

B2-Bombers – RF Antenna Design

Final Draft Report – ECE 582

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Executive Summary

1. Introduction

The purpose of this document is to propose the research, design and production of a phased array antenna in fulfillment of the requirements of ECE 582 and ECE 682z. This project requires the creation on an antenna that should be suitable for use in a future Ohio State ECE lab. During ECE 582 the group will research, create a preliminary design and develop a detail specification of the antenna project. During the ECE 682z class, the group will simulate, build, and test the antenna and complete as many iterations necessary to reach the final product.

2. Background and Market Research

Phased array antennas are useful for a variety of applications. The key aspects are the ability to define the directivity and antenna pattern by arraying single elements as well as the ability to redirect the antenna beam by shifting the phase and gain of the array elements. There are two types of phased array antennas; active and passive. Impedance matching will play a large role in the antenna design and manufacture.

3. Additional Requirements Analysis Content and Specifications

While most of the design requirements have been left open to the engineer, it is known that the antenna will operate around 1-2 GHz. The antenna must be able to function in Dreese Lab, act in a passive phased-array model, and perform under matched and unmatched impedance conditions.

4. Design Approach

The design approach will be to develop the initial phased array antenna using the simulation tool HFSS, while considering the requirements, constraints, and various antenna performance parameters. Once a good initial design is reached, the antenna will be built. After it's created,

the antenna will be connected to test equipment and characterized by its impedance and spectral characteristics. After modification of the initial design due to character testing, a final design will be reached. Finally, the final antenna will be documented and presented to the customer Prof Lee.

5. Statement of Work

During 582, research on phased array antennas will be done to generate a set of requirements for our antenna design. The team will work together to determine a suitable design to fulfill the requirements. The team members dedicated to simulating the antenna design will begin work on learning the HFSS program. In 682z, tasks include more in-depth simulation of the design, the physical creation of the antenna at the ElectroScience lab and testing and tweaking of the design to better meet the requirements. The final task will be the creation of the phased array from the designed antenna element. Lastly, beyond 682z the group may optimize the antenna for use as a training aid in an electrical and computer engineering lab course.

6. Resources

The individual responsibilities of the team have been broken up into various small sections. These include the initial design team, simulation and build teams, and a measurement team. The ElectroScience Lab on Kinnear Road will provide the equipment needed.

7. Schedule and Costs

The schedules for ECE 582 and 682 are broken down into specific steps from the proposal to creation of the antenna. Since the ElectroScience Lab at OSU is providing the simulation software as well as the test and fabrication equipment, the only project costs will be associated with the Duroid material set at approximately \$100.

8. Design Review Strategy

The project design flow has followed the description setup in section 4 so far and has stayed on track with our schedule. We have moved through the research and produced a requirements analysis. Also, some preliminary simulations have begun of an antenna design. The next objective is to produce a final design report before moving to tasks defined for ECE 682.

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1. Introduction

1.1 - Purpose

We propose to research, design and produce a passive phased-array antenna suitable to fulfill the ECE 582 and ECE 682z class requirements.

1.2 - Problem Statement

The project requires the design of an antenna to be used in future lab coursework in the Department of Electrical and Computer Engineering. The coursework will relate to the study of radio wave propagation around campus with specific concern in the cellular and wireless networking bandwidths.

1.3 - Scope

A block diagram of the project scope can be seen in Figure 1.3 below.

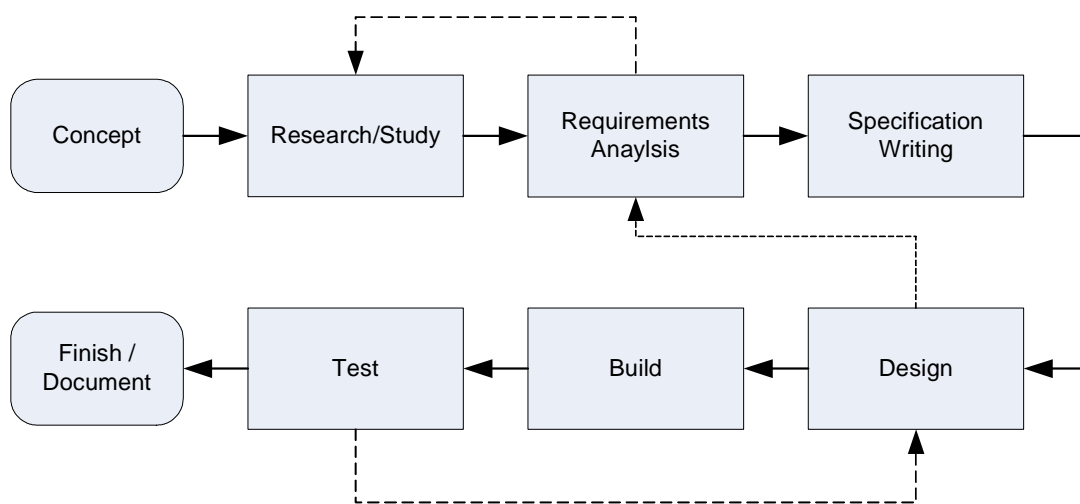


Figure 1.3: Block diagram of project scope

The above actions listed in the block diagram will be broken down between ECE 582 and ECE 682z in the following way:

- ECE 582 Tasks:
 1. Customer Interview with Professor Lee
 2. Create an overall concept for the project
 3. Research of information relating to antenna design
 4. Develop a list of requirements for the antenna design
 5. Iterate the requirements after further research and study
 6. Develop a detailed specification of our design and final report
 7. Form initial design and simulate it using HFSS
- ECE 682z Tasks:
 1. Further design and simulation of the ideas developed in ECE 582
 2. Iterate the design after further development of requirements
 3. Build of the design
 4. Test the design
 5. Iterate testing after design modification
 6. Produce final working antenna
 7. Document entire process

2. Background and Market Research

Phased array antennas are useful for a number of applications including radar, satellite communications and even cellular base stations. The main purpose of an array of antennas is to create a new antenna with a different directivity. The directivity is a measure of the angular width of radiated energy from an antenna. The spacing of radiating elements causes phase

differences between the individual waves radiated. These phase differences lead to constructive and destructive interference, which in turn leads to a different radiating pattern. This concept gives the user the ability to quickly “steer” or redirect the beam of the antenna by simply shifting the phase and gain of the elements in the array. This allows the user to electronically aim the antenna instead of having to mechanically reposition it.

There are two types of phased array antennas: active and passive. A passive phased array can produce a main beam but only in a fixed direction, while an active phased array is capable of dynamic beam scanning. A passive array is adequate for communications with satellites in a geosynchronous orbit above the equator; but for tracking low-Earth-orbiting satellites, an active phased array is required. Another application of an active array is missile guidance where the ability to quickly change the beam of the antenna allows for greater accuracy and ability in tracking single or multiple guided weapons.

One key concept when it comes to antennas is the idea of impedance matching. This requires the impedance of the antenna to be tuned in order to match it to the impedance of the feeding system. Normally, this impedance is a 50-ohm transmission line. If the line and antenna impedances are mismatched, part of the signal fed to the antenna will be reflected back down the line thus reducing the amount of the signal being transmitted or received. Due to the shape of an antenna, there are going to be inductances and capacitances associated with the design. By altering these designs in various ways, elimination of such impedances can be reached. For example, an antenna with negative imaginary impedance could be slightly wound to promote inductance. If an antenna had positive imaginary impedance, an air gap of some sort could be introduced to promote capacitance. These are only two possible examples.

3. Requirements Analysis and Specifications

The requirements for the phased array antenna are somewhat ambiguous for this report. Since the purpose (described in more detail in the Introduction) is for OSU research and student exploration during lab sessions, the antenna does not have very restrictive design constraints. This ambiguity allows for many possible design options for the engineer. The few specs that will be incorporated in the design process are listed below.

- Transmit and receive a signal in the mobile phone and personal computer wireless networking frequency range (1 – 2 GHz)
- Function throughout Ohio State’s Dreese Labs building
- Act in the passive phased-array mode
- Operate with maximum efficiency for the particular specs that originate from the design – a balance between physical size, cost, accuracy, and precision
- A \$100 constraint for the dielectric material and $2 \leq \epsilon_r \leq 3$

Possible material found:

- Rogers Corp RT/Duroid 5880
- $\epsilon_r = 2.2$

4. Design Approach

4.1 System Design

A block diagram of the final working system with the integrated phased-array microstrip antenna can be viewed in Figure 4.1.

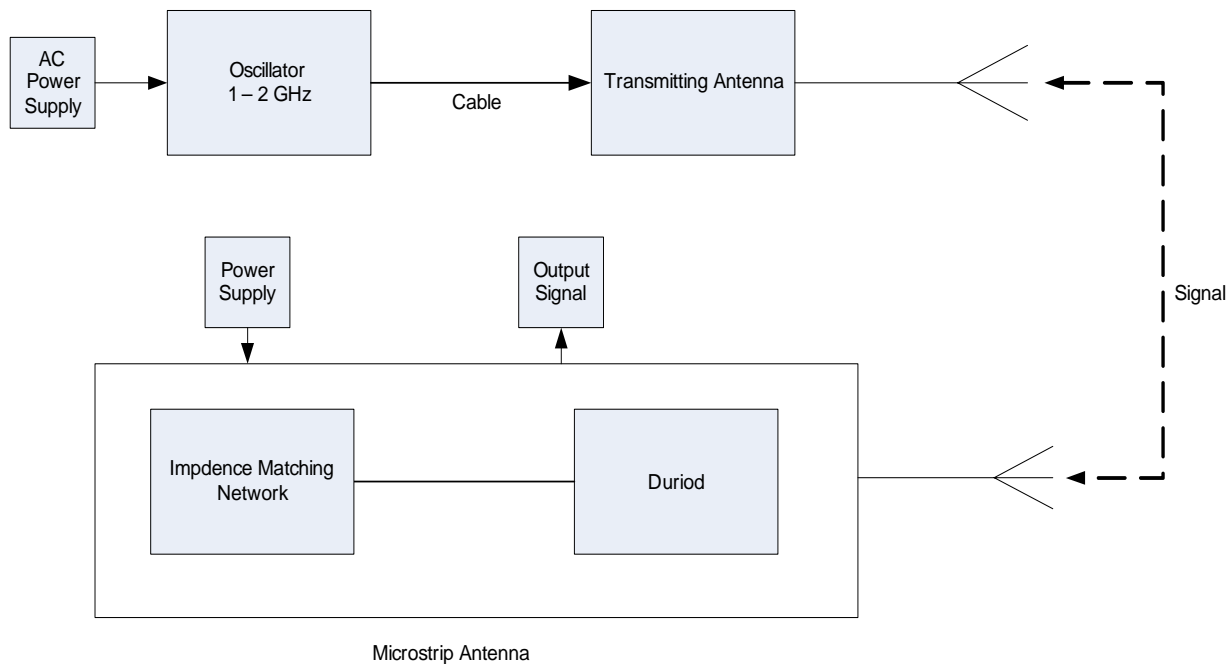


Figure 4.1: Block diagram of final working system with phased-array antenna integrated

The system design above illustrates how the phased-array microstrip antenna will be used once the final design is complete. The system design is important because the integration of the microstrip antenna must be considered during the designing process. The system shows that the antenna must be able to receive a 1-2 GHz signal from a transmitting antenna and relay a correctly reconstructed signal through a matched impedance network. This system design will be considered throughout the analysis and evaluation sections below.

4.2 Analysis and Evaluation

4.2.1 Analysis

There are multiple performance factors that must be taken into consideration when designing an antenna including radiation pattern, gain, voltage standing wave ratio (VSWR), and return loss. These factors are explored below.

Radiation Pattern

A radiation pattern is a plot of the transmitted signal gain in various directions on an x-y-z axis. Depending upon the application, one particular beam pattern may be desired over another due to the tradeoff between directivity and beamwidth. By varying the configuration and phase of the antenna array elements, one can control the tradeoff. A simple example of this relationship between directivity and beamwidth is discussed below:

One example of an antenna radiation pattern can be seen in Figure 4.2. This plot shows a horizontal 3 DB beam width (around edge of donut shape) of 360 degrees and a vertical beam width (the angle between the red on top to the red on bottom) of approximately 90 degrees. Because the pattern has such a large horizontal beamwidth, it has a rather small directivity (the amount of pattern concentration in a particular direction).

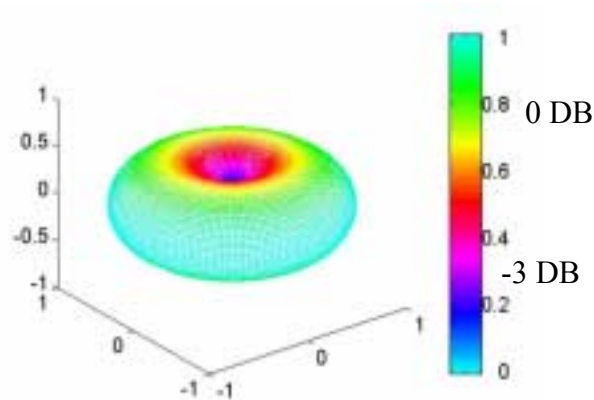


Figure 4.2: Radiation Pattern for a Half-Wave Dipole

In contrast to this configuration, look at another radiation pattern seen in Figure 4.3. The pattern for this case possesses a much smaller horizontal beam width (≈ 90 degrees) and slightly larger vertical beam width (≈ 100 degrees). Consequently, this pattern has a greater directivity than the previous example and a higher peak transmitted power.

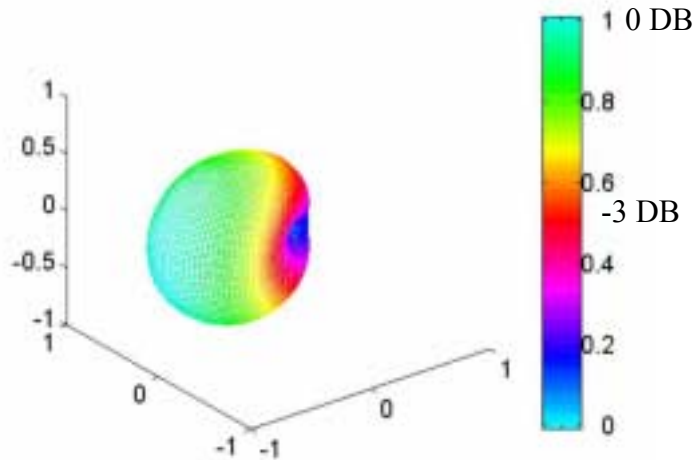


Figure 4.3: Radiation Pattern for a 3-Element Yagi Configuration

Since the antenna for this project does not have a particular application, the phased-array antenna will allow the user to electrically change the phases of the antenna elements. This will change the gain, direction, and directivity of the radiation pattern to obtain optimum results for a particular application.

Antenna Gain

Antenna gain and bandwidth are also important factors to consider when designing an antenna. This is due to the fact that antenna performance changes with changing frequency (see Figure 4.4 for a plot of this relationship). The peak power shown in Figure 4.4 is the maximum power that can be transmitted when operating at the optimum frequency. Antenna bandwidth is also shown on the plot and is defined as the change in frequency from the 70% ($1/\sqrt{2}$) degradation points of the peak power. Our desired bandwidth for this project is about 1 GHz (spanning the 1 – 2 GHz range), thus requiring our peak power to be transmitted around 1.5 GHz.

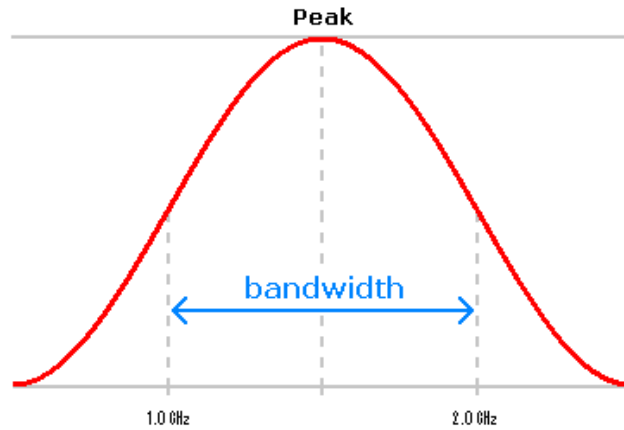


Figure 4.4: Plot Showing Bandwidth and Transmitted Power vs. Frequency

Voltage Standing Wave Ratio (VSWR)

Another important factor in measuring the performance of an antenna is the Voltage Standing Wave Ratio (VSWR). A network analyzer can measure the VSWR and is a benchmarking tool used to gauge the severity of wave reflections. If a high VSWR is present, there will be a large percentage of the signal that will not be transmitted by the antenna and will instead be reflected back to the source. The goal of any antenna design is to obtain a VSWR of 1:1, which means all of the signal power gets transmitted. Normally a VSWR of 2:1 is acceptable because very little of the signal will be reflected.

The equation for VSWR is as follows:

- $VSWR = \frac{1+\Gamma}{1-\Gamma}$, where $\Gamma = \frac{Z_S - Z_L}{Z_S + Z_L}$

Z_L is the load impedance and Z_S is the source impedance, where Z_S is assumed to be 50Ω (standard practice). In order to realize a VSWR to 1:1, one needs to minimize the reflection coefficient, which can be accomplished through load matching. This requires the development of a load impedance as close to 50Ω as possible. A perfectly matched load will have a VSWR of

1:1, but this is an optimized value and impossible to reach. Table 4.1 below shows the relationship between VSWR and percentage of reflected back power.

VSWR	Return Loss (dB)	% Power / Voltage Loss	Reflection Coefficient	Mismatch Loss (dB)
1	∞	0 / 0	0	0.000
1.15	23.1	0.49 / 7.0	0.07	.021
1.25	19.1	1.2 / 11.1	0.111	.054
1.5	14.0	4.0 / 20.0	0.200	.177
1.75	11.3	7.4 / 27.3	0.273	.336
1.9	10.0	9.6 / 31.6	0.316	.458
2.0	9.5	11.1 / 33.3	0.333	.512
2.5	7.4	18.2 / 42.9	0.429	.880
3.0	6.0	25.1 / 50.0	0.500	1.25

Table 4.1: Relationship Between VSWR, % Power Loss and Return Loss

For example, an antenna with a VSWR of 2:1 would have $\Gamma=0.333$ and 11% of the transmitted power is reflected back. In comparison, an antenna with a VSWR of 3:1 would have $\Gamma=0.5$ and 25% of the transmitted power is reflected back. Obviously, the antenna with a VSWR of 2:1 would be the more optimum. If a high VSWR is unavoidable, one can help overcome the efficiency problem by simply boosting the power of the signal source. However, if the signal source is set too high, there will be a reflection large enough to cause over-voltage. Over-voltage is when the source receives a voltage higher than rated and causes damage to its electrical components. RF engineers focus on obtaining low VSWRs in order to prevent this occurrence.

Return Loss

Another factor relating to VSWR and performance measures is the concept of return loss. The term ‘Return Loss’ can be confusing at first because it sounds like it has a negative connotation. However, ‘Return’ refers to the reflected signal and ‘Loss’ refers to a lack thereof, so return loss

is really the amount of signal that is not reflected, or the amount being transmitted. Return loss is normally put in dB, and the equation is below:

- $Z_{Loss}(dB)=20\log_{10}[(Z_S+Z_L)/(Z_S-Z_L)]$

It is easy to see that for a matched load ($Z_L=Z_S$) the return loss will be infinite, which means that all of the generated signal will be transmitted. Table 4.1 also shows various return losses compared with VSWRs.

4.2.2 Evaluation

The evaluation of the design performance comes in two parts:

- 1) Testing the design during simulation
- 2) Testing the design after it is built

Both testing methods are described below.

1) Testing using the simulation tool HFSS (example)

Step1: Set up experiment (see Figure 4.5)

Figure 4.5: HFSS set-up

A 10-inch wide, by 10-inch long, by 25-inch high box is created to simulate the free space around the antenna where HFSS solves for the electromagnetic fields. The antenna is made to conform to the design specifications by having a one-sided micro-strip board of Rogers Duroid 5800 and a relative permittivity of 2.2. The antenna will also have a rectangular slot cut out of the copper with length 10 cm (half the wavelength of the design frequency). The width of the slot, which determines the bandwidth of the antenna, will be 5 cm wide. The antenna is then placed in the center of the box. Next, radiation boundaries are set-up on all the faces of the box to simulate perfect absorbers at every face. This is to make sure no signals would reflect off the face and come back into the box. Finally we specified an incident plane wave with power 1 Watt and frequency 1.5 GHz. The build-in error checking algorithms are then used to make sure that there are no HFSS modeling errors. Then the solver is initiated, which will create equations for the electric fields at all the different regions inside the box.

Step 2: Initial test

For this first test, we want to find how much of the electric field is transmitted through the phased-array antenna at 1.5 GHz. In HFSS, a plane is specified about a $\frac{1}{4}$ wavelength behind the array. The $\frac{1}{4}$ wavelength is chosen to satisfy the far-field approximations of the transmitted fields. After waiting approximately 1.5 hours for the simulation to complete, HFSS allows the user to input specific points, planes, or volumes for quantities of interest. The following quantities are looked at with respect to the total, incident, and scattered fields and plotted in the simulation results below: electric field, magnetic field, and current density.

Step 3: Simulation Results (see Figures 4.6 – 4.9)

The animations of the electric fields, magnetic fields, and current densities reveal that the phased-array antenna is not fully transmitting the input signal at 1.5 GHz. The magnitudes of the

scattered electric fields are very high in the circumspect direction. This means that a large portion of the input field is being reflected back toward the source (Figure 4.6). Also, the total magnetic field received on the other side of the phased-array antenna is small. This means that not much of the input signal is making it through (Figure 4.7).

Figure 4.6: Scattered electric field at the source. Large magnitude indicates a large reflection at 1.5 GHz.

Figure 4.7: Total magnetic fields received. The numbers on the graph indicate that a small percentage of the input signal has been received.

The cross-sections of the magnetic fields through the phased-array antenna show a clear magnetic dipole formed over the length of the slot. This radiation pattern is a good indication that our antenna is working, although it only verifies the operation for a frequency of 1.5 GHz (Figure 4.8).

Figure 4.8: Total magnetic field received through the phased-array antenna

2) Testing after the design is built

During the testing phase of this project we will use two separate test setups in order to measure the antenna's parameters. For one test, a spectrum analyzer will be used to plot the antenna gain at certain frequencies. The test setup up block diagram can be seen below in Figure 4.10. In order to perform this test; the antenna constructed by the group will first be attached to a signal generator. The signal will then be sent to a receiving antenna whose specifications are already known. This will allow to group see the gain in the desired bandwidth range of 1 GHz to 2 GHz. This test will be done in the semi-anechoic chamber at the ElectroScience Lab. This is done so as to block out any outside electromagnetic waves that may interfere with the test setup, and cause incorrect measurements to be taken.

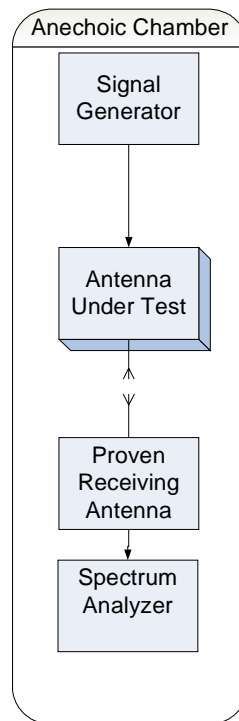


Figure 4.10: First Test Setup

The second test setup, seen below in Figure 4.11, will use a network analyzer to plot the real and imaginary impedances of the antenna on a smith chart. This test will not be required to be done in the anechoic chamber, as the antenna will be directly connected to the analyzer. This will allow the group to match the antennas impedances in order to minimize losses.

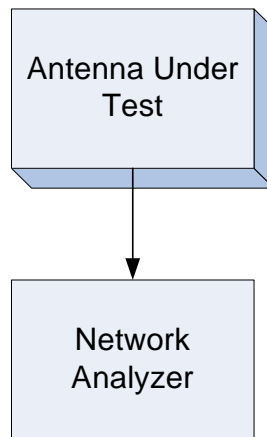


Figure 4.11: Second Test Setup

4.3 Some Detail Design

The first step in designing a phased-array antenna that realizes the given requirements is to build one single antenna out of the researched materials. As an initial design, we can consider the half-wave dipole antenna. The half-wave dipole can be thought of as a wire whose length is one-half the wavelength of the desired frequency in air. The input of the antenna is located in the center of the wire. For our application, the center frequency used is 1.5 GHz, which has a wavelength of 20 cm.

The dipole can be built as a microstrip antenna where a film of copper 10 cm in length and some determined width is present on a dielectric substrate with a copper ground plane on the opposite side of the dielectric. The signal will be fed to the dipole from the bottom of the substrate.

Once the antenna is built, it will be connected to a network analyzer and plotted on a Smith Chart. The Smith Chart will then be used to balance the capacitive and inductive loads on the antenna and bring the impedance close to 50Ω in order to make it matched. This can be done by adjusting the feed point of the input signal as well as adjusting the width of the dipole strip on top of the substrate.

Once the antenna meets the design requirements, duplicates can be produced to integrate into an array of radiating elements where each element is a duplicate of the original antenna design. The team will then work on experimenting with different configurations between the elements to determine the best orientation to achieve a direct and efficient radiation pattern. The adjustments to the configuration will mostly be the phases between elements.

5. Statement of Work

5.1 - ECE 582 Tasks

- Conduct customer interviews
- Research information on phased array antennas
- Produce a proposal and requirements specification for the project
- Select a design and produce a report detailing the design
- Time permitting, run preliminary simulations of the design in HFSS

5.2 – ECE 682z Tasks

- Formal simulation of the design chosen in 582

- Generate a CAD layout of the design in Advanced Design System (ADS)
- Fabrication of the antenna design at the ElectroScience Lab
- Testing and analysis of the antenna; includes gain, radiating pattern and spectral characteristics
- Creation of an array based on our antenna design
- Characterization of the array through testing and analysis

5.3 - Beyond 682z

- Optimize phased antenna array for a specific application
- Possibly use as a training tool in a future electrical and computer engineering lab

6. Resources

6.1 - Personnel Responsibilities

- Lauren Achor: Work will focus on the initial design of the antenna. Previous experience in EM from ECE course work will be applied to the project.
- David Daniel: I am working on the simulation of our phased array design. Part of the task in the simulation is to have a good understanding of the design requirements. This will allow for iterative analysis of simulation test results and tweaking of the parameters of the array to meet the design requirements.
- Adam Dowdy: Primary focus is the initial design of the antenna. Previous RF work experience will be applied in the design, testing, and benchmarking of the designed antenna.

- Steve Meredith: Responsible for the actual construction of the antenna with the materials and tools provided by the ElectroScience Lab. Previous class work in EM such as ECE 311, 312 and 614 will be applied to various tasks.
- Jim Moore: Responsibilities are group contact and simulation of the antenna designs in HFSS. Previous class work in microwave circuits and EM as well as experience with lab test equipment will be applied to the project.
- Bei Wang: Responsible for construction of antenna and helping with simulations. Previous experience in EM from ECE 311 and 312 will contribute to the project.

It is anticipated that these group members will act as the leaders in their assigned area. The rest of the team will be required to help with any tasks if need be.

6.2 - Facilities and Equipment

The main facility to be used for this project will be the ElectroScience Lab located at 1320 Kinnear Road. This facility will provide a compact range semi-anechoic chamber for testing the antenna, plus the tools associated with the construction of the antenna. The group will have access to high-performance computers, a milling machine, and a network analyzer.

7. Schedule and Costs

7.1 – Anticipated Schedule

- Early November – Proposal approval
- Early November – Simulation begins
- Mid December – Finalize design and finish simulations
- Early January – Prepare materials

- Early January – Build begins
- Early February – Test measurements begin
- Early to Mid March – Analysis and report
- Late March – Meet to discuss innovation and project scope beyond 682z.

7.2 - Associated Costs

The costs associated with this project should be minimal. The facilities and all equipment needed should be provided at the ElectroScience Laboratory. The only cost to the university will be the purchase of Duroid microstrip from the Rogers Corporation: The material is Rogers Corp RT/Duroid 5880 with a dielectric constant of 2.2 at a price of approximately \$100.00 per sheet. A quote from Rogers Corporation for RT Duroid 5880 having a dielectric constant $\epsilon_r=2.2$ stated that a sheet is approximately \$90 but there is a minimum order of 250 sheets. Surplus Sales based in Nebraska lists the same Duroid in varying dimensions and thicknesses priced from \$19 to \$85 per board. There does not appear to be a minimum quantity per order.

8. Design Review Strategy

The design strategy begins with research and gathering information about phased array antennas. This first step is an ongoing process throughout the project but has led to enough information to generate an analysis of the requirements for our antenna design. From the requirements, a specification for the antenna design can be created. This will lead to the design of the antenna as well as the final design report for ECE 582. Thus far, the requirements analysis has been completed and the next step is to produce the detailed design. Also, we have begun some preliminary simulations of an antenna design as we learn to work in HFSS.

Once the final design is produced, detailed simulations as well as optimizations on the design will be carried out. The design might need to be revised after simulations and the process repeated. After the simulations are complete, the design will be built and tested. Based on the outcome of the tests performed, it may be necessary to return to the design phase to make adjustments in order to better meet the requirements. Once the design passes all tests to our satisfaction, the final documentation of the design is produced.