutions. She then will relay the information to the team and if the request is granted, order the selection. A record of these analyses and budget adjustments will be kept.

Software Lead – Christian Balos

Takes charge of the software aspects of the project. He is responsible for knowing details of the software design and presenting the options for each aspect to the team for the decision process. Keeps all design documentation for record and is responsible for gathering all reports.

Hardware Lead – Andrew Cayson

Takes charge of the hardware aspects of the project. He is responsible for knowing details of the hardware design along with each required component. Keeps all design documentation for record and is responsible for gathering all reports.

Hardware Integration Lead – Billy Snyder

Takes charge of the hardware integration aspects of the project. He is responsible for finding the best options for the hardware needed for the project. He will take charge in reading spec and datasheets for our team to make the most efficient decisions when purchasing hardware. Keeps all design documentation for record and is responsible for gathering all reports

All Team Members:

- Work on certain tasks of the project
- Buys into the project goals and success
- Delivers on commitments
- Adopt team spirit
- Listen and contribute constructively
- Be effective in trying to get messages across
- Be open minded to others' ideas
- Respect other roles and ideas
- Be ambassador to the outside world in own tasks

<u>Communication:</u>

The main form of communication will be through our discord group chat. Each member is an active user of discord, for this is the best form of communication to contact the team immediately. Email will be a secondary form of communication for issues not being time-sensitive. For the passing of information, i.e. files and presentations, email will be the main form of file transfer and proliferation.

Members must check their emails at least twice a day to check for important information and updates from the group. Although members will be initially informed through discord about meeting dates and pertinent information from the sponsor, emails will additionally be sent so it is very important that each group member checks their email frequently.

If a meeting must be canceled, an email must be sent to the group at least 24 hours in advance.

Any team member that cannot attend a meeting must give advance notice of 24 hours informing the group of his absence. Reason for absence will be appreciated but not required if personal. Repeated absences in violation with this agreement will not be tolerated.

Team Dynamics:

The students will work as a team while allowing one another to feel free to make any suggestions or constructive criticisms without fear of being ridiculed and/or embarrassed. If any member on this team finds a task to be too difficult it is expected that the member should ask for help from the other teammates. If any member of the team feels they are not being respected or taken seriously, that member must bring it to the attention of the team in order for the issue to be resolved. We will NOT let emotions dictate our actions. Everything done is for the benefit of the project and together everyone achieves more.

Ethics:

Team members are required to be familiar with the NSPE Engineering Code of ethics as they are responsible for their obligations to the public, the client, the employer, and the profession. There will be stringent following of the NSPE Engineering Code of Ethics.

Dress Code:

Team meetings will be held in casual attire. Sponsor meetings and group presentations will be business casual to formal as decided by the team per the event.

Weekly and Biweekly Tasks:

Team members will participate in all meetings with the adviser and instructor. Team members will meet weekly and meet with the advisor biweekly. They will also meet with the instructor as needed. During said times ideas, project progress, budget, conflicts, timelines and due dates will be discussed. In addition, tasks will be delegated to team members during these meetings. Repeat absences will not be tolerated.

Decision Making:

It is conducted by consensus and majority of the team members. Should ethical/moral reasons be cited for dissenting reason, then the ethics/morals shall be evaluated as a group and the majority will decide on the plan of action. Individuals with conflicts of interest should not participate in decision-making processes but do not need to announce said conflict. It is up to each individual to act ethically and for the interests of the group and the goals of the project. Achieving the goal of the project will be the top priority for each group member. Below are the steps to be followed for each decision-making process:

- Problem Definition – Define the problem and understand it. Discuss among the group.
- Tentative Solutions – Brainstorms possible solutions. Discuss among group most plausible.
- Data/History Gathering and Analyses – Gather necessary data required for implementing Tentative Solution. Re-evaluate Tentative Solution for plausibility and effectiveness.
- Design – Design the Tentative Solution product and construct it. Re-evaluate for plausibility and effectiveness.
- Test and Simulation/Observation – Test design for Tentative Solution and gather data. Re-evaluate for plausibility and effectiveness.
- Final Evaluation – Evaluate the testing phase and determine its level of success. Decide if design can be improved and if time/budget allows for it.

Conflict Resolution:

In the event of discord amongst team members the following steps shall be respectfully employed:

- Communication of points of interest from both parties which may include demonstration of active listening by both parties through paraphrasing or other tools acknowledging a clear understanding.
- Administration of a vote, if needed, favoring majority rule.
- Team Leader intervention.
- Instructor will facilitate the resolution of conflicts.

Project Description:

An array of antennas will be used to create a transmitter that utilizes beamsteering within the ISM band. The ISM band is a designated frequency band that the Industrial, Scientific, and medical community are allowed to operate in. The beam steered transmitter should be able to focus radio waves at a specified direction done through an algorithm that controls the phase for each of the signals. This would be done by having a microcontroller that allows the user to pick the direction of the beam. The microcontroller will then feed its outputs into the FPGA which will do the calculations. It will calculate the special delay that is needed for each of the signals to direct the beam in a particular direction. The FPGA's output will be fed into the Direct Digital Synthesizer (DDS). The DDS will create the signals and apply the special delays that the FPGA calculated. The DDS has four output signals, one for each antenna. The output of the DDS will not be in the correct frequency band, so the output of the DDS will need to go into a mixer. The mixer's output will retain the same information that the DDS is trying to output but bump the frequency up to the required ISM band. The four signals will then be sent to the array of antennas.

Key Goals:

- Convert four digital signals to four analog signals
- Control phase shift of each channel to adjust propagation direction
- Increase signal frequency to 2.4 GHz by mixing 200.3 MHz DDS output with 2.2 GHz oscillator output
- Increase gain of each signal to ensure a strong signal
- Create a four-antenna linear array to propagate signal in direction specified by changing the phase shift of each signal

Market:

Beam steering antenna arrays are used in a variety of applications. With L3Harris as our team's sponsor, it is anticipated that the project will be used in military applications, such as, radar and anti-jamming. However, there are many other civilian applications where beam steering can be used, such as, 5G/LTE communication systems, ultrasounds, light detection for ranging purposes (lidar), and satellite to ground communications.

Assumptions:

It is assumed that the final signal from the system is within the ISM band (6.765 ~ 6.795MHz, 13.553~13.567MHz, 26.957~27.283MHz, 40.660~40.700MHz, 430.050 ~ 434.790MHz, 868 ~ 870 MHz, 888 ~ 889MHz, 902 ~ 928 MHz, 2.4 ~ 2.483GHz). It is also assumed that the parts will not require the manufacturing of a PCB board and are easily integratable. The final product is assumed to have 4 antennas integrated with a 4-channel digital baseband.

Stakeholders:

- Advisor: Dr. Uwe Meyer-Baese
- Sponsor: L3Harris
- Sponsor Substitute/Customer: Dr. Jerris Hooker
- Faculty Consultant: Dr. Bayaner Arigong

Attendance Policy:

Attendance is mandatory, whether through virtual applications or in-person. Attendance will be managed by Christian Balos using an Excel Spreadsheet. In addition, reminders of meetings will be sent 2 hours in advance. If a person is absent during a virtual meeting, the virtual host will record the meeting in Zoom and is expected of the absentee to view the missed meeting by the next meeting.

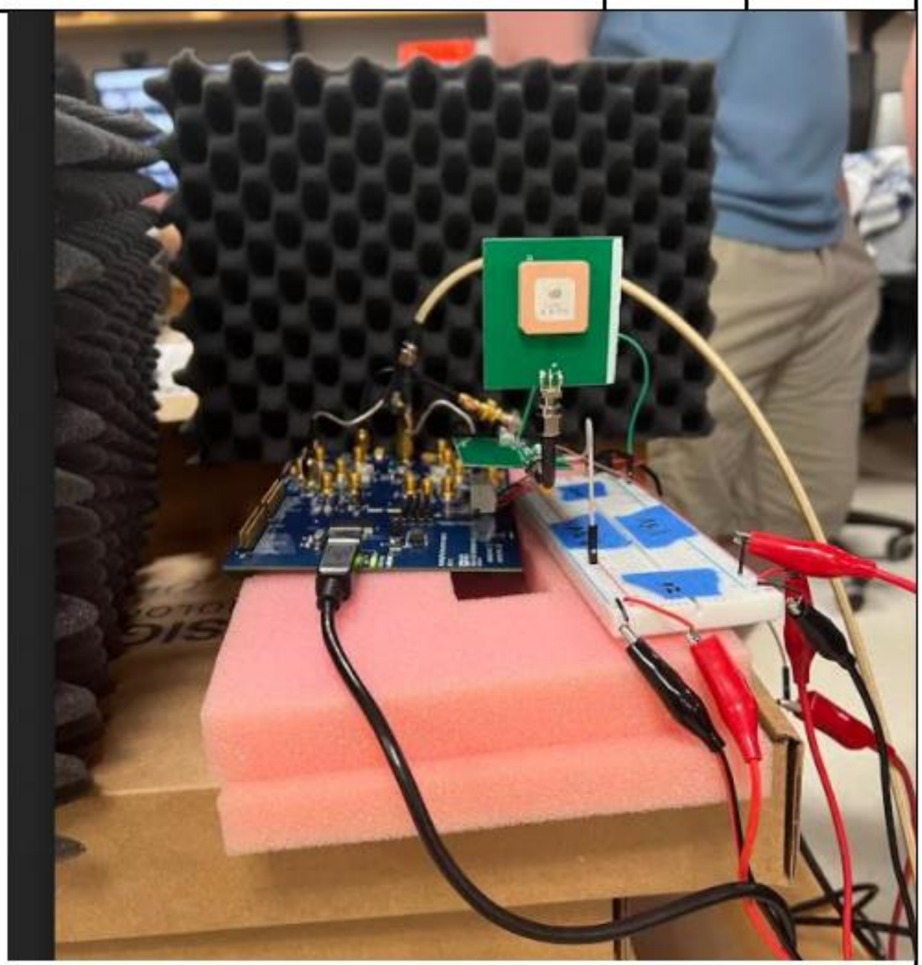
Statement of Understanding:

By signing this document, the members of Team 311 agree to all of the above and will abide by the code of conduct set forth by the group.

Name & Date	Signature
Katheryn Potemken 01/19/2022	DocuSigned by: Katheryn Potemken
Christian Balos 01/19/2022	DocuSigned by: [illegible]
Tiernen Pan 01/19/2022	DocuSigned by: Tiernen P
Andrew Cayson 01/19/2022	DocuSigned by: Andrew Cayson
William Snyder 01/19/2022	DocuSigned by: William D Snyder

Appendix C: Target Catalog

<u>Testing Sheet:</u>

Test Writer: Katheryn Potemken			
Test Case Name	Subsystem testing	Test ID #:	N/A
Description	We tested each subsystem of our project.	Type	N/A
Tester Information			
Name of Tester	Team 311	Date	04/17/22
Hardware/Software Ver.	Both	Time	Many times
Setup			

Step	Actions	Expected Results	Pass	Fail	N/A	Comments
1	DDS testing	200 MHz outputted signal	Yes			DDS worked as expected
2	Antenna Testing	-7 dB return loss	Yes			Actual results is - 11.41 dB. This is good.
3	Components Testing	Power is in 0 to 10 dB range	Yes			Power was 3 dB.
4	Single Channel Testing (in picture above)	Successfully transmit 2.4 GHz signal with -38 dB loss.	Yes			We successfully transmit 2.4 GHz signal with -43.33 dB loss.
Overall Test Result We have two channels successfully transmitting on our final design. More testing later this week is to come.						

Team: 311

Code:

Please refer to the github links for full project code:

- https://github.com/NaniMoh/FSU-Team-311-BeamSteering
- https://github.com/nandland/spi-master/blob/master/VHDL/source/SPI_Master.vhd

Appendix D: Engineering Drawings

Parts Propagation:

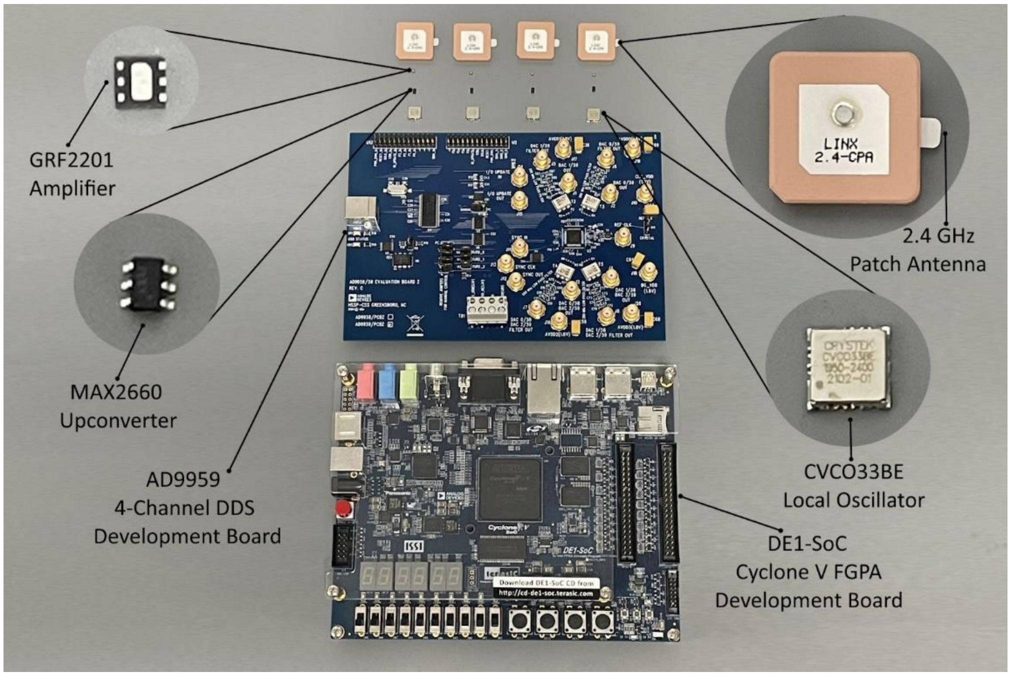


Figure 17. Part Propagation

Block Diagram of VHDL Code:

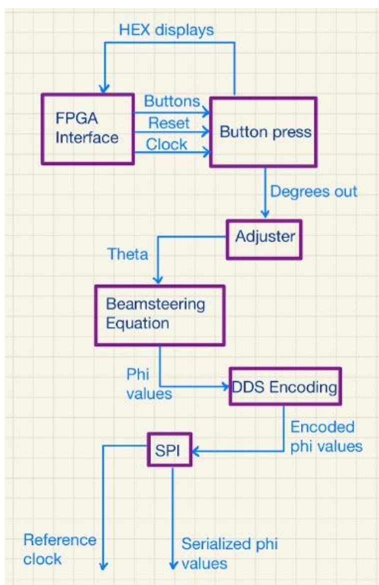


Figure 18. Block Diagram for VHDL Code

Block Diagram for Python Code:

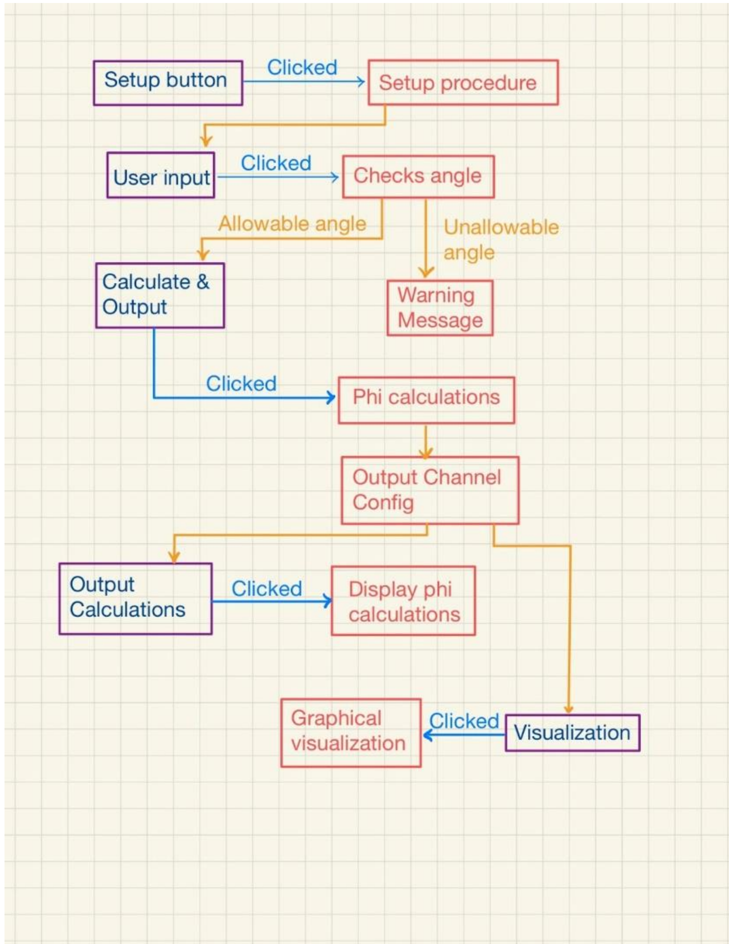


Figure 19. Block Diagram for Python Code

Code diagram and Github: https://github.com/NaniMoh/FSU-Team-311-BeamSteering

Appendix E: Calculations

<u>Expected Power Received:</u>

Friis Equation:

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2$$

$$\lambda = 0.1249135\ meters$$

$$d = 1\ meter$$

$$P_t\ (per\ antenna) = input\ power - loss = 3\ dbm - 11.41\ dB = -8.41\ dBm \rightarrow 0.00014421153515\ watts$$

$$4\ (4\ antennas, so\ ratio\ of\ 4) = 12.0412\ dB$$

$$P_t\ (4\ antennas) = -8.41\ dBm + 12.0412\ dB = 3.6312\ dBm = 0.0023073846546\ Watts$$

$$G_t = G_r = 4.5\ dB = 1.6788040181225603$$

$$P_r = 0.0023073846546\ Watts \times (1.6788)^2 \times \left(\frac{0.1249135\ meters}{4\pi(1\ meter)}\right)^2 = 6.42565 \times 10^{-7}\ Watts$$

$$P_r = -31.920828662\ dBm$$

<u>Beamsteering Equation:</u>

Referencing Figure 11, we are using a distance of lambda (wavelength) divided by two between each antenna because of the performance of using this distance. Below you can see the two commonly used separation distances between antennas.

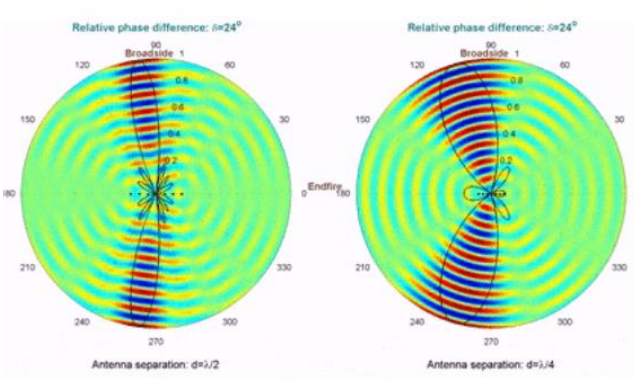


Figure 20. Radiation Pattern for Spacing of d = $\lambda/2$ and d = $\lambda/4$

The left radiation pattern is using an antenna separation of lambda divided by two and the right radiation pattern is using a separation of lambda divided by four. You can see that by using a distance of lambda divided by two (the left radiation pattern) we get a more focused beam. Knowing this we can formulate the beamsteering equation used in the project:

$$d = \frac{\lambda}{2} \qquad \phi = \frac{2\pi}{\lambda} d \times \sin(\theta) \qquad \phi = \frac{2\pi}{\lambda}\frac{\lambda}{2} \times \sin(\theta) \rightarrow \phi = \pi \times \sin(\theta)$$

Note that theta is the angle from the perpendicular to the beam direction and phi are the phase shift factors that are sent to the transmitting device. Looking at the first diagram in this section, we can see that the first antenna (also known as the master antenna) has a phase shift of 0. The second antenna has a phase shift of phi. The third antenna has a phase shift of two times phi and so on. Giving us the general equation of:

$$\gamma_n = (n - 1) \times \phi$$

Where gamma sub n represents the phase that the signal enters the transmitting device and n is the antenna number starting with n = 1.

Appendix F: Risk Assessment

Project Hazard Assessment- Project Narrative

Name of Project: Digital Beamsteering Phased Array		Date of submission: April 1st, 2022
Team member	**Phone number**	**E-mail**
Andrew Cayson	(850) 524-3458	ac12m@my.fsu.edu
Tiernen Pan	(305) 989-7609	tjp17@my.fsu.edu
Christian Balos	(941) 348-4615	cb16t@my.fsu.edu
Katheryn Potemken	(240) 252-8118	kfp18@my.fsu.edu
William Snyder	(904) 570-8928	wjs18b@my.fsu.edu
Faculty mentor	**Phone number**	**E-mail**
Dr. Uwe Meyer-Baese	(850) 410-6220	umb@eng.famu.fsu.edu
Dr. Bayaner Arigong	(850) 410-6410	barigong@eng.famu.fsu.edu

Rewrite the project steps to include all safety measures taken for each step or combination of steps.

1. Soldering
    a. Safety controls are planned by both the worker and supervisor.
    b. A second worker knowledgeable of the task and hazards is in the vicinity (buddy system).
    c. Proceed with supervisor authorization
2. Configuring I/O Ports
    a. Safety controls are planned by both the worker and supervisor.
    b. Proceed with supervisor authorization.
3. Program FPGA to create a clock that feeds into the DDS to create a sinusoidal signal and calculate the phase of slave antennas from the master antenna.
    a. Safety controls are planned by both the worker and supervisor.
    b. Proceed with supervisor authorization.
4. Connecting Hardware Together
    a. Safety controls are planned by both the worker and supervisor.
    b. Proceed with supervisor authorization.
5. Drilling holes in junction box
    a. Safety controls are planned by both the worker and supervisor.
    b. A second worker knowledgeable of the task and hazards is in the vicinity (buddy system).
    c. Proceed with supervisor authorization
6. Testing components using DC power supplies, oscilloscope, spectrum analyzer, etc.
    a. Safety controls are planned by both the worker and supervisor.
    b. A second worker knowledgeable of the task and hazards is in the vicinity (buddy system).
    c. Proceed with supervisor authorization

Thinking about the accidents that have occurred or that you have identified as a risk, describe emergency response procedures to use.

- Always call emergency response for severe accidents.
- Locate the nearest fire extinguisher if a fire breaks out.
- When connecting hardware make sure that there are no active wires and everything is turned off. Only turn on the system when hardware assembling is complete and ready for testing. We will have a buddy system to make sure that everything goes smoothly
- When drilling holes in the junction box keep body parts out of the way of the drill. We will have a buddy system to make sure that everything goes smoothly. Depending on the severity, use a first aid kit or go to the emergency room.
- When soldering make sure not to touch the soldering iron tip, components, or board while it is still hot. If burned the person injured will follow first aid procedures for a minor burn starting with running cool water over the burn. If a severe burn occurs go to the emergency room.

List emergency response contact information:

• Call 911 for injuries, fires or other emergency situations • Call your department representative to report a facility concern

Name	**Phone number**	**Faculty or other COE emergency contact**	**Phone number**
Natalie Cayson	(305) 298-6195	Dr. Bruce Harvey	(850) 410-6451
Allison Fox	(828) 606-0904	Dr. Jerris Hooker	(850) 410-6463
Karly Evans	(407) 761-0823	Dr. Uwe Meyer-Baese	(850) 410-6220
Daniel Murphy	(808) 230-1382	Dr. Oscar Chuy	(850) 410-6468
Safety review signatures			
Team member	**Date**	**Faculty mentor**	**Date**
Andrew Cayson	04/01/22	Dr. Uwe Meyer-Baese	04/01/22
Tiernen Pan	04/01/22	Dr. Bayaner Arigong	04/01/22
Christian Balos	04/01/22	Dr. Jerris Hooker	04/01/22
Katheryn Potemken	04/01/22		
William Snyder	04/01/22		

Report all accidents and near misses to the faculty mentor.

FAMU-FSU College of Engineering

Project Hazard Assessment Policy and Procedures

INTRODUCTION

University laboratories are not without safety hazards. Those circumstances or conditions that might go wrong must be predicted and reasonable control methods must be determined to prevent incident and injury. The FAMU-FSU College of Engineering is committed to achieving and maintaining safety in all levels of work activities.

PROJECT HAZARD ASSESSMENT POLICY

Prior to starting an experiment, laboratory workers must conduct a project hazard assessment (PHA) to identify health, environmental and property hazards and the proper control methods to eliminate, reduce or control those hazards. PI/instructor must review, approve, and sign the written PHA and provide the identified hazard control measures. PI/instructor continually monitor projects to ensure proper controls and safety measures are available, implemented, and followed. PI/instructor are required to reevaluate a project anytime there is a change in scope or scale of a project and at least annually after the initial review.

PROJECT HAZARD ASSESSMENT PROCEDURES

It is FAMU-FSU College of Engineering policy to implement the following:

1. Laboratory workers (i.e. graduate students, undergraduate students, postdoctoral, volunteers, etc.) performing research in FAMU-FSU College of Engineering are required to conduct PHA prior to commencement of an experiment or any project change in order to identify existing or potential hazards and to determine proper measures to control those hazards.
2. PI/instructor must review, approve and sign the written PHA.

3. PI/instructor must ensure all the control methods identified in PHA are available and implemented in the laboratory.
4. In the event laboratory personnel are not following the safety precautions, PI/instructor must take firm actions (e.g. stop the work, set a meeting to discuss potential hazards and consequences, ask personnel to review the safety rules, etc.) to clarify the safety expectations.
5. PI/instructor must document all the incidents/accidents that happened in the laboratory along with the PHA document to ensure that PHA is reviewed/modified to prevent reoccurrence. In the event of PHA modification a revision number should be given to the PHA, so project members know the latest PHA revision they should follow.
6. PI/instructor must ensure that those findings in PHA are communicated with other students working in the same laboratory (affected users).
7. PI/instructor must ensure that approved methods and precautions are being followed by :
    0. Performing periodic laboratory visits to prevent the development of unsafe practice.
    1. Quick review of the safety rules and precautions in the laboratory members meetings.
    2. Assigning a safety representative to assist in implementing the expectations.
    3. Etc.
8. A copy of this PHA must be kept in a binder inside the laboratory or PI/instructor's office (if experiment steps are confidential).

Project Hazard Assessment Worksheet				
PI/instructor: Dr. Bayaner Arigong	Phone #: (850) 410-6410	Dept.: Electrical Engineering	Start Date: August 23rd, 2021	Revision number: 2
Project: Digital Beamsteering Phased Array			Location(s): FAMU-FSU College of Engineering	
Team member(s): Andrew Cayson Tiernen Pan Christian Balos William Snyder Katheryn Potemken			Phone #: (850) 524-3458 (305) 989-7609 (941) 348-4615 (904) 570-8928 (240) 252-8118	Email: ac12m@my.fsu.edu tjp17@my.fsu.edu cb16t@my.fsu.edu wjs18b@my.fsu.edu kfp18@my.fsu.edu

Experiment Steps	Location	Person assigned	Identify hazards or potential failure points	Control method	PPE	List proper methods of hazardous waste disposal, if any.	Residual Risk	Specific rules based on the residual risk
Soldering	Senior Design Lab	Andrew	Risk: burns, inhaling dangerous fumes. Fire hazard Toxic fumes	Don't put a soldering iron tip on anything flammable. Don't breathe fumes.	Ventilator Safety Glasses	Make sure solder is discarded in the proper container.	HAZARD: 3 CONSEQ: Minor Residual: low med	Safety controls are planned by both the worker and supervisor. Proceed with supervisor authorization. A second worker knowledgeable of the task and hazards are in the vicinity (buddy system).
Configuring I/O Ports	Anywhere	Tiernen	Risk: getting aches from sitting at a desk for too long, eyes hurting from looking at screen, Ergonomic Hazard	Take breaks and stretch in intervals. Sit in a good chair.	Blue light glasses (optional). ergonomic chair	N/A	HAZARD: 1 CONSEQ: Negligible Residual: low	Safety controls are planned by both the worker and supervisor. Proceed with supervisor authorization.
Program FPGA to create a clock that feeds into the DDS to create a sinusoidal signal	Anywhere	Christian	Risk: getting aches from sitting at a desk for too long, eyes hurting from looking at screen,	Take breaks and stretch in intervals	Blue light glasses (optional)	N/A	HAZARD: 1 CONSEQ: Negligible	Safety controls are planned by both the worker and supervisor.
and calculate the phase offset the slave antennas from the master antenna.			Ergonomic Hazard				Residual: low	Proceed with supervisor authorization.
Connecting Hardware Together	Senior Design Lab	Katheryn	Risk: getting shocked (but not serious damage). Short circuits Electrical Shock	Double check every connection	Safety Glasses Fire extinguisher	Dispose of ruined components at a proper electronics disposal area.	HAZARD: 2 CONSEQ: Minor Residual: Low	Safety controls are planned by both the worker and supervisor. Proceed with supervisor authorization.
Drilling holes in junction box	Senior Design Lab	Andrew	Risk: Causing injury to body parts with the drill. Being struck by	Has a lot of experiences	Safety goggles & gloves	N/A	HAZARD: 2 CONSEQ: Moderate Residual: Low Med	Safety controls are planned the worker and supervisor. A second worker knowledge the task and hazards is in the (buddy system). Proceed with supervisor authorization.
Testing components using DC power supplies, oscilloscope, spectrum analyzer, etc.	Senior Design Lab	William	Risk: potential shock or inhalation of fumes if a component burns Electrical Shock	Double check connections. Ensure power is off when changing connections	Safety Glasses	Dispose of components at a proper electronics disposal area.	HAZARD: 2 CONSEQ: Minor Residual: Low Med	Safety controls are planned the worker and supervisor. A second worker knowledge the task and hazards is in the (buddy system). Proceed with supervisor author

Principal investigator(s) PHA certification: I certify that I have reviewed and approved the PHA worksheet and will ensure the control measures are available and implemented in the laboratory.

Name	Signature	Date
Oscar Chuy4/1/2022 | 3:21 PM EDT	Oscar Chuy	

Team members' certification: I certify that I have reviewed the PHA worksheet, am aware of the hazards, and will ensure the control measures are followed.

Name	Signature	Date
Andrew Cayson4/1/2022 | 4:16 PM EDT	Andrew Cayson	
Tiernen Pan4/1/2022 | 1:04 PM EDT	Tiernen Pan	
Christian Balos4/4/2022 | 2:02 AM EDT	[illegible]	
William Snyder4/1/2022 | 12:53 PM EDT	William J Snyder	
Katheryn Potemken4/1/2022 | 1:10 PM EDT	[illegible]	

DEFINITIONS:

Hazard: Any situation, object, or behavior that exists, or that can potentially cause ill health, injury, loss or property damage e.g. electricity, chemicals, biohazard materials, sharp objects, noise, wet floor, etc. OSHA defines hazards as "*any source of potential damage, harm or adverse health effects on something or someone".* A list of hazard types and examples are provided in appendix A.

Hazard control: Hazard control refers to workplace measures to eliminate/minimize adverse health effects, injury, loss, and property damage. Hazard control practices are often categorized into the following three groups (priority as listed):

1. **Engineering control:** physical modifications to a process, equipment, or installation of a barrier into a system to minimize worker exposure to a hazard. Examples are ventilation

(fume hood, biological safety cabinet), containment (glove box, sealed containers, barriers), substitution/elimination (consider less hazardous alternative materials), process controls (safety valves, gauges, temperature sensor, regulators, alarms, monitors, electrical grounding and bonding), etc.

2. **Administrative control:** changes in work procedures to reduce exposure and mitigate hazards. Examples are reducing the scale of process (micro-scale experiments), reducing time of personal exposure to process, providing training on proper techniques, writing safety policies, supervision, requesting experts to perform the task, etc.
3. **Personal protective equipment (PPE):** equipment worn to minimize exposure to hazards. Examples are gloves, safety glasses, goggles, steel toe shoes, earplugs or muffs, hard hats, respirators, vests, full body suits, laboratory coats, etc.

Team member(s): Everyone who works on the project (i.e. grads, undergrads, postdocs, etc.). The primary contact must be listed first and provide a phone number and email for contact.

Safety representative: Each laboratory is encouraged to have a safety representative, preferably a graduate student, in order to facilitate the implementation of the safety expectations in the laboratory. Duties include (but are not limited to):

- Act as a point of contact between the laboratory members and the college safety committee members.
- Ensure laboratory members are following the safety rules.
- Conduct periodic safety inspection of the laboratory.
- Schedule laboratories clean up dates with the laboratory members.
- Request for hazardous waste pick up.

Residual Risk: Residual Risk Assessment Matrix is used to determine a project's risk level. The hazard assessment matrix (table 1) and the residual risk assessment matrix (table2) are used to identify the residual risk category.

The instructions to use the hazard assessment matrix (table 1) are listed below:

1. Define the workers familiarity level to perform the task and the complexity of the task.
2. Find the value associated with familiarity/complexity (1 – 5) and enter the value next to: HAZARD on the PHA worksheet.

		Complexity		
		Simple	Moderate	Difficult
Familiarity Level	Very Familiar	1	2	3
	Somewhat Familiar	2	3	4
	Unfamiliar	3	4	5

Table 18 ***Hazard Assessment Matrix***

The instructions to use the residual risk assessment matrix (table 2) are listed below:

1. Identify the row associated with the familiarity/complexity value (1 – 5).
2. Identify the consequences and enter the value next to: CONSEQ on the PHA worksheet. Consequences are determined by defining what will happen in a worst-case scenario if controls fail.

a. Negligible: minor injury resulting in basic first aid treatment that can be provided on site.

b. Minor: minor injury resulting in advanced first aid treatment administered by a physician.

c. Moderate: injuries that require treatment above first aid but do not require hospitalization.

d. Significant: severe injuries requiring hospitalization.

e. Severe: death or permanent disability.

1. Find the residual risk value associated with assessed hazard/consequences: Low –Low Med – Med– Med High – High.
2. Enter value next to: RESIDUAL on the PHA worksheet.

Assessed Hazard Level	**Consequences**				
	Negligible	Minor	Moderate	Significant	Severe
5	Low Med	Medium	Med High	High	High
4	Low	Low Med	Medium	Med High	High
3	Low	Low Med	Medium	Med High	Med High
2	Low	Low Med	Low Med	Medium	Medium
1	Low	Low	Low Med	Low Med	Medium

Table 19 ***Residual Risk Assessment Matrix***

Specific rules for each category of the residual risk:

<u>Low:</u>

- Safety controls are planned by both the worker and supervisor.
- Proceed with supervisor authorization.

<u>Low Med:</u>

- Safety controls are planned by both the worker and supervisor.
- A second worker knowledgeable of the task and hazards is in the vicinity (buddy system).
- Proceed with supervisor authorization.

<u>Med:</u>

- After approval by the PI, the Safety Committee and/or EHS must review and approve the completed PHA.
- A written safety plan is required and must be approved by the PI before proceeding. A copy must be sent to the Safety Committee.
- A second worker must be in place before work can proceed (buddy system).
- Limit the number of authorized workers in the hazard area.

<u>Med High:</u>

- After approval by the PI, the Safety Committee and/or EHS must review and approve the completed PHA.
- A written safety plan is required and must be approved by the PI and the Safety Committee before proceeding.
- Two qualified workers must be in place before work can proceed.
- Limit the number of authorized workers in the hazard area.

High:

- The activity will not be performed. The activity must be redesigned to fall in a lower hazard category.

Type of Hazard	**Example**
Physical hazards	Wet floors, loose electrical cables objects protruding in walkways or doorways
Ergonomic hazards	Lifting heavy objects Stretching the body, twisting the body, poor desk seating
Psychological hazards	Heights, loud sounds, tunnels, bright lights
Environmental hazards	Room temperature, ventilation contaminated air, photocopiers, some office plants acids
Hazardous substances	Alkalis solvents
Biological hazards	Hepatitis B, new strain influenza
Radiation hazards	Electric welding flashes Sunburn

Chemical hazards	Effects on the central nervous system, lungs, digestive system, circulatory system, skin, reproductive system. Short term (acute) effects such as burns, rashes, irritation, feeling unwell, coma and death. Long term (chronic) effects such as mutagenic (affects cell structure), carcinogenic (cancer), teratogenic (reproductive effect), dermatitis of the skin, and occupational asthma and lung damage.
Noise	High levels of industrial noise will cause irritation in the short term, and industrial deafness in the long term
Temperature	Personal comfort is best between temperatures of 16°C and 30°C, better between 21°C and 26°C. Working outside these temperature ranges: may lead to becoming chilled, even hypothermia (deep body cooling) in the colder temperatures, and may lead to dehydration, cramps, heat exhaustion, and hyperthermia (heat stroke) in the warmer temperatures.
Being struck by	This hazard could be a projectile, moving object or material. The health effects could be lacerations, bruising, breaks, eye injuries, and possibly death.
Crushed by	A typical example of this hazard is tractor rollover. Death is usually the result

Entangled by	Becoming entangled in machinery. Effects could be crushing, lacerations, bruising, breaks, amputation and death.
High energy sources	Explosions, high pressure gases, liquids and dusts, fires, electricity and sources such as lasers can all have serious effects on the body, even death.
Vibration	Vibration can affect the human body in the hand with `white-finger' or Raynaud's Syndrome, and the whole body with motion sickness, giddiness, damage to bones and hearing, blood pressure and nervous system problems.
Slips, trips and falls	A very common workplace hazard from tripping on floors, falling off structures or downstairs, and slipping on spills.
Radiation	Radiation can have serious health effects. Skin cancer, other cancers, sterility, birth deformities, blood changes, skin burns, and eye damage are examples.
Physical	Excessive effort, poor posture and repetition can all lead to muscular pain, tendon damage and deterioration to bones and related structures
Psychological	Stress, anxiety, tiredness, poor concentration, headaches, back pain and heart disease can be the health effects
Biological	More common in the health, food and agricultural industries. Effects such as infectious disease, rashes and allergic response.

Table 20 ***Hazard Types and Examples***

References

- C. Fulton, M. Yeary, D. Thompson, J. Lake, A. Mitchell, "Digital Phased Arrays: Challenges and Opportunities," Proceedings of the IEEE, vol. 104, pp. 487-503, March 2016.
- https://www.youtube.com/watch?v=A1n5Hhwtz78
- https://www.youtube.com/watch?v=P-8-v_M7TWM
- https://www.youtube.com/watch?v=HKpQP8H4JRc
- https://www.youtube.com/watch?v=n8_iSL4xKj8

Datasheets:

- https://www.mouser.com/datasheet/2/94/CVCO33BE_1950_2400-2303170.pdf
- https://www.mouser.com/datasheet/2/256/MAX2660-MAX2673-1515397.pdf
- https://www.mouser.com/datasheet/2/777/GRRF_S_A0010122589_1-2575831.pdf
- https://www.mouser.com/datasheet/2/238/LNNC_S_A0009494921_1-2551007.pdf