ECSE 458N1/N2 - Capstone Design Project

FINAL PROJECT REPORT

Software and Hardware Improvements for the Low-power Microwave Breast Cancer Radar-based Screening Prototype

Design Group No.2:
Haoran Du (ID: 260776911)
Jacob Silcoff (ID: 260767897)

Project Supervisor:
Prof. Milica Popovich
RF Breast Cancer Detection Research Group
McGill University Computational Electromagnetics Laboratory

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Abstract

Our research project focused on developing software and hardware improvements to a microwave-based breast cancer detection system that is currently being developed at McGill's RF Breast Cancer Detection Research Group, which is led by our project supervisor Dr. Milica Popovic. Specifically, we worked on two primary goals. The first, which was carried out over the Winter 2020 semester, focused on creating software to automate the process of running tests on the prototype the team was using. In this part of our project, we researched ways to circumnavigate the GUI currently being used to run tests of the prototype. We wrote a sample program using a python library `Pylibftdi`, which we expected would function as expected based on our research. Unfortunately, the testing of the proposed software was made impossible by the COVID-19 campus shutdowns since March 13, 2020. Therefore, our work on this part of the project was left inconclusive. The second goal, spanning over the Fall 2020 semester, focused on researching and modelling flexible substrates that could be used to integrate components of the prototype onto a single hemispherical circuit. For our substrate research, we researched and selected what seemed like the three most viable substrates based on a review of the literature on flexible substrates. We then designed circuit models, one planar and one hemispherical, and simulated them using ANSYS HFSS. We used these models to compare materials with each other on a variety of metrics to choose the single substrate that we propose the lab should use.

Acknowledgments

The past 12 months for our design group have been an unforgettable and invaluable experience for us. When the group first started looking into our Capstone project in January 2020, we barely knew about the microwave approach for breast cancer detection, let alone how to apply our knowledge and skills as undergraduate computer engineering students in this area. Now, we are writing this report to finish this project towards completing our degrees during a global pandemic. Our group would not have been able to make this journey without the help and support of many, many people, and we feel deeply grateful to them.

First and foremost, our greatest thanks go to the project supervisor Prof. Milica Popovich. We felt very privileged to have taken her course, ECSE 353 - Electromagnetic Fields and Waves, and also have a chance to work with one of the most brilliant and dedicated minds in this field. She is very detail-oriented and offered us much-needed guidance throughout the project. More importantly, she has been an extremely kind, caring and supportive advisor to us, especially when the group was facing unforeseen challenges due to the global pandemic. This project would not be made possible without her guidance. The design group is forever grateful to her for being such an important figure at this last stage of our undergraduate degrees.

It is also our great honour to have met the graduate students on Dr. Popovic's team, who played an integral role in guiding us through our project, providing resources, and responding to our many questions, including Lena Kranold, Leonardo Fortaleza, and Wesley Kendall. They have dedicated their valuable time providing timely responses to our detailed-questions about the project.

The group would like to thank Richard Lee from McGill EMF and McGill IT Services for helping the group obtain access to the simulation software (HFSS) through Remote Desktop Protocol during the on-going campus shutdown.

We would also like to express our gratitude to Prof. Mark Coates and his research group for working with us at our first design project meeting back in February 2020 to explain how the research lab works.

List of Abbreviations and Notations

No.	Name	Description
1	LTC6946	The LTC6946 is a frequency synthesizer made by Linear Technologies. It is used to drive the antennae that scan breast tissue in hopes of detecting tumors [1].
2	DC590	The DC590 is a usb-controlled SPI/I2C converter that is used to connect the LTC6946 to a computer via USB. It is also created by Linear Technologies [2].
3	Pylibftdi	Pylibftdi is a python library designed to interface with devices using FTDI chips that wraps FTDI's own interface in a comparatively simpler one, to enable streamlined programming of FTDI hardware [3].
4	Phantoms	The phantoms are synthetic models of breast tissue that are designed to simulate the electromagnetic properties of various types of human tissue, including healthy breast tissue, glands, fat, and tumors. They are used to test breast imaging prototypes in a cheap, repeatable way that does not require human test subjects [4].
5	PI	"PI" is an abbreviation for "polyimide," a flexible substrate material.
6	PET	"PET" is an abbreviation for "polyester," a flexible substrate material.
7	LCP	"LCP" is an abbreviation for "liquid crystal polymer," a flexible substrate material.
8	Ansys HFSS (or just HFSS)	HFSS is short for "High Frequency Structure Simulator," and is a tool used to simulate electromagnetic systems using the finite element method (FEM).
9	Z_0	Z_0 refers to the characteristic impedance of a transmission line.
10	S_{12}	S_{12} refers to the amount of power that is received on the output of a 2-port network for a unit input, and is one of 4 S parameters that describe a 2-port network.

Contents

1 Introduction

In Canada, 1 in 8 women are diagnosed with breast cancer at some point in their lives [5]. It is a disease that kills 1 in 33 Canadian women [5], and changes the lives of many more, with a global death toll of 40,000 people on an annual basis [6]. One of the core challenges in combating breast cancer is developing new screening methods that can detect tumors earlier in their development when they are more easily treated, since traditional screening methods such as x-ray mammography use ionizing radiation that would cause lasting damage if used too frequently [4].

A proposed solution to this problem is to use an array of low-powered microwave antennas to image breast tissue, leveraging the differences in electromagnetic properties of healthy and cancerous tissue to create a rough map of suspicious growths, in a manner that is analogous to RADAR. The underlying theory is that by observing how microwave pulses are distorted as they propagate through the tissue, one can reason about the refractive properties of the tissue that the pulse travelled through, which can, in turn, differentiate cancerous tissue from healthy tissue [4]. This technique would expose the user to approximately the same level of radiation as receiving a phone call, and could therefore be used much more frequently than more invasive approaches, enabling earlier detection of cancer while reducing the need for screening techniques with more dangerous side effects. The technology is still in the early stages of research and development, and faces a number of challenges, including overcoming a low SNR, creating data processing techniques to accurately assess the device's output across varied testing conditions, and sourcing materials to integrate components into a cohesive prototype [4]. Multiple research teams are currently attempting to tackle these problems, including a team led by Dr. Milica Popovic and Prof. Mark Coates of McGill University. One of their current prototypes can be seen in Figure 1.

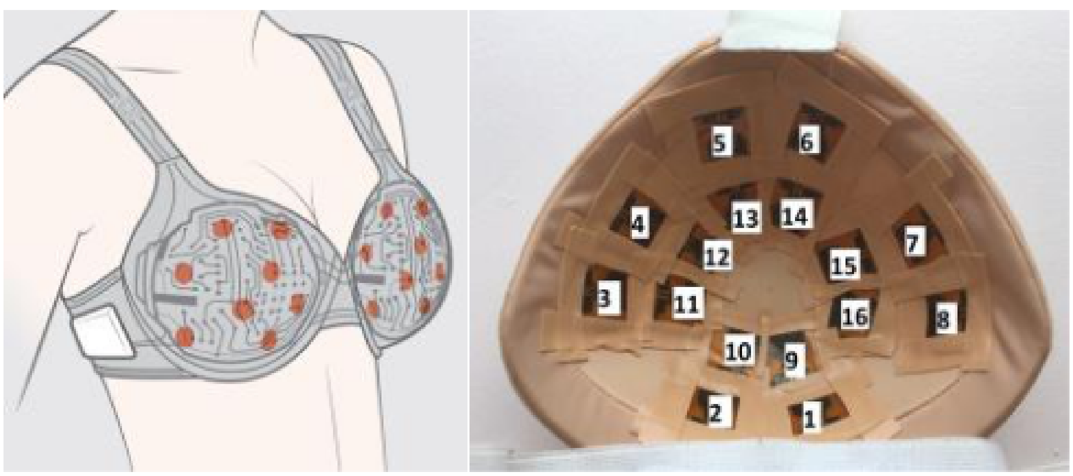


Figure 1: Left: an artists rendering of the proposed product. Right: an interior view of the prototype, displaying the 16 microwave antennae. [7]

When we joined their research team, one of the major bottlenecks in their design process was gathering a sufficiently large pool of test data that could be used to design a data processing pipeline to convert the outputs of the prototype into meaningful results. A major limitation in this regard was the software that the team was using to run their tests, which involved relying on a relatively slow GUI to send instructions to the prototype. Our first goal was to create a software solution to circumvent this GUI, and make the testing process substantially faster. In addition to being an important tool for the team to move forward on their research, the problem we were tackling was one that could apply to anyone prototyping with the LTC6946 frequency synthesizer, which has many applications across electrical engineering fields.

Another problem facing the team was that the individual components of the prototype, such as the antenna and impulse generator, were unable to be unified without a flexible substrate that could conform to the shape of the prosthetic bra that the team was using. Although they had attempted to find such a substrate in the past, the team encountered difficulties with getting the substrate to adopt the positive curvature required to fit properly onto the prototype. Consequently, we were tasked with researching other viable substrates, taking care to find ones that had both the necessary physical properties as well as the necessary electromagnetic properties to meet the team's requirements.

2 Background

2.1 Software Background

Since the software component of this project is detailed in the midterm report, we will only briefly summarize highlights within this report. All information about the technical background, design decisions, and results for that portion of the project can be found in the Mid-project Report (see Appendix A). That report also goes into substantially more detail on how the prototype works, and the specific testing methods that the team is using.

2.2 Transmission Line Design & Optimization

In this project, the team utilized the knowledge from materials and theories covered in ECSE 353 (Electromagnetic Fields and Waves) and ECSE 308 (Introduction to Communication Systems and Networks) at McGill University. We especially relied on a theoretical understanding of transmission lines and signal transmission, focusing specifically on microstrips. The core concepts are summarized here.

The first idea that we drew on was the notion of impedance matching, which is the idea that maximum power transfer will occur when the load of a circuit matches the impedance of the circuit that is powering it. This rule arises from the reflection coefficient, Γ, which represents the amplitude ratio of the reflected signal and the incident signal. The equation for calculating gamma for a circuit with a characteristic impedance Z_0 and a load impedance Z_L is shown below.

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{1}$$

Since transmitted power is equal to incident power less reflected power, maximum power transfer occurs when Γ is equal to zero, implying $Z_L = Z_0$.

The second idea we used was the use of S parameters to describe the behavior of a multi-port network. For the sake of this project, the only relevant background is that S parameters enable a network to be treated as a black box, with output signals at each port being calculated by multiplying a vector of input signals with the S matrix. For our project, we only looked at S_{21}, which is the specific S parameter relating the output at port 2 (the port where the load would be attached) with the input at port 1 (the port where the signal is inputted). The higher the value of S_{21}, the more power is being transmitted through the circuit.

Lastly, we leveraged our understanding of microstrip design to optimize the circuits we were simulating. A microstrip is a type of transmission line consisting of a thin strip of conductive material separated from an infinitely large[1] conductive ground plate by an insulating substrate. This type of transmission line is often used due how easy it is to manufacture, since it can be created by selectively removing the copper coating on a copper-coated substrate sheet.

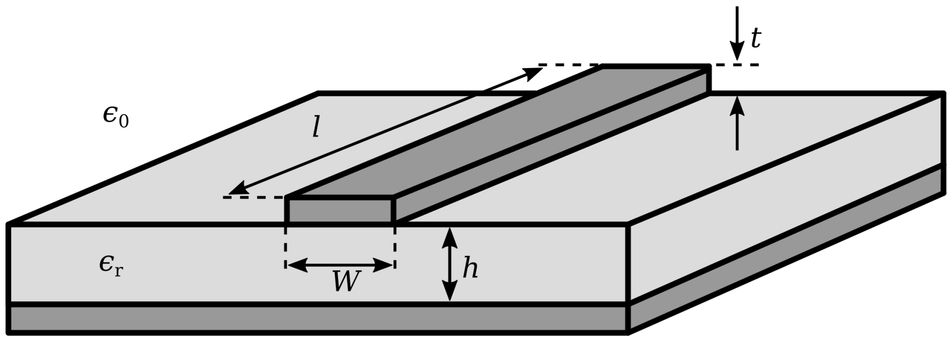


Figure 2: A diagram of a microstrip, including the relevant dimensions [8]

The microstrip's characteristic impedance is governed by the dimensions t (the thickness of the strip), W (the width of the strip), h (the substrate thickness), and ϵ_r (the relative permittivity of the substrate). These dimensions are illustrated in Figure 2. Provided $t << W$, the characteristic impedance is given as

$$Z_0 \approx \frac{42.4\,\Omega}{\sqrt{\epsilon_r + 1}} \times \mathbf{ln} \left[1 + \frac{4h}{W} \left(\Phi + \sqrt{\Phi^2 + \frac{1 + 1\,/\,\epsilon_r}{2} \pi^2} \right) \right] \tag{2}$$

Where Φ is given by

$$\Phi \triangleq \frac{14 + 8\,/\,\epsilon_r}{11} \left(\frac{4h}{W} \right) \tag{3}$$

When designing our models, these were the equations we used while tuning the microstrip dimensions so that its Z_0 would be as close to the impedance of the antennas the lab uses as possible.

2.3 Simulation Techniques

In this project, we relied heavily on Ansys HFSS to simulate our designs. HFSS is a 3D EM simulation software for designing and simulating high-frequency electronic products such as antennas, antenna arrays, and RF or microwave components. It is widely used both in the industry and academia for RF substrate designs. The HFSS version used in this project is ANSYS Electronics Desktop 2020 R1 installed at selected workstations of McGill Engineering Microcomputing Facility (EMF). While we needed to learn how to use this software in depth, no detailed understanding of its operation is necessary in order to understand the procedures or results described in this report, besides knowing that it can be used to measure the characteristics of a microwave circuit.

[1]Obviously, infinitely large plates are not possible in reality—the ideal microstrip is a mathematical construct, and so long as the ground plate is sufficiently large compared to the strip, the equations governing microstrips will still apply.

2.4 Hardware and Software Integration

In our project, we utilized our experience in hardware programming when designing the software interface for the registers on the antenna in python. Specifically, the experience of VHDL programming on FPGA for digital and mixed-signal systems (ECSE 325: Digital Systems) and C/ARM Assembly programming on Cortex-M4 (ECSE 444: Microprocessors). These courses gave us the skills needed to read and understand technical documentation for integrated circuits, and provided the basic knowledge of communication frameworks used by such systems to access and modify memory using an external device (which was the focus of our work).

3 Requirements and Challenges

3.1 Software Improvements: Improved Automation Interface

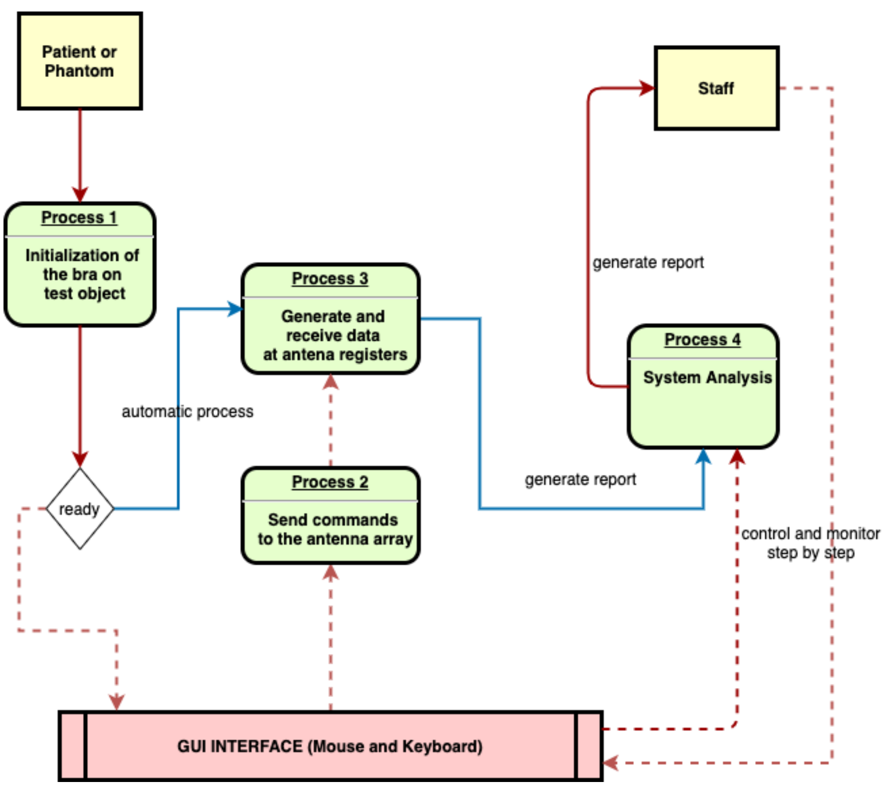


Figure 3: Proposed Software Automation Interface Functionality

3.1.1 Requirements

The goal of this component of the project was to upgrade the automated testing suite used by the team to send commands to the prototype in order to collect data. Specifically, we were tasked with improving the run time by creating a solution that does not involve using the relatively slow GUI that the team was currently relying on. We were to integrate our code within the team's GitHub testing repository, specifically redesigning the pre-existing python function `freq_set(freq)`, which sends the appropriate commands to the prototype to run tests using the frequency passed as `freq`.

As shown in the flow chart in Figure 3, the new interface is expected to communicate directly with the register map of the antenna driver for testing. In order to be considered successful, the new approach must achieve the same functional behavior as the current testing software, while running in less time than the GUI approach. This also implied we would need our solution to be either written in python, or easily activated by a python program, restricting our approaches.

3.1.2 Available Hardware

Our solution would need to be tailored to the LTC6946 frequency synthesizer that the team was using, conforming to the specifications laid out in its technical documentation. In order to use a USB interface to issue serial commands using the SPI protocol that the LTC6946 expected, we would be able to use the DC590 SPI/I^{2}C converter.

3.1.3 Challenges

Since the design must only use software that can run on a personal computer and interfacing with the LTC6946 through a DC590 board, the choices are very limited. When we began the process of designing our solution, we were given access to the repository used by the team on GitHub. However, while the boards themselves had technical documentation, there was very little documentation we could find on the software libraries that should be used to actually interface with them, with the technical documentation referencing non-existent software libraries. After a significant amount of time was spent on researching the proper python library and documents for DC590 & LTC6946, and familiarizing ourselves with the specifications for both boards, campus was shut down and the group was not able to test the program using physical hardware.

A smaller, but worth mentioning challenge, was that many of the libraries we researched had relatively little or no documentation. This was made more challenging by the limited community of users that worked with these libraries, meaning that tools like Stack Overflow or other such forums were much less useful than in other, more mainstream software projects.

3.2 Hardware Improvements: Substrate Selection

3.2.1 Problem

For this portion of the design project, our problem was to find a substrate material that could be used for the research teams next prototype.

3.2.2 Physical Requirements

For physical requirements, we needed a material that would fit on the prosthetic bra that the team was using for their prototype. Since PCBs are printed on a flat sheet, the material would need to be able to bend from a flat sheet into a hemisphere. This is not a trivial task, since the positive curvature implied by this process means that the material would not be able to be uniformly transformed (which is the same reason continents get distorted when projected from a globe onto a map, regardless of the approach used) [9]. Of course, while flexibility is an implicit goal, it is not the only way to meet the explicit goal of having a hemisphere shape. For instance, there is nothing preventing us from designing a solution that is cut from a rigid material already in the shape of a sphere, using something like a 4-axis CNC router. However, doing so would likely come with the trade off of needing to have parts custom made using non-traditional approaches, as opposed to working with existing PCB manufacturers that can produce flexible circuitry for relatively low prices.

In order to accomplish flexibility, this meant we not only needed a material that by itself would be flexible, but also that our design should be as thin as possible, minimizing the size of both the substrate itself as well as any copper ground plate that would hinder flexibility. Since modulating these parameters will have impacts on the electromagnetic properties of the system, it is possible that a less flexible material may actually be a better option if its optimal electrical design allows us to use a thinner substrate shape. The methods to quantify this flexibility are also somewhat difficult, since something like the Young's Modulus that typically measures flexibility only considers transformations that preserve a material's intrinsic curvature [10]. One consideration that is important here is to determine whether or not changing the intrinsic curvature is actually necessary; for instance, certain folding techniques can approximate spherical geometries without actually changing intrinsic curvature [11]. These approaches usually do not allow for the entire hemisphere to be covered, as shown in Figure 4, and may require wiring parts of the PCB together across cuts that would need to be made. This makes modelling more complicated, but is still a viable approach, meaning that the ability to adopt positive curvature is not a necessary requirement so much as a useful one. Since the ability to conform to the desired geometry is, for the most part, a binary outcome, we decided that the specific material properties would be used to eliminate options more so than to compare them to each other. This simplification was sub-optimal, but was made because we were unable to find research specifying the specific material properties that would accurately convey the materials' ability to conform to a hemisphere. Luckily, ordering engineering samples of the materials is relatively cheap, meaning physical testing is not an unreasonable approach.

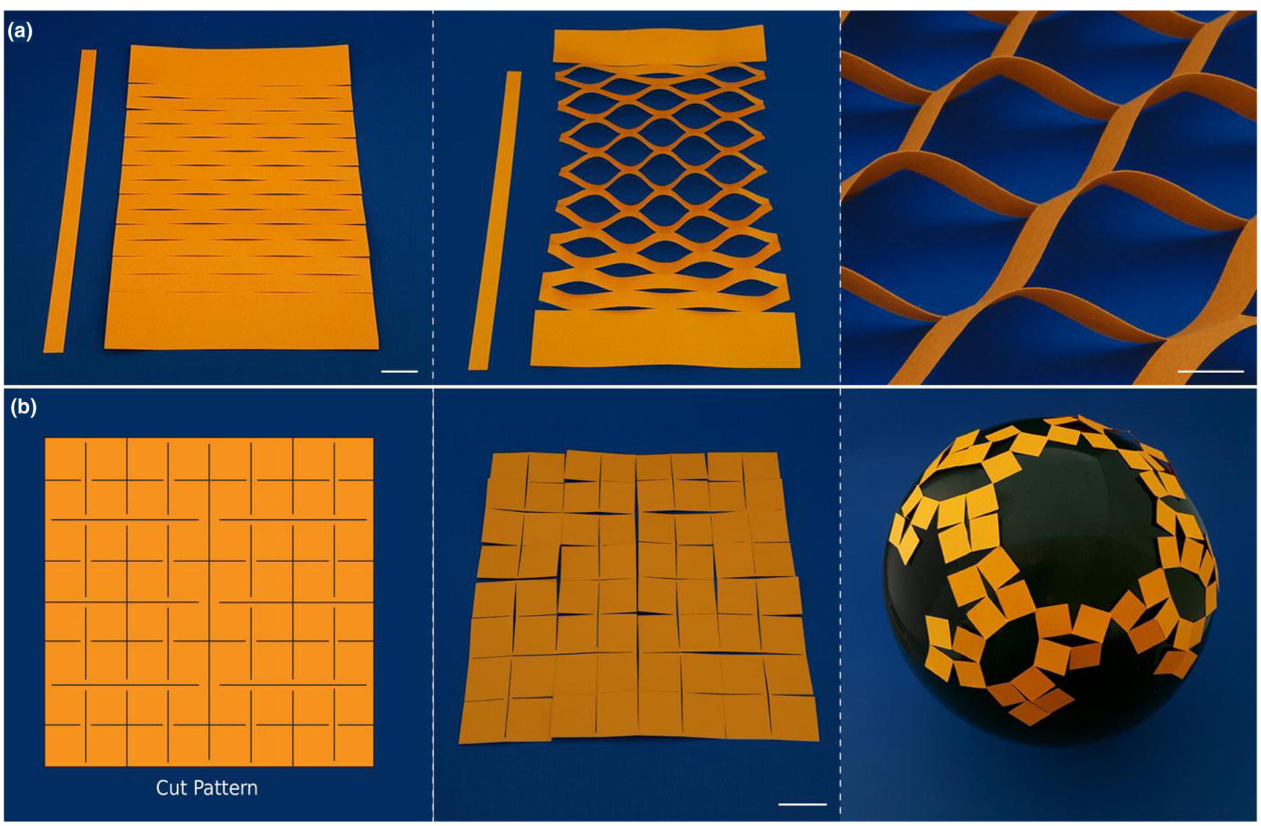


Figure 4: Method for Folding Plane onto a Hemisphere (propsed by Callens & Zadpoor [11])

3.2.3 Electromagnetic Requirements

The ultimate goal of substrate selection is to maximize the amount of power that is transmitted without loss or distortion, which is especially important in this context since overcoming a low SNR is one of the core challenges the team faces. Relevant parameters here are the relative conductance and permittivity of the substrate. However, the geometry of the circuit traces will also play a role in the electrical properties of the circuit as a whole. To best compare materials, we decided on two values that reflected these concerns. The first was to look at the root-mean-square deviation between the observed impedance (Z_0) of the transmission line and the antenna impedance of 50 Ω[2], across each frequency in the operating frequency range. This would determine the extent to which we could achieve optimal impedance matching with the given substrate material, which in turn would enable us to make sure that as much power as possible was transmitted as opposed to being lost as a reflected wave. The second value we used as a metric was the S parameter of the circuit. Since we are essentially designing a series of two port networks, the magnitude of the S_{21} parameter will reflect how much of the power of the signal incident to the input port is seen at the output port. This will represent the gain of the circuit, and should be maximized in order to ensure as little power as possible is lost.

For a given substrate material, these two values (Z_0 and S_{21}) are a function of the specific geometry of the circuit. Therefore, getting a fair comparison between two substrate materials requires first optimizing the circuit for that material, and then comparing the optimal values of each material. Since optimizing for both values simultaneously is obviously impossible, we decided to optimize for Z_0, since in our experimentation it varied substantially more than S_{21}. This was an acceptable decision since in all but 1 of our experiments, the two values were locally optimized at the same set of dimensions, and the one outlier had negligible differences between the observed S_{21} and the minimum possible S_{21}.

3.2.4 Economic Requirements

Given that the research team operates off of a finite budget, and that initial prototypes are likely to be changed frequently, ensuring that the circuit could cheaply and easily be manufactured on the given substrate was important. This meant three things. Firstly, we decided to limit ourselves to PCBs that could be printed on a planar sheet, since this is the industry standard for PCB manufacturing [12], and is subsequently a process that has been optimized by manufacturers to the point that PCB prices are relatively cheap. This allowed us to rule out more complex approaches that would require custom manufacturing processes unique to the project, i.e., manufacturing a rigid hemispherical substrate and using a CNC router to carve out the desired circuitry, since ordering such a customized part would be substantially more expensive and involved. The second related consequence is that our geometry would be constrained by the manufacturing capabilities of suppliers, e.g., things like substrate thickness and copper thickness are typically quantized by manufacturers, and going outside of those discrete measurements would dramatically increase manufacturing costs as it would require a custom process. This meant the major parameter we would be fine tuning would be the width of our copper traces, since within certain tolerances, any width can be manufactured cheaply. Finally, it meant our materials choices would be limited by our ability to find a manufacturer that can create a circuit using the desired material as a substrate.

[2] The 50 Ω value was given to us by the research team as the impedance of the antennas that they intended to use.

3.2.5 Challenges

Accomplishing this task posed some key challenges to us as a team. The first was that neither of us had any prior experience with physical circuit design, since the Computer Engineering curriculum doesn't have any courses involving how PCBs are manufactured, let alone anything on actually designing PCBs for production with practical CAD tools. We also had extremely limited experience with 3D modelling, and no experience with running electromagnetic simulations. By far the largest challenge was getting access to the simulation software, which cost $40,000 to license and wasn't available on the McGill computers we had access to. We were eventually able to contact McGill EMF to have them install it on computers in Trottier that we could access via RDP, but we were only able to get this done with less than a month left in our project, which meant that although we had done a lot of background research and watched a lot of tutorials on using HFSS, we didn't get to practice using those skills until late in the semester. We also had latency issues using the software remotely over a poor internet connection, with a delay of about 5 seconds between pressing a button and getting a response. This problem didn't stop us from gathering results, but it did delay the process dramatically, and made relatively straightforward tasks more painful than they otherwise would be. We would advise future teams to figure out a way to install the software locally, or access it in-person at one of the labs, since the latency we experienced was extremely sub-optimal.

4 Design Results

4.1 Software Automation

Our solution used the `pylibftdi` library, which wraps the D2xx drivers that the documentation for both the DC590 and LTC6946 reference. This library is necessary both because we were not able to find any documentation on the D2xx library itself[3], and because the underlying interfaces were written in ARM, requiring low level commands that would be challenging to make use of in Python without a wrapper library. This decision is described in substantially more detail in the midterm report, along with problems we dealt with along the way involving unresolved ambiguities in the documentation. Our code using the library is shown in Listing 1.

[3] The board documentation referenced a "programmer's guide," but the link to it went to the FTDI homepage with no indication of where to find the "programmers guide" that the documentation said the link would bring us to

```python
from pylibftdi import Device
# from register_mapping import register_values
from Transmitter_LTC6946_USB.register_mapping import register_values

"""
Written by: Jacob Silcoff & Haoran Du
Description:
1. Module for controlling the LTC6946 through the DC590B demo controller without the need for a GUI
2. Requires pylibftdi (if I understand correctly!), and its dependencies, including libFTDI and libusb/libconfuse
3. This code is currently untested, and very likely does not work as of this commit!
4. Functions::
    freq_set : sets a Tx frequency by setting registers from a register file
"""

def freq_set(freq):
    reg_vals = register_values(freq)
    if not reg_vals: return
    # construct command string:
    # start by sending a 0 byte to specify writing to register 0
    dc590_command = b'S00'
    for reg_val in reg_vals:
        if len(reg_val) is 1:
            reg_val = '0' + reg_val
        dc590_command += str.encode("S" + reg_val)
    print(dc590_command)
    with Device(mode='b') as dc590:
        # set baudrate?
        dc590.write(dc590_command)
```

Listing 1: Our approach on the freq_set(freq) function

The program we wrote used the bulk transfer protocol outlined in the LTC6946 documentation, and translated the register values for the given frequency to a command that met the interface defined by the DC590 into a string, that to the best of our knowledge would program the registers to the desired values. We then instantiated a connection to the device, and attempted to write this string to it. The code was very simple, fitting into only 14 lines, but represented weeks of research into various libraries and approaches.

The above piece was finished in late February without proper testings, meaning the performance is inconclusive.

The design process and results are described in substantially more detail in our Mid-Project report (see Appendices), but since there have been no updates on this project since the winter semester, we are only including the most important highlights in this report (as previously mentioned).

4.1.1 Suggestions for Future Work

The overwhelming majority of our design work for this component of the project was spent researching various libraries that we could use, since none of them had particularly good documentation. We are very optimistic about the `pylibftdi` library, but due to campus shutdowns were not able to test it on physical hardware. If a future team were to start where we left off, the first step would be to run the code given here and observe the results. As with any programming, there would likely be debugging involved, but we suspect that being able to start with a viable python library should make the automation process extremely straightforward. Since the serial interface that the LTC6946 provides is very simple, we suspect that once the correct interface is established (which we suspect the `pylibftdi` library should accomplish), the remainder of the work could be accomplished in a single day with the hardware.

We would recommend that anyone deciding to pick up this project read through our Mid-project report, which covers the relevant serial interfaces that they would need to use, and lists some alternative libraries that could be tested if `pylibftdi` does not work.

4.2 Substrate Selection

4.2.1 Initial Design Decisions

We began this part of the project by researching which flexible substrates were most widely used in industry in order to come up with a shortlist of materials to compare in our simulations. We decided on three materials to compare going forward.

The first was Polyimide (aka Kapton or PI), which was overwhelmingly the most commonly referenced flexible substrate material. We were particularly interested in it over other materials because we were able to find examples of researchers using it in an application that required two axes of curvature, such as a flexible sensor used to measure gas flow through a curved pipe [13].

The second material was polyester (aka PET), which was also commonly cited. PET was promising both because of its flexibility as well as its electrical stability across bending cycles. A study conducted by Merilampi et. al. found that during a single bending cycle, properties like sheet resistance varied by less than 2%, and across 10,000 bending cycles, these values changed by up to 10% in a linear manner [14]. Since the substrate will likely not endure nearly this degree of abuse, remaining attached to a rigid prosthetic bra, the relatively insignificant degree of variation for a small number of bending cycles is an appealing characteristic. The main drawback of polyester is its lack of heat resistance, which makes soldering to it difficult [15]. However, provided we are able to manufacture the circuit with reasonable connectors on both ports, this shouldn't be an issue. Were we to manufacture something like a flexible motherboard, with thousands of surface mount components, polyester would be impossible to use, but since we are effectively just designing wires, this is not a drawback in the context of this project.

The final material we examined was Liquid Crystal Polymer (LCP). It is commonly referenced as a low-loss flexible substrate specifically used in microwave frequency biomedical applications [16], indicating that it was likely a good fit for this project. One such example is provided by Hwang et. al., who used LCP substrates in long term *in vivo* applications, where the circuity needed to survive in a live animal while operating consistently at microwave frequencies. The researchers concluded that the material had "excellent electrical performance and mechanical stability" [16]. A summary of the basic properties of each material is shown in Table 1 below.

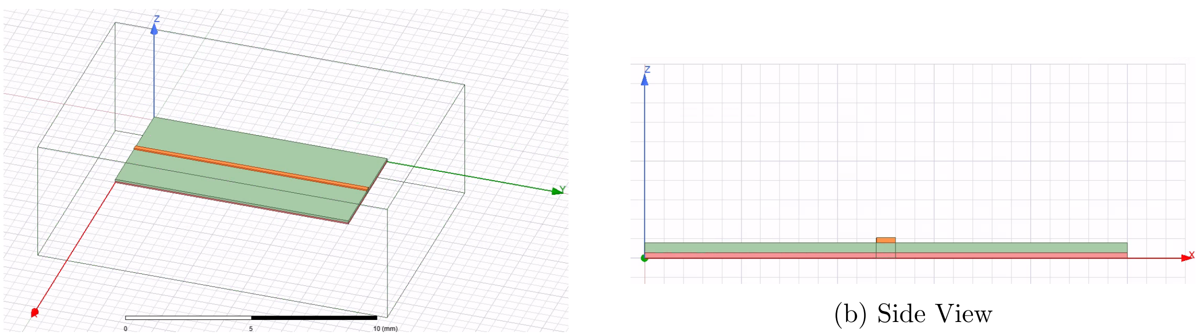
Table 1: Material Properties

Material	Relative Permittivity (ϵ_r)	Dissipation Factor	Min. Substrate Thickness (mm)	Supplier
PI [17]	3.4 at 1 MHz	0.01 at 1 MHz	0.08	PCB Way
PET [18]	3.0 at 1 MHz	0.018 at 1 MHz	0.12	Dreamland Industries
LCP [19]	2.9 at 10 GHz	0.002 at 10 GHz	0.025	Matrix Electronics

4.2.2 Creation of Planar Model

In order to test each material, we would use ANSYS HFSS, which simulates electromagnetic systems to analyze and design them. The first model would be a plane with a single microstrip running across it. This model would be extremely simple, and therefore require relatively little computational power to analyze. This was important for us because we intended to run hundreds of simulations to find optimal dimensions, meaning lengthy simulation times would dramatically delay the project. The second model was a hemisphere model with all of the traces in place. We would be able to use the dimensions simulated in the plane as a good estimate for the appropriate spherical dimensions, and then optimize within a small window around those dimensions, reducing computation time by limiting the range of dimension options based on our results from the planar model.

In order to easily modify single parameters and observe the resulting performance changes, the models were designed to be entirely parameterized, meaning when a single dimension was updated, every other dimension would be updated to scale. The planar model, which consists of a single microstrip on a rectangular section of substrate, is shown in Figure 5 below. This model can be accessed on our public GitHub repository (see Appendix A).



(a) Orthographic View

(b) Side View

Figure 5: Rendering of the Planar Model in HFSS

4.2.3 Simulation Methodology for Planar Model

To create dimensions for each material's optimized microstrip, we used a feature of HFSS called the "optimizer," which takes a specified dimension variable and varies it across a specified range in order to optimize an output of a simulation. For instance, we could specify that we wanted to vary the `stripWidth` dimension between 0.1 and 0.5 mm, perform a frequency sweep from 2-6 GHz for each one, and minimize the distance between the average Z_0 and 50 Ω. Running these simulations enabled us to determine what dimensions would optimize the output variables that we cared about.

Figure 6 shows what the output of the optimizer looked like. Each color is a different frequency, meaning the optimum width was the one where all of the lines were as large in value as possible (to maximize the average value of S_{12}).

One of the challenges we faced was that the output data we would receive for a given set of dimensions was a function of frequency as opposed to a concrete value, meaning additional post-processing was necessary to boil down the simulation results. To do this, we exported data from HFSS as a CSV file and imported it into Excel, where we were able to convert the $Z_0(freq)$ curve for a given model into the root-mean-squared (RMS) deviation from 50 Ω over all frequencies examined within the operating range. All of the excel files we used to manipulate the data, as well as the raw

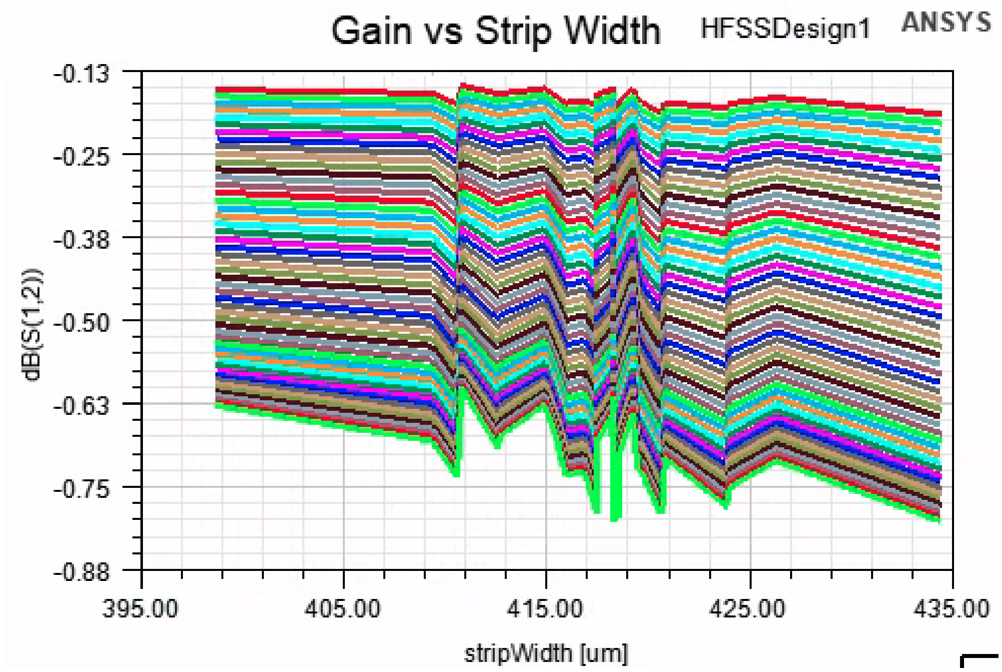


Figure 6: Gain vs Strip Width for LCP from 2 to 6 GHz

Table 2: Optimized Dimensions by Material

Material	Strip Width (mm)	Substrate Thickness (mm)	Copper Thickness (μm)	Z_0 RMSD (Ω)	Average S_{21} (dB)
PI	0.1823	0.1	55	7.665	−0.3207
PET	0.2326	0.12	89	7.627	−0.2433
LCP	0.4182	0.075	18	12.033	−0.4819

data in CSV format, can be found on our GitHub repository. For the S parameter, we simply took an average of the gain readings over the frequency range.

At the end of this process, we were able to arrive at a set of optimal dimensions for each material.

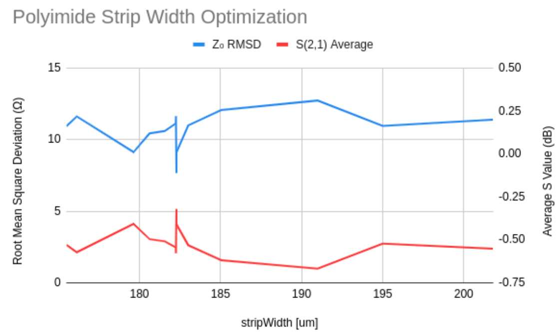
4.2.4 Simulation Results for Planar Model

The summations of our findings from running simulations with the planar model is shown in Table 2.

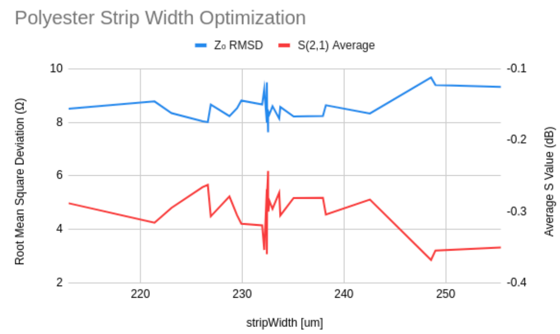
For each material, we began by collecting optimizer data across a range of strip widths. We exported this data to excel, where we created the graphs shown in Figure 7.

These graphs show how changing the width dimension of the microstrip impacts the two metrics we were comparing, and allows us to visually see where the extrema of interest were. This allowed us to set the correct dimensions for each substrate such that they could be fairly compared. We then reran a frequency sweep for all 3 materials using the optimized models, and graphed the data as shown in Figure 8.

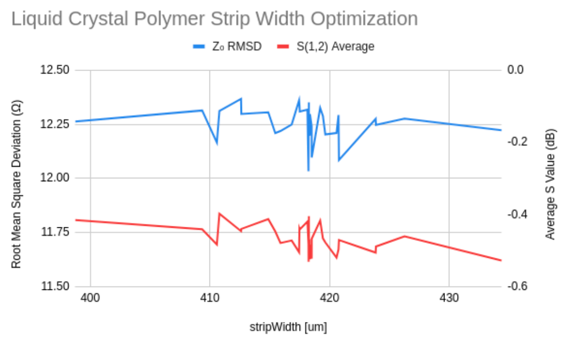
Using this graph, we can see how each material would function over the operating frequency



(a) Polyimide Optimization Graph



(b) Polyester Optimization Graph



(c) LCP Optimization Graph

Figure 7: Rendering of the Planar Model in HFSS

range of the research team's prototype, and observe how each would deviate from the desired values at given dimensions.

4.2.5 Suggested Improvements for Planar Model Simulation

During this process, we limited our design approaches largely to modifying the strip width, in part because we only got access to the simulation software late in the semester, and were time constrained in terms of the number of options we could explore. One important parameter that we would have liked to explore would be changing the shape and size of the ground plate. For the equations governing microstrips, there is an assumption that the ground plate is essentially infinite in size relative to the positive line, but in reality all this means is that the equations become less accurate as the ground plate shrinks relative to the microstrip. In order to maximize flexibility, we wanted to use as small of a ground plate as we could get away with for each line in order to reduce the board thickness. This would look like both using a rectangular ground plate that was smaller than the entire PCB, but could also encompass more elaborate solutions. One such idea was to perforate the ground plate (while preserving electrical continuity of course) in such a way that folding would be more straightforward. Using mesh ground plates is a known technique in flex PCB design, and involves a complex design process to trade off flexibility and signal integrity. We would likely modify traditional techniques slightly to suit our specific application, using a thinner mesh near the outermost parts of the PCB that would experience the greatest deformation when wrapped over a hemisphere. Unfortunately, we were unable to fully simulate solutions with these techniques due to time constraints, and technical difficulties modelling such designs in HFSS. This

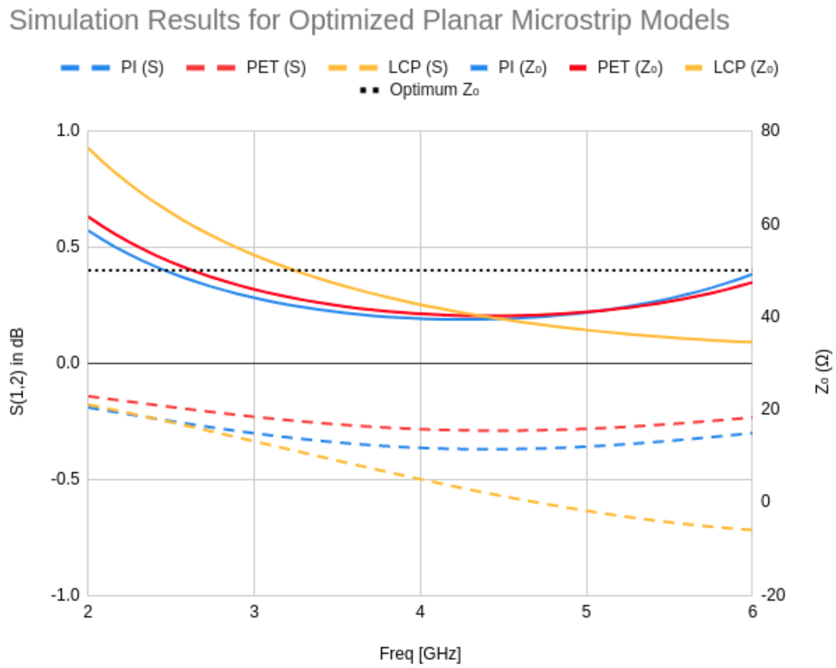


Figure 8: Comparison of Materials Using Optimized Geometry

is something we would recommend any future teams that take our place in future semesters to look into. We outlined methods for accessing the HFSS software in Appendix B for any teams wishing to continue on this work.

4.2.6 Simulations on Spherical Model

With a basic understanding of how to design microstrips with each material, the next step was to use a spherical model. We actually designed this model in parallel to our testing with the planar model, with the assumption that we could easily modify it based on the dimensions we find with our planar testing, since the hemisphere design would be fully parameterized. Since we found that HFSS lacked many of the basic tools to design complex 3D models, we used a free CAD software called OnShape to create an .STL file that could be imported into HFSS. Our design is shown in Figure 9, and can be accessed on our GitHub repository (see Appendix A).

We designed the model such that 16 copper strips create an electrical connection from one strip on the side of the hemisphere (where something like a ribbon cable could be connected) to 16 evenly spaced points on the hemisphere where antennas could be placed. Note that the traces shown in Figure 9 are unrealistically wide in the model shown for ease of visualization, but changing a single variable in the design would automatically shrink all of them and move them closer together where they meet. The inside of the sphere is coated with a solid continuous copper ground plate. One of the core issues with this model was drawing paths on a non-euclidean geometry. We ended up drawing the paths in a plane above the sphere and projecting them onto the surface, which was the only technique we could figure out how to implement in the CAD software we were using, although it is worth noting that neither of us are proficient enough in 3D modeling to claim it is the only way. This technique got us approximately the right results, but led to some strange distortions in

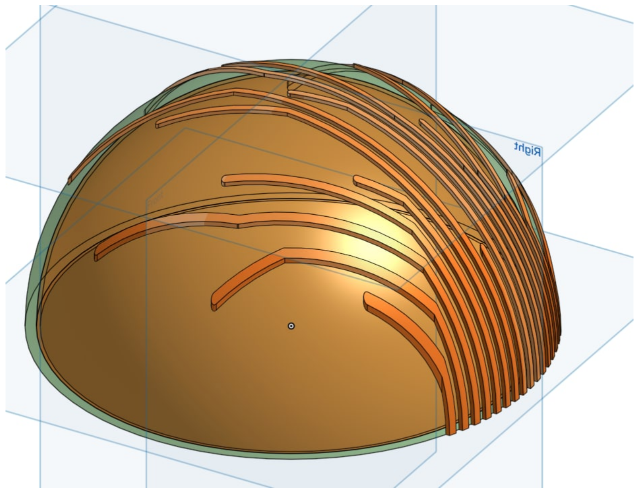


Figure 9: Spherical Model Rendered in OnShape

the parts of the design that were further from the pole of the hemisphere, leading to strips whose cross section was no longer a perfect rectangle among other issues.

Although we were told that a spherical model could be provided, we wanted to design it ourselves in order to have more flexibility with how we modified it, and to teach us the 3D modeling skills required to approach more complicated designs, e.g., replacing the ground plane with a mesh for improved flexibility.

Due to time constraints, we were not able to fully simulate our substrate materials with this model, but we will describe our technique here so that future teams can continue our work. The model should first be modified by updating the dimension variables based on the material, then imported into HFSS, where appropriate materials should be assigned to each part. Lumped ports should be specified on either end of all copper strips, and a radiation box should be added to allow simulation. An initial frequency sweep should be simulated to see how different the results for the spherical and planar model are, and optimization should proceed as with the planar model, but this time using a smaller possible range of values to reduce computation time. Once each material has been tested in this fashion, results should be compared in an identical fashion to the planar model.

4.2.7 Tentative Recommendations

Although further testing should be conducted to better compare the proposed materials, we would tentatively recommend pursuing a solution using polyester, as it had the highest gain and smallest deviation from the desired Z_0 when comparing the optimized planar models for each material.

5 Impact on Society & the Environment

Since our direct research for this project has largely focused on small components of the larger research projects that likely won't have broad societal or environmental impacts in and of themselves, we will mostly be focusing on the project as a whole when assessing the impact it has on society and the environment.

As a screening technology for breast cancer, there are a lot of biomedical ethics concerns that need to be examined. For instance, even in the best case scenario where this technology is demonstrated to be able to find tumors with 100% efficacy, this does not always imply that patient outcomes will improve, and historically over-screening for many types of cancer has done more harm than good. Elmore & Fletcher describe the problem of overdiagnosis of breast cancer in the Annals of Internal Medicine, writing ”overdiagnosis has been documented [even] in effective screening programs” [20]. This is because cancer is heterogeneous; some tumors may be malignant, while others either don’t grow at all, or grow so slowly that they pose no health risks within the expected lifetime of the patient [20]. When treatment is given for these benign tumors, invasive procedures ranging from biopsies to surgery and chemotherapy can dramatically reduce the quality of life for patients with no positive health benefits. While rates of overdiagnosis are difficult to pinpoint, even reasonably well studied techniques like mammography have been shown to have an over-diagnosis rate between 15%-25% [21]. The dangers of ”medicalizing” a patient should not be understated, as during any of the possible follow-up procedures, detrimental adverse effects can occur that can have major impacts on a person’s quality of life [22], and in countries like the US where healthcare coverage is not universal, can lead to patients bankrupting themselves along the way [23]. It is sometimes easy to focus on the limited technical problem of detecting cancer in the first place, while overlooking the much more nuanced problem of the treatment process as a whole. Given the early stage of research, it is too premature to speculate on how these issues will play out, but they will be necessary to consider as the technology develops.

Beyond the ethical questions of how such a screening technology should be used, there are procedural problems associated with when a seemingly promising technology should be released to the public. If the screening device has been shown extremely promising results but hasn’t fully finished being studied, it is non-trivial to determine whether it is ethical to withhold the technology from the public, a challenge facing many researchers in the bio-medical devices field [24]. Given the nature of the research, all traditional ethics concerns within scientific research such as procedural integrity and unbiased analysis of results become heightened, since this product has the potential to have large impacts on people that use it.

Moreover, since human trials are being conducted with the prototype, additional ethical requirements are imposed. Participants must be informed of the risks of participation, which luckily are relatively little due to the non-invasive nature of the prototype, and should be ensured that any information gathered about them, such as the presence or absence of tumors, will be kept entirely confidential given the sensitive nature of this type of personal information.

In terms of environmental impacts, any side effects of manufacturing the prototype are likely limited in the early stages of development, but as the technology progresses it is important that the materials and processes being used in manufacturing the device are ethically sourced, and contribute as little pollution as possible. Methods should be taken to reduce waste, such as designing in a modular way that enables easy recycling and repairs of broken or unused models, as e-waste is a serious environmental concern. The waste associated with PCB manufacturing has been shown to be associated most strongly with PCB size, which means waste can be reduced both by designing the circuit to be as small as possible while still meeting requirements, and also by designing it to tessellate efficiently onto the sheet it is printed on [12].

6 Report on Teamwork

Broadly speaking, work throughout the year was split evenly between the two team members. Starting at the beginning of the project in January, we planned weekly meeting times for us to meet one-on-one to go over the plans for the coming week and check in on progress, in person in the beginning of the Winter 2020 semester, and online once campus was shut down. These meetings were crucial for ensuring that we were consistently on the same page about work, and dividing tasks fairly.

For reports, we tended to have one person lead, alternating based on our schedules, and the other person edit the report and add detail where needed prior to submission. Since each of us had many other major commitments, being able to reduce our workload when we were comparatively busier than the other person made completing the reports substantially less stressful, and likely improved the quality of the reports as a result.

We generally both were responsible for individually learning about all of the tools and concepts that we were applying in the project. For instance, both of us spent a lot of time learning how to use HFSS so that we could both communicate about what work needed to be done, even if only one person spent more time running simulations. That being said, Haoran tended to take on tasks more closely related to general research, getting background information about the research team by reading through their publications, and liaising with the team, while Jacob tended to take on tasks that were more low-level, such as data processing tasks for the substrate design, or writing the code for the test automation software once the right library had been found.

When possible, we would split tasks in a way that would allow us to work asynchronous. For instance, Haoran was able to design the planar model while Jacob worked on creating a spherical model, since neither were dependent on the other being done. This reduced bottlenecks that can often occur in team projects when one person's tasks are contingent on the completion of the other person's tasks.

Since we were only two people as opposed to a much larger team, we were able to be relatively flexible about division of work, since it was easier to keep track of what the other person was doing and collaborate on single tasks.

7 Conclusion

Overall, although under unforeseen constraints, we were able to complete significant work in both software and hardware improvements of the prototype.

The software interfaced is completed and ready for testing.

For hardware, we designed and simulated both the planar model and the spherical model. The properties and performance of 3 substrate materials, namely PI, PET, LCP are tested over the operating frequency (2-6 GHz). Overall, the PET is found to be the most suitable substrate material. We created models that can be used by future teams to run similar testing, including more complex spherical models, and proposed several solutions to flexibility requirements, including using a mesh ground plate, or a folding technique that preserves intrinsic curvature.

8 Appendices

8.1 Appendix A: Relevant Files & Documents

All the files and designs that are referenced in this report can be found in this GitHub repository, including:

1. `Mid-project Report.pdf`: Containing more details on the background and design process of the software improvement part of this project.

2. `planar_model.aedt`: The planar model used in this project for substrate simulations.

3. `hemisphere_model.stl`: A CAD file for the proposed spherical model, which should be able to be imported into HFSS to conduct further testing on material properties. This file can alternatively be accessed using OnShape being going to this url, where it can be forked and directly edited.

4. `material_comparison_data.xlsx`: Spread sheets used to compare the frequency sweep data for each optimized planar model. This is how we created the combined $S21$ / Z_0 vs frequency graph in our results section.

5. `width_optimization.xlsx`: Spread sheets used to analyze the data obtained from optimization of strip width. These sheets can be used to quickly analyze any future simulations, since the calculations are mostly automated.

6. `raw_data/`: A set of organized CSV files including all of the raw data collected during our simulations.

8.2 Appendix B: Software Access Instructions

Per the request of our design group, the simulation software ANSYS HFSS has been installed on the machines operated and owned by McGill Engineering Microcomputing Facilities (EMF). As of the time this report is drafted, the simulation software is remotely accessible as "ANSYS ElectronicsDesktop 2020 R1" through RDP on the following workstations:

- `025TR5F1A.campus.mcgill.ca`
- `025TR5F2A.campus.mcgill.ca`
- `025TR5F3A.campus.mcgill.ca`
- `025TR5F5A.campus.mcgill.ca`

For details on using RDP at McGill EMF, please refer to the EMF RDP Guide FALL 2020 or contact McGill EMF directly.

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