EVALUATING THE PERFORMANCE OF SINGLE-ELEMENT VERSUS ARRAY-TYPE WIRELESS POWER HARVESTERS

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STATEMENT OF CANDIDATE

I, Hagop Keoroghlanyan, declare that this report, submitted as part of the requirement for the award of Bachelor of Engineering in the Department of Electronic Engineering, Macquarie University, is entirely my own work unless otherwise referenced or acknowledged. This document has not been submitted for qualification or assessment an any academic institution.

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Date: 14th of October

ABSTRACT

Electromagnetic energy is all around us. Particularly in urban environments. This energy can be harvested and used. Harvesting this power and converting it to DC power would be beneficial and can be used in various different applications such as charging biomedical devices like cochlear implants or providing a charge to more common items such as mobile phones. During this thesis CST will be used to work towards finding a design whether its single-element or an array-type antenna to effectively harvest power wirelessly. This design will then be tested in real life.

Contents

List of Figures

Chapter 1

Introduction

Not long after the discovery of electricity people such as Nikola Tesla tried to gather power electricity wirelessly from the environment around us. Nikola Tesla pursued to use Tesla coils to harvest power. This Thesis focuses on attempting to harvest this power wirelessly through the use of antennas.

Antennas are designed to receive and/or radiate electromagnetic waves in the radio waves spectrum. The transmission line or guiding device of the antenna may take the form of a hollow pipe or a coaxial cable. This transmission line is used to transport the surrounding electromagnetic energy from the antenna to the receiver if it's a receiving antenna or from the transmitting source to the antenna if it's a transmitting antenna. [3] For this project we will be using antennas to convert said waves into electric power. Regardless of the type of antenna used there will be a limited available bandwidth. By attempting to increase the frequency range and enhance the bandwidth capabilities of an antenna we can increase the different types of signals received by the antenna to increase the potential power harvested. If we harvest enough power wirelessly from the antenna we can use it to power smaller devices. [6] [3]

It is important to address this problem as there is currently power in the form of electromagnetic energy all around us. This energy can be harvested and used. However to effectively harvest this power on a day to day basis it is important to design an effective antenna that harvests considerable amounts of energy while using clothing material such as felt as the substrate.

There are a number of goals will be attempted to achieve throughout the project. The first goal is designing a single element antenna. After designing the antenna there will be an attempt to fabricate the antenna and with any luck the real world measurements will be similar to the results received while simulating. The next goal is to design a multi-array antenna and following the same steps of fabricating the antenna and testing it. Finally once both antennas are operating as intended the final goal is to conclude whether using single element or multi-array power harvesters will be more effective in harvesting power.

Each one of these goals will be individually simulated with the final goal being to be able to show the results of which power harvester more effectively harvests power with real world applications.

Chapter 2

Background and Related Work

2.1 Wireless Power Harvesting

Wireless power harvesting or wireless energy harvesting is as the name suggests the process of harvesting power from external sources. Wireless power harvesting allows for remote charging applications and allows for a battery or charger to be taken out and not be required for a particular application. There are many ways to harvest power now such solar power which uses the photovoltaic effect to convert solar radiation into DC electricity or wind and water turbines which turn kinetic energy into electric current. This thesis focuses on RF energy harvesting which attempts to turn RF energy into DC electricity. RF energy is available in a wide range of frequency bands due to modern technology such as:

- Mobile Phones
- Wi-Fi Routers
- Television signals
- Radio Towers

2.2 Properties of Antennas

As mentioned in the introduction, an antenna is used to receive and radiate electromagnetic waves. To design an antenna for a particular application you need to consider which type of antenna best suits your application and what characteristics are desired for the application. A number of characteristics required to design an antenna are discussed below. [3]

2.2.1 Operating Frequencies

The information we would like to receive or send is in a range of frequencies in a spectrum between two limits, this spectrum is known as the frequency band.

The bandwidth is the difference between the signals highest and lowest frequency where the performance of the antenna meets certain characteristics or standard. The bandwidth of an antenna is inversely proportional to the gain of the system. [3] [12]

2.2.2 Wavelength

The wavelength as suggested by the name is the length of a wave. That is the distance between two identical points on a wave at a fixed time, regardless of whether its a peak or trough or somewhere in the middle. The wavelength can be found with the following formula. [3] [12] [4]

$$\lambda = \frac{V}{f} \tag{2.1}$$

Where λ, is for the wavelength, f is frequency and V speed of the wavelength.
To find V you need to use the following formula.

$$V = \frac{C}{\epsilon_R} \tag{2.2}$$

Where C is the speed of light in a vacuum and as we know ϵ_r is the dielectric constant of the material.

2.2.3 Phase Velocity

Phase velocity is used to describe the speed of at which a constant phase point travels through the wave. The mathematical expression for phase velocity is: [3] [12]

$$V_p = \lambda * f \tag{2.3}$$

2.2.4 Radiation Patterns

A radiation pattern is a graphical representation of the power radiated and the direction of radiation by an antenna. The farfield shows the power variation and as a function of the arrival angle. Different antenna types have different patterns of radiation, the radiation pattern for a basic micro-strip antenna can be seen below in figure 2.1. [3] [12]

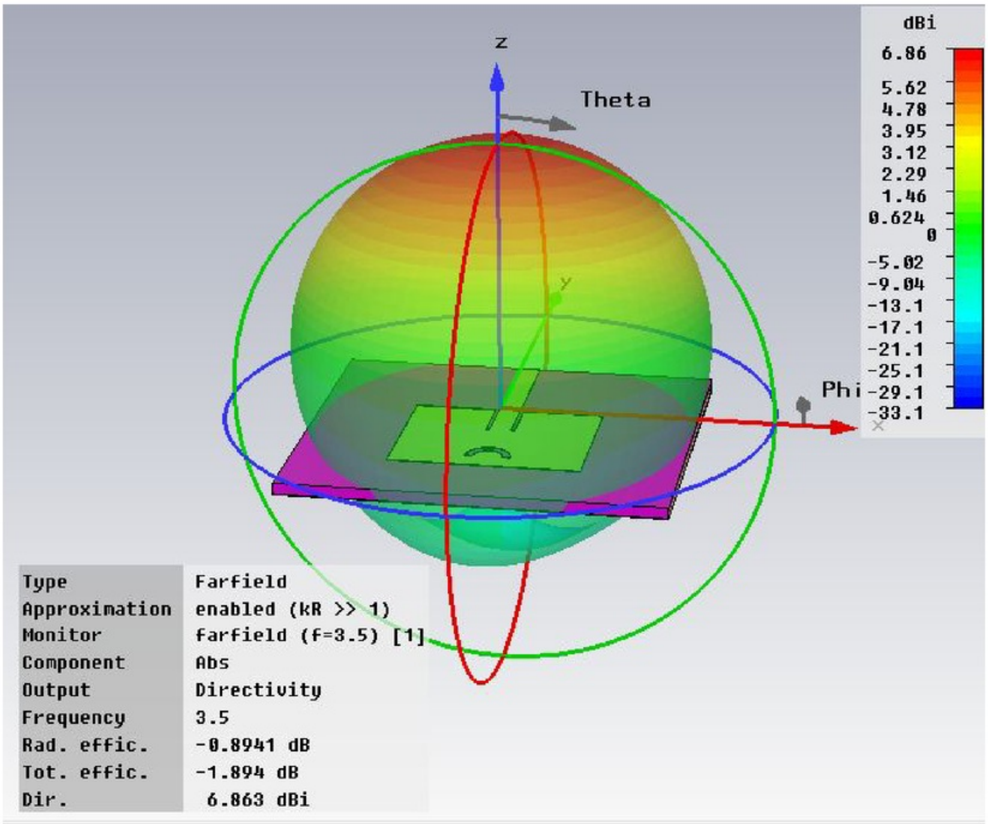

Figure 2.1: The radiation pattern of a micro-strip antenna.

2.2.5 Directivity

The mathematical expression for directivity is:

$$D = \frac{U}{U_o} = \frac{4 * \pi * U}{Prad} \tag{2.4}$$

Directivity is a measure of the direction of an antennas radiations pattern. That is, if an antenna had a radiation pattern that radiated evenly in through all possible directions, the directivity of this antenna would be 1. [3] [12]

2.2.6 Efficiency

Antenna efficiency is the ratio of power received by the antenna compared to the antennas radiated power. This means that if an antenna has high efficiency most of the power

received is radiated, contrary to this an antenna with low efficiency has most the power lost or reflected by poor impedance matching. [3] [12]
The mathematical equation for an antennas radiation efficiency is:

$$\epsilon_R = \frac{P_{radiated}}{P_{input}} \tag{2.5}$$

While equation 2.5 shows the antennas radiation efficiency, to find the total efficiency of the antenna, the antennas losses due to impedance matching, $\mathrm{M_L}$ needs to be taken into account which gives us equation 2.6. [3] [12]

$$\epsilon_T = M_L * \epsilon_R \tag{2.6}$$

2.2.7 Gain

Gain is used to describe the power radiated in a particular direction, usually the peak direction of radiation. Gain takes into account directivity and total antenna efficiency. [3] [12]

The mathematical representation of gain is shown below in equation 2.7.

$$G = \epsilon_R * D \tag{2.7}$$

2.2.8 Beamwidth

Beamwidth is simply speaking the angular sepreation between two perfectly identical points on opposite sides of the radiation pattern. [3] [12]

The main types of beamwidths are:

- Main beam - Found on the maximum radiation the main beam is usually within 3db of the peak
- Sidelobes - Away from the main beam, there are smaller beams called sidelobes. Usually occuring and radiating in unhelpful and unwanted direction, these sidelobes can never by completely removed.
- Half Power Beamwidth - Half power beamwidth or HPBW is the separation found where the radiation pattern has decreased by 3db or 50% from the peak of the radiation.

2.2.9 Dielectric Constant

The dielectric constant of a material is best described as a ratio of the permittivity of a substance to the permittivity of free space. As the dielectric constant increases, the electric flux density increases which in turn allows materials to hold their electric charge. Hence materials with high dielectric constants are often used in the design and manufacture of inductors and capacitors. [3] [6] [1]

2.2.10 Impedance of Antennas

As with all electronics the impedance or resistance of the system can be described with Ohms law which relates the voltage, current and resistance as seen below in equation 2.8.

$$R = \frac{V}{I} \tag{2.8}$$

An antennas input impedance similarly to Ohms law is the ratio of voltage to current at the antennas terminals. With no load the impedance of an antenna can be shown as:

$$Z_A = R_A + jX_A \tag{2.9}$$

Where $\mathrm{Z_A}$ is the impedance at the antennas terminals, $\mathrm{R_A}$ is the resistance at the antennas terminals and $\mathrm{X_A}$ is the reactant at the antennas terminals. [3] [12]

2.2.11 S-Parameters

Four particularly important measurements for the design of electronics such communication systems particularly those operating in microwave frequencies are the S-parameters. S-parameters relate to most properties seen in electronics such as power, gain, return loss and the voltage standing wave ratio (VSWR). S-parameters are observed by sending a signal through an one port and observing the response on another port. The system needs to be impedance matched properly before calculating S-parameters due to the reflections that will be recorded on the output feed. These reflections will cause standing waves to appear which causes the system to produce outputs that are not desired. There are four types of S-parameters, these are: [3] [12]

- S_{11} which represents the input reflection.
- S_{22} which represents the output reflection.
- S_{12} which shows the reverse transmission coefficient.
- S_{21} which shows the systems overall gain.

2.2.12 Voltage Standing Wave Ratio

Voltage standing wave ratio or VSWR is shown when the transmission line is not matched to the element and some of the energy is absorbed by the element and some of the energy is reflected back through the transmission line. This interference between the incident and reflected wave creates a standing wave on the transmission line. The measurement of the mismatch on the transmission line is known as the VSWR. [3] [12] [4]

$$VSWR = \frac{V_{\max}}{V_{\min}} = \frac{1+\Gamma}{1-\Gamma} \tag{2.10}$$

Where Γ is the reflection coefficient of the transmission line and VSWR has to be: $1 <$VSWR $<\infty$, where 1 shows a matched load.

2.3 Types of Antennas

Depending on the application different types of antennas are used, there are numerous types of antennas many of which are discussed below. Taking into account the advantages and disadvantages of antennas a better choice can be be made for the project at hand.

2.3.1 Wire Antennas

The most well known antenna as it is often seen on the vehicles on the road, on buildings and even on aircraft and spacecrafts. These antennas are variations of the dipole antenna. [3]

2.3.2 Reflector antennas

Reflector antennas rely on a parabolic reflector which is used to communication over millions of kilometers. Antennas have been built with reflector diameters as larger than 300m. [12]

2.3.3 Microstip antennas

Microstrip antennas are extremely useful antennas for use at frequencies within the microwave spectrum where the frequency itself is greater than 1Ghz. Microstrip antennas consist of 3 planes, at the bottom a ground plane, above this ground plane is a dielectric substrate and finally above the substrate sits the metallic patch. Microstrip antennas come in a variety of shapes and sizes such as, square, rectangular, dipole, circular, elliptical, triangular, disc sector, ring sector and circular ring as can be seen in in figure 2.2. [14] [7] [1] [3] [12]

Micro-strip antennas have gained popularity due to their low cost, low weight, ease of fabrication, easy to feed, their flexibility to conform to a particular surface and are easy to use in an array antenna system. However micro-strip antennas do have a few disadvantages as they have a narrow frequency bandwidth, low efficiency as micro-strip antennas cannot handle large amounts of power due to dielectric break down and the final disadvantage is that microstrip antennas are only useful at frequencies at the and greater than microwave spectrum . [12] [3] [9] [6] [14] [7] [1]

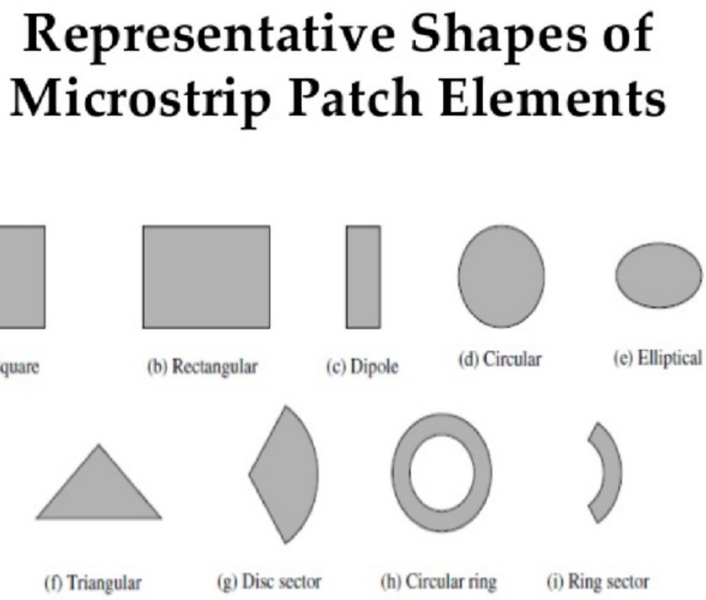

Figure 2.2: Possible patch designs for microstrip antennas.

Rectangular Patches

Rectangular patches are the most commonly seen microstrip antenna design. Easy to analyse with either a transmission line or a cavity model. Consider figure 2.3 which shows a rectangular patch with a transmission line feed. Adjusting the dimensions shown adjusts the performance of the antenna. Adjusting L, the length of the patch, affected the frequency the antenna best operates at, while adjusting W, the width of the patch affects the effectiveness of the antenna, this can be seen in an S11 plot as the magnitude of the S11 plot increases accordingly. In a scenario with an adjustable substrate height, h, the height of the substrate affects the bandwidth of the antenna. [3] [5]

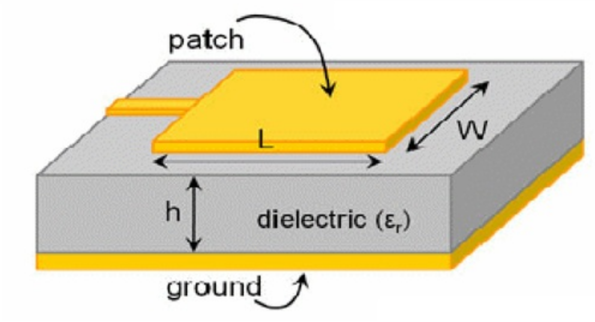

Figure 2.3: The design of a rectangular patch.

Circular Patches

After the rectangular patch the circular patch is the most common configuration for microstrip antennas. With circular patches there is only the radius of the patch to control the length of, adjusting the radius affects the resonant frequency. A circular patch microstrip antenna cannot be fed with a transmission line and can only be analysed using the cavity model. [3] [1]

Feeds

The Microstrip antenna requires a feed. There are numerous types of feeds, the most common feeds include:

- Transmission Line Feed One of the most common methods to feed a microstip antenna is with a transmission feed line. A transmission line feed is visible in figure 2.3. A transmission line feed is a strip of the same material as the patch connecting the edge of the patch to the edge of the substrate for the feed to connect to both the patch and the ground plane simultaneously. The Transmission line feed is popular as it is easy to fabricate and simple to impedance match, the only main disadvantage of the transmission line feed is that this design limits the final bandwidth of the antenna. [3] [12] [11]

- Coaxial Probe Feed As shown in figure 2.4 a coaxial probe feed has the inner conductor meeting the microstrip antennas patch and the outer conductor metting the ground plane. The pros of using a coaxial probe feed is that its easy to impedance match and it's easy to fabricate, however the coaxial probe feed has a smaller bandwidth and is harder to model particularly for larger substrates. [3] [12]

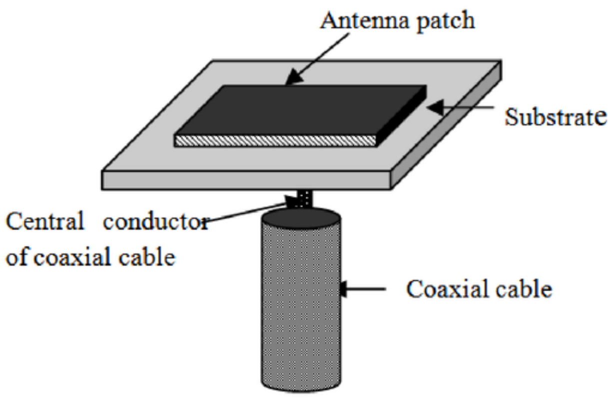

Figure 2.4: A coaxial probe feed.

2.3.4 Array Antennas

An array antennas is a set of at least two single element antennas used simultaneously. These are used for applications that require characteristics of antennas that may, for some reason, not be feasible with a single element. The arrangement can be in many different ways so that the required characteristics such as radiation direction are achieved. [3] Consider figure 2.5 to see some of the different possible antenna array types. Although an array antenna can be used to improve the performance over a single element antenna by increasing overall gain and/or canceling out interference gained on the single element antenna design the trade off is that the array antenna will be require more time to design, will be more difficult to fabricate and in turn will be more costly in every way compared to a single element antenna. [3] [9] [6]

There are two ways to feed a microstrip array antenna, these methods of feeding the array are known as series feed and corporate feed. A series fed design can be seen in figure 2.6 and a corporate fed design can be seen in figure 2.7.

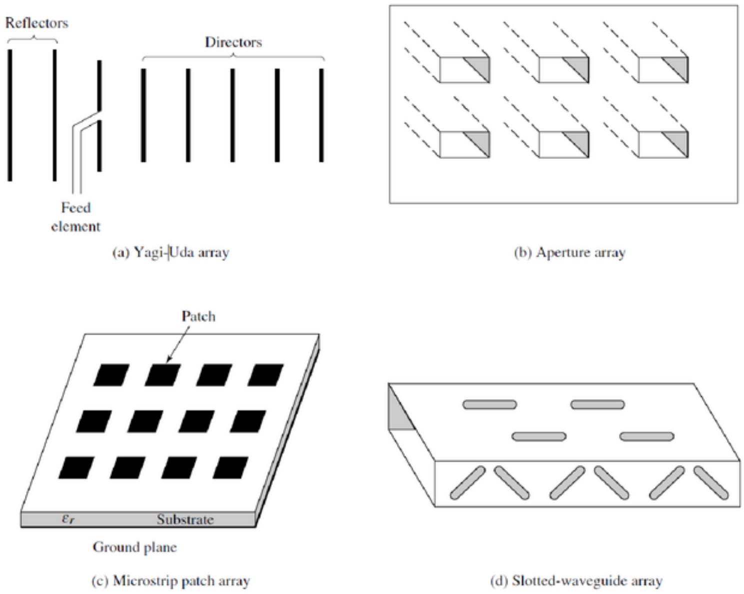

Figure 2.5: Typical designs for array antennas.

The series fed antennas can have both the patches and the feeds easily fabricated through photolithography, a process where light is used to etch a geometric pattern onto the substrate. However there are a couple disadvantages of the series fed array antennas, firstly the change in one element or feed line results in the complete unit being effected and secondly the series fed array antenna results in a phase delay. [3] [12] [10]

A corporate feed is named appropriately as it is set out to look like a corporate job position layout. The patch are laid next to each other and feed lines connect them as seen in figure 2.7. The corporate layout has to be set at for a patch impedance of 100Ω to be fed using a 50Ω input using a quarter wavelength impedance transformer. [3] [12] [10] [15]

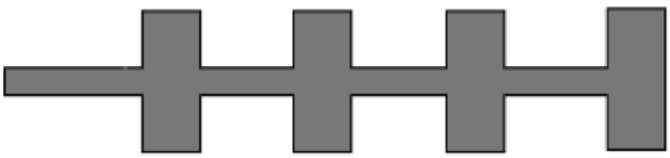

Figure 2.6: A series fed array antenna design.

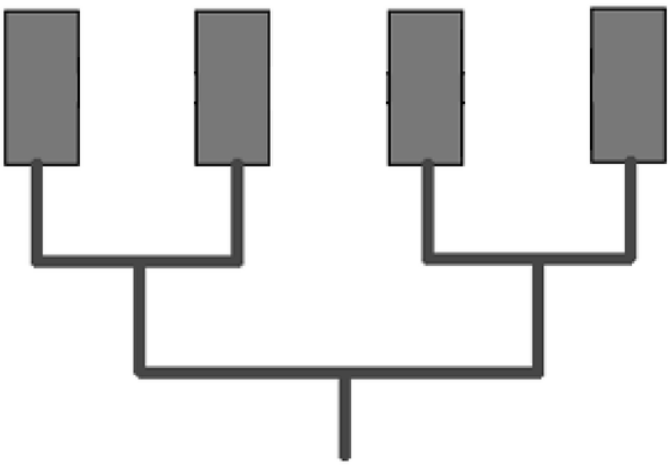

Figure 2.7: A corporate fed array antenna design.

Chapter 3

Approach and Methodology

For the sake of testing and real world feasibility it was decided to try and harvest power from Wi-Fi as Wi-Fi signals would be everywhere at the university. This meant that the antenna had to be capable of harvesting power from either 2.4GHz or 5GHz. From the research conducted it was concluded to move forward with a rectangular patch microstrip antenna design and a corporate fed array design.

In order to reach the final goal of wirelessly harvesting power at 2.4GHZ using single element and array type antennas, first designs needed to be modeled and simulated designs in the 2014 version of CST, Computer Simulation Technology. The data gathered from these was plotted in MATLAB R2017a. Once I had designs which met the required characteristics desired, a prototype was made using felt and copper tape, this prototype was tested on an Agilent Technologies PNA-X Network Analyser, model no: N5242A which in turn was calibrated using an Agilent Technlogies electronic calibration kit model no: N4691-60006. The data gathered from the Agilent Technologies PNA-X Network Analyser was also plotted in MATLAB R2017a.

3.1 Modeling and Simulations

3.1.1 Determining Parameters of Materials

When designing the antenna there were a number of characteristics that needed to be met. Firstly the materials that will be used have to be taken into consideration as different materials affect antennas in different ways. By choosing to use the felt provided by the university for the substrate and choosing to use copper tape for the patch and ground plane the some of the physical parameters were already set by the components being used. Firstly the height of the felt and hence the substrate was predetermined at 2.5mm. This meant the height of the substrate couldn't be changed for the means of designing a better antenna. Secondly the height of the ground plane and patches had to be 0.13mm as this was the height of the copper tape which was being used.

The next physical parameter that needed to be refined before simulation began was the dielectric constant. The best source found to get the dielectric constant of felt was table 1 on page 2 of "A Flexible 2.45GHz Power Harvesting Wristband With Net System Output From - 24.3 dBm of RF Power" by Salah-Eddine Adami, Plamen Proynov, Geoffrey S. Hilton, et al. where the dielectric constant, ϵ_r, of felt is shown to be 1.2. [13] This table can be seen in figure 3.1.

The electric conductivity of the copper tape was provided by the co-supervisor Roy Simorangkir which was given to be 1012615[S/m].

TABLE I

CHARACTERIZATION RESULTS OF VARIOUS SUBSTRATE MATERIALS AT THE 2.45-GHz BAND

Category	Candidate materials	h (mm)	Two-Line Method		T-resonator Method	α_{Typ} (dB/m) Typical Microstrip line, w=3 mm and h=1.6 mm	Suitable for screen printing
			ε_r	$tan\delta$	ε_r		
Sandwich used in [12]	Polycotton (1/3 of thick.) + standard Interface material (2/3 of thick.)	0.95	3.23	0.06	3.2	22.4	Good
Interface (Smart Fabric Inks Ltd.)	Standard interface material (Fabink-UV-IF1, used in [12])	1.94	3.26	0.063	3	23.6	Good
	Waterproof interface material (Fabink-UV-IF010)	1.4	2.68	0.052	2.75	17.9	Good
Felt (Fabric Land, UK)	Polyester felt	1.65	1.2	0.023	1.14	5.8	Poor
Woven (Fabric Land, UK)	Cotton woven	0.41	2	0.028	2.05	8.5	Acceptable
	Woven polyester	0.33	1.5	0.028	1.52	7.6	Acceptable
Polymers (DuPont™)	Flexible thin Kapton® polyimide film	1	2.8	0.014	2.83	4.9	Excellent
Reference	Duroid-5880 (Roger Corp.)	1.57	NPB	NPB	2.18	0.3	Excellent
	FR4 (Mega-electronics, UK)	1.6	4.22	0.017	4.2	7.6	Excellent

Legend: h: height of the substrate, **Suitable for screen printing**, from low to high: Poor-Acceptable-Good-Excellent, **NPH**: Non-Physical behaviour.

Figure 3.1: Table of material properties used as substrates. [13].

3.1.2 Simulations in CST

The material information gathered and discussed in the previous section for was used to create two new materials in CST for the simulations. These two materials were used to create the models which would then be simulated.

Once the custom materials were added into CST, a basic microstrip antenna was created for the purposes of testing. Parameter sweeps were run with a changing the height of the substrate as well as the length and width of the patch itself. This was done to see how the changing of the dimensions affects the microstrip antenna.

Next through a similar parameter sweep there was an attempt to make the first single element this model. This was done by running a parameter sweep where the width and

and length were adjusted over an array of numbers to find which combination of width and length on the patch that creates an single element microstrip antenna that has an S11 that has a bandwidth that covers 2.4GHz at -10dB.

This model was then worked on and improved. The first step to improving this model was improving the feed line. Initially there was a feed line that was put in was the length required to reach from the edge of the patch to the edge of the substrate, it was also just a random width. The length needed to be changed so that the length of the feed line was a quarter wavelength ($\frac{\lambda}{4}$) transmission line.

This single element model was translated into a multi-array model by copying the single element four times over. These four single elements were fed by the corporate feeding method. The results didn't come out as expected so the basic patch was redesigned. The initial re-design had the 50Ω input feed meet with a 70.7Ωtransmission line which then fed into the 100Ω transmission line which would bridge two elements together. This was repeated to connect all four tickets together and create a corporate feed. This design can be seen in figure 3.2. This design had an impressive S11 result however the farfield result were horrendous. Due to not being able to rectify this error in a timely manner the design was scrapped and was restarted.

It was soon discovered that the input impedance was not properly taken into consideration. Using an antenna input impedance calculator online as seen in figure 3.3 it was found that a length of 54.266mm and a width of 59.591mm was required.

This information could not be translated directly as it would be impossible to be able to make a prototype with copper tape which was exactly 54.266mm long and 59.591mm wide. Using this newly found data a new patch was multi-array patch was made, with 100Ω feed lines meeting to a 50Ω feed line.
The final design can be seen below in figure 3.4. The length of each patch is 52mm and the width is 60mm .

3.2 Prototyping and Testing

Once there was a final design which met the required specifications prototyping began. This involved using copper tape for the patches, feeds and ground plane and felt provided by the university for the substrate. The positioning of the feeds and patches was mapped onto the felt with pen, then copper tape was used to fill in the required positions. This can be seen below in figure 3.5 and 3.6. Once the prototype was made a small input feed had to be added which was connected with copper tape.

This prototype was tested on an Agilent Technologies PNA-X Network Analyser, model no: N5242A which was calbrated on a Agilent Technologies electronic calibration kit, model no: N4691-600096. It was tested on a large piece of foam which in turn

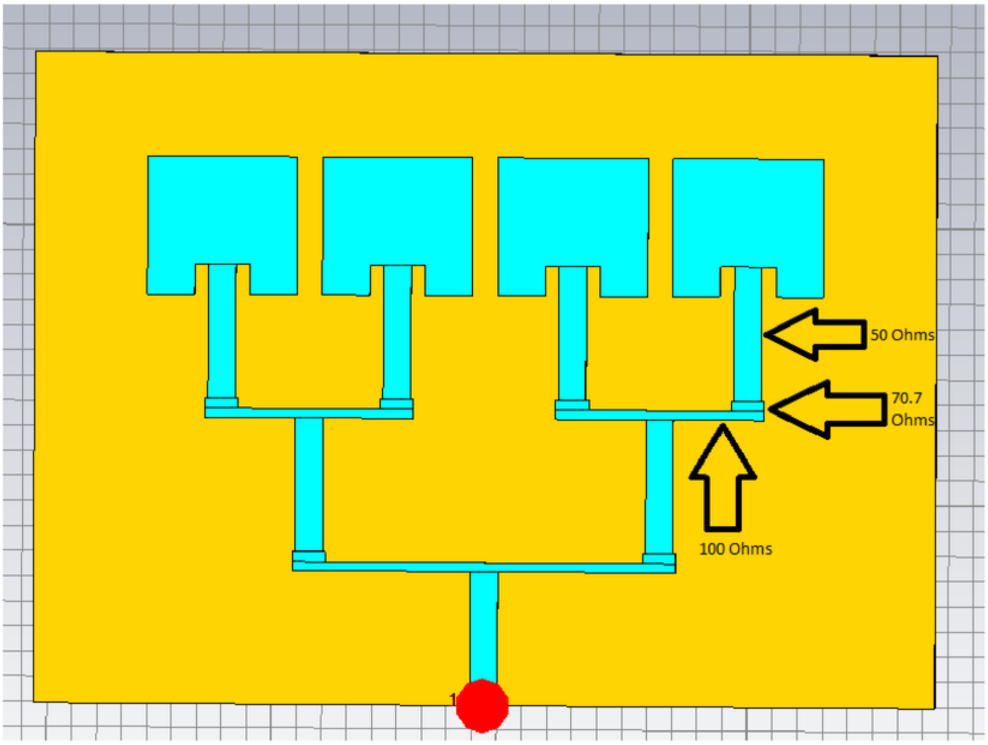

Figure 3.2: The initial redesign of the multi-array antenna.

acts as free space. Once it was tested in lying flat on the foam which acted as free space. The prototype was then tested to see how it would act in imperfect conditions, it was then put into less than perfect conditions. The first test was bending the complete multi-array antenna over itself, this was simply to see if the network analyser was functioning correctly. The next set tests required using small bottle to bend the prototype. The first of these tests had the prototype of the multiarray antenna bend in the middle, the second test had the prototype bent on the left hand side of the input feed and the final test had the prototype bent on the right side of the input feed. The bending of the fabric was kept constant by leaning the antenna onto small bottle which was placed under it. The testing conditions described above can be seen in figures 3.7, 3.8, 3.9 and 3.10 below.

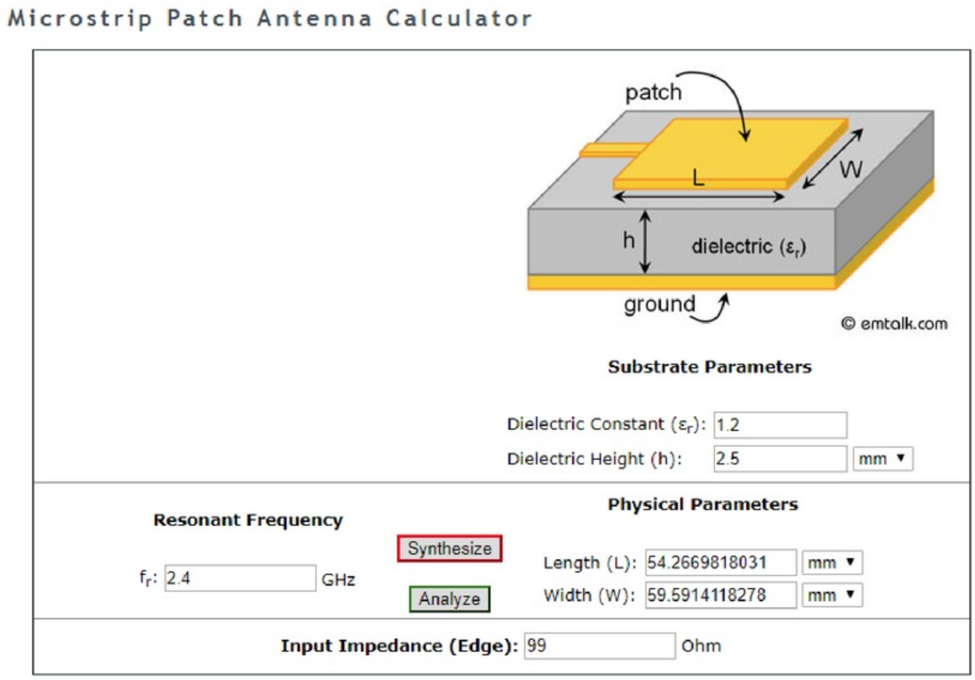

Figure 3.3: The calculator showing the physical parameters required for an input impedance of 99 Ω

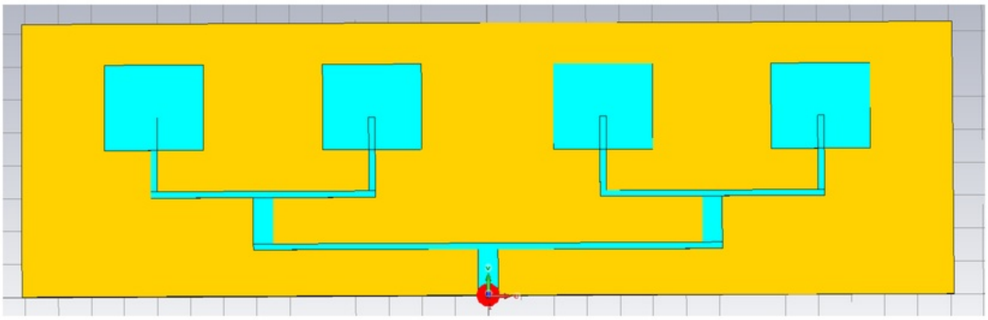

Figure 3.4: The final multi-array antenna design

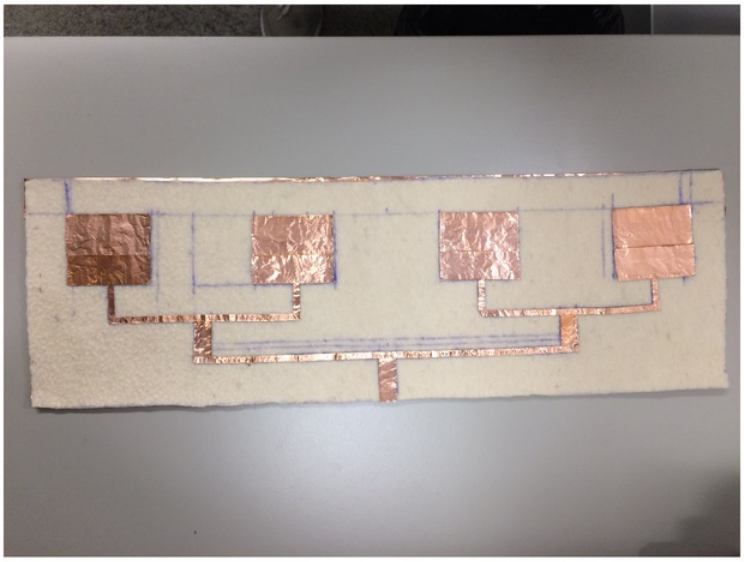

Figure 3.5: The top of the prototype of the multi-array antenna design. This acted as the elements and transmission lines

Figure 3.6: The bottom of the prototype of the multi-array antenna design. This acted as the ground plane.

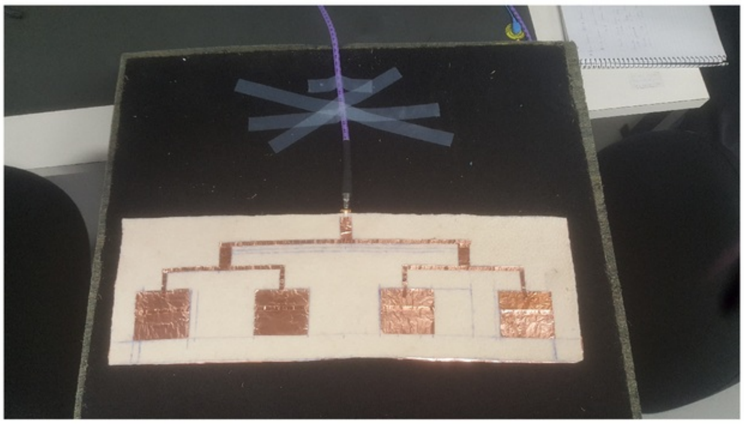

Figure 3.7: The initial testing conditions, the array is lying flat on the foam which is acting as free space.

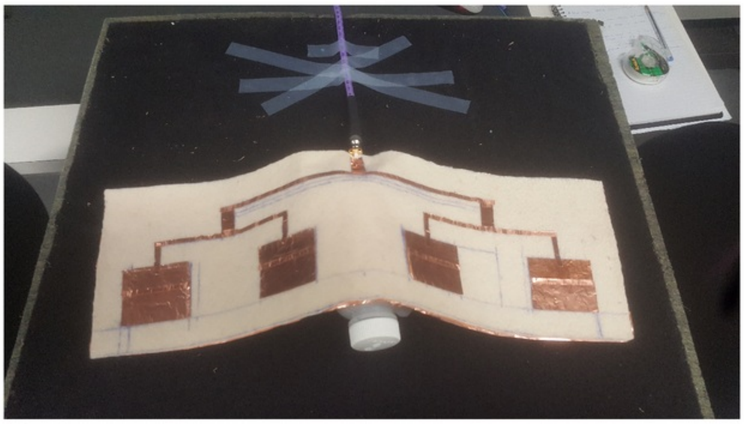

Figure 3.8: The first change in testing conditions, the array is has been bent from the middle and is lying on the foam which is acting as free space.

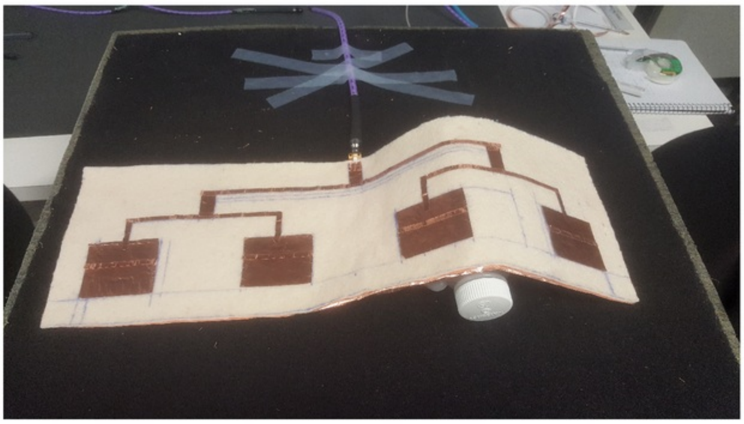

Figure 3.9: The first change in testing conditions, the array is has been bent from the left hand side of the feed and is lying on the foam which is acting as free space.

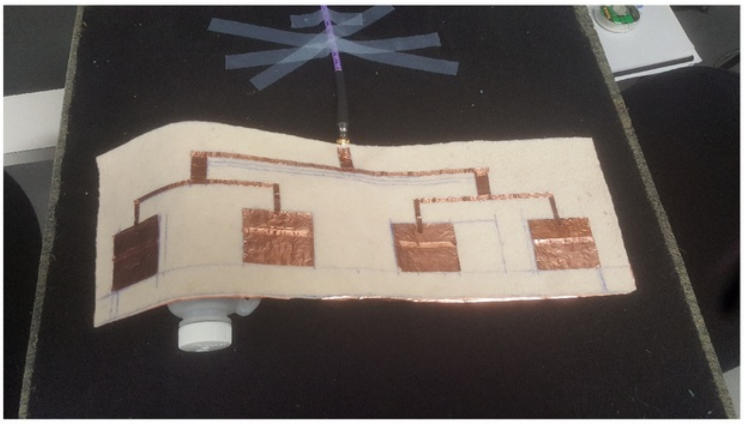

Figure 3.10: The first change in testing conditions, the array is has been bent from the right hand side of the feed and is lying on the foam which is acting as free space.

Chapter 4

Results and Discussion

4.1 Modeling and Simulations

As discussed in the previous chapter the first action taken in CST was to experiment with a basic single element design to see how adjusting the dimensions effects the antenna. It was seen through the parameter sweeps that adjusting the height of the substrate effected the functioning bandwidth of the unit. The second parameter sweep changing the width of the patch effected the magnitude in dB of the antenna achieved in S11. The final set of parameter sweep, swept through various values for the length of the antenna. Using this information is helpful as it assists in decision making when making adjustments to the design in future.

Below in figures 4.1 and 4.2 the implementation of an inset in the patch to get a quarter wavelength transmission line is shown. This inset as expected resulted in better overall results. The resultant S11 of figure 4.2 can be seen in figure 4.3. It was clear that the antenna with the inset seen in figure 4.2 was more effective than the antenna without the inset seen in figure 4.1 as the farfield results were considerably better.

When the antenna in figure 4.2 was copied four times over to create the multi-array antenna, the S11 results were still very applicable however the farfield results were quite bad forcing us to redesign the antenna. The S11 and farfield results of figure 3.2 can be seen in figure 4.4 and 4.5 respectively. There was a considerable improvement in the S11 of the unit which can be seen as the bandwidth at -10dB of figure 4.4 is much better than the bandwidth at -10dB of figure 4.3. However as mentioned the farfield results were not good and this design was given up in favour of redesigning a unit from scratch rather than using limited time to improve upon this design.

The new design which ended up being the final design seen in figure 3.4 was made by running a parameter sweep of a basic rectangular patch multi-array antenna which was corporate fed, knowing that the length should be about 54mm and the width 59mm allowed for a much smaller parameter sweep. The best simulated results came from a

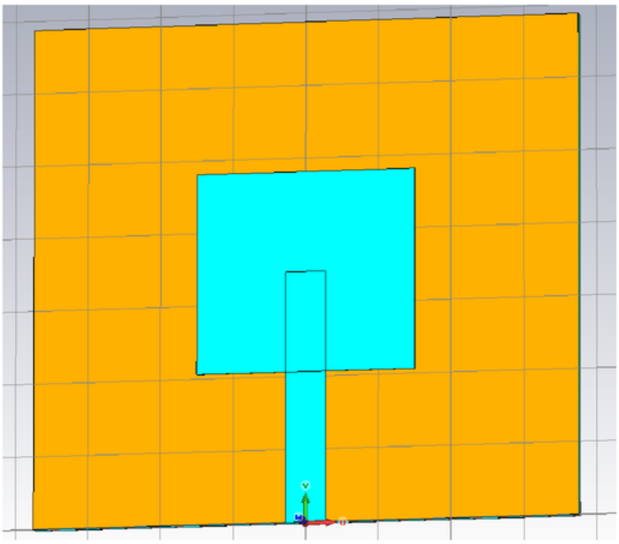

Figure 4.1: The initial design of the microstrip antenna.

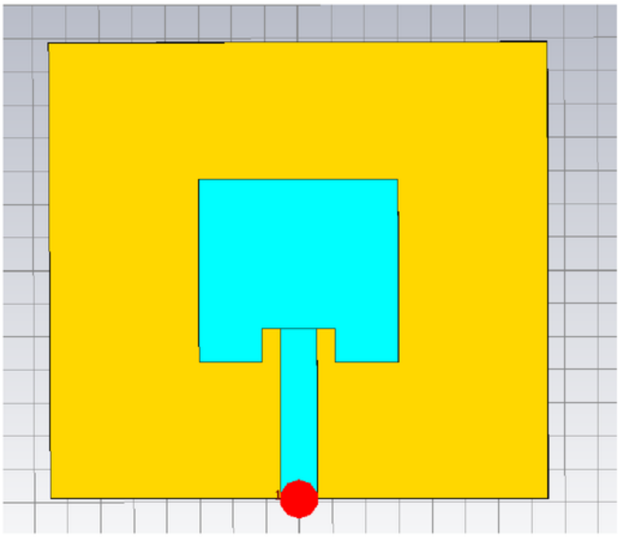

Figure 4.2: The design of the microstrip antenna with an inset to meet the quarter wavelength tranmission requirement.

length of 52mm and a height of 60mm. The resultant S11 can be seen in figure 4.6 and the resultant farfield results can be seen in figure 4.7. The bandwidth at -10db was more

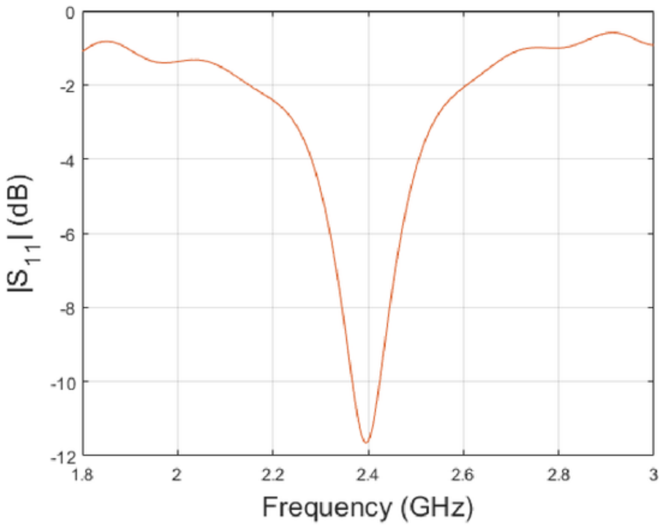

Figure 4.3: The S11 of the microstrip antenna seen in figure 4.2.

than large enough to cover 2.4GHz and the farfield results although were not perfect as they were slightly skewed they were still applicable.

By comparing the plotted the resultant S11 of both the single element microstrip antenna as well as the array antenna as seen in figures 4.3 and 4.4 it shows how the array type antenna has both had a wider bandwidth and larger magnitude at 2.4GHz which meant that the array type antenna was more effective in wirelessly harvesting power from 2.4GHz.

4.2 Testing the Prototype

As discussed above in Chapter 3, Approach and Methodology, the prototype was tested on an Agilent Technologies PNA-X Network Analyser, model no: N5242A which was calbrated on a Agilent Technologies electronic calibration kit, model no: N4691-600096. The initial test of the prototype on freespace yielded very positive results. The results can be seen in figure 4.8,which compares the simulated S11 results to the measured S11 results. To confirm that these results were correct and wasn't some sort of inaccuracy or machine fault the antenna was as described previously folded to have the ground plane both on the top and bottom, this completely stopped all waves the antenna was receiving which in turn completely ruined the results, the fact that the S11 results were ruined showed that the S11 results measured wasn't an anomaly.

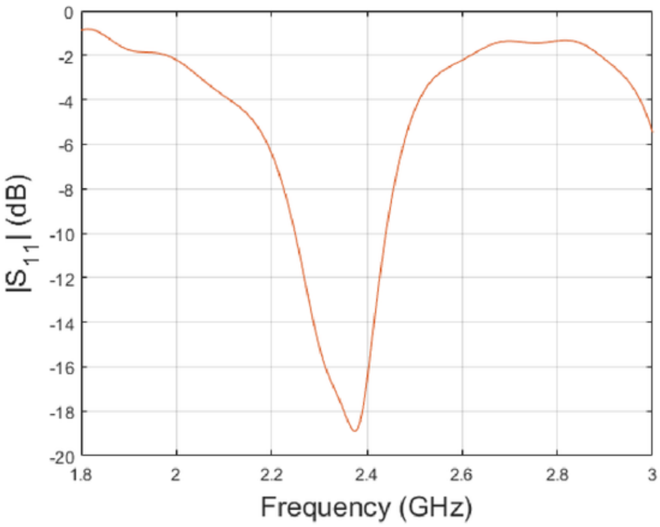

Figure 4.4: The S11 result of the antenna from figure 3.2.

As described earlier, the antenna was then tested in imperfect conditions. This meant using a small bottle to bend the antenna as seen in figures 3.8, 3.9 and 3.10. This was done to see how the antenna would function went bent as the final application for an antenna like this would be to use it with clothing. Below in figure 4.9 a graph can be seen below of all the measured S11 results compared against the simulated designs S11 result. From this graph in figure it is clear that the bend of the antenna does have an impact on the effectiveness of the antenna. Interestingly the bandwidth of the prototype is more narrow than the bandwidth of the simulated antenna, this was unexpected, it was expected for the prototype to have a wider bandwidth as bandwidth is inversely proportional to loss, hence with the increased loss in a non-perfect system the bandwidth should increase. There are various reasons for the bandwidth decreasing instead of increasing as expected, the most likely explanations are either that it has to do with the substrate or the copper taping used for the patches and feed lines. So the substrate provided did not have a height of exactly 2.5mm, the substrates dielectric constant could be different to the dielectric constant from the felt in figure 3.1, or imperfect measurements when cutting the copper tape affected the performance antenna. It is more likely that this occurred from the an error in simulations for the substrate parameters rather than an error in measuring the prototype.

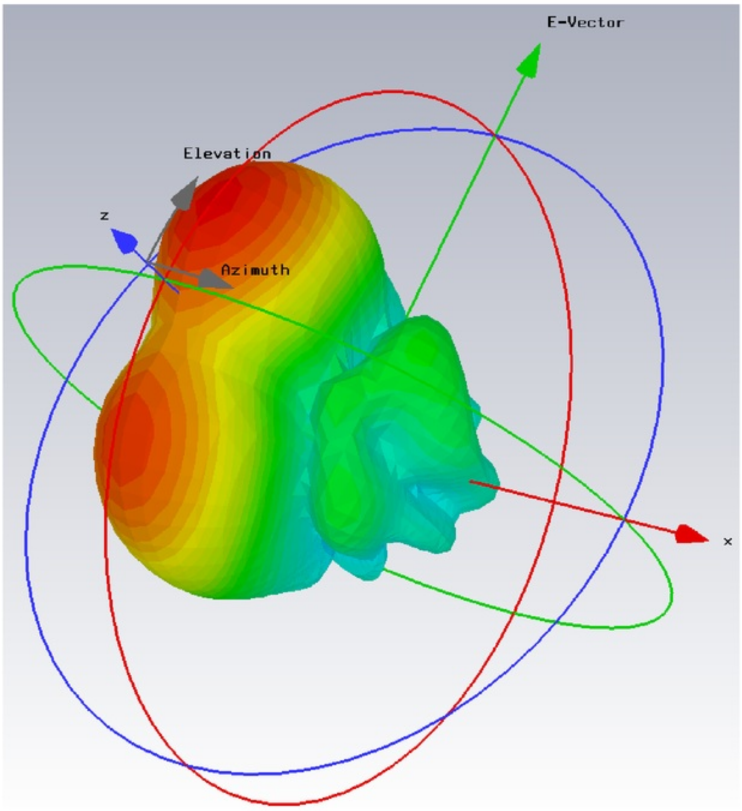

Figure 4.5: The farfield result of the antenna from figure 3.2.

4.3 Discussion

Throughout this thesis there were many difficulties and challenges to overcome. The first and main difficulty of this project came through as the time constraints. Due to difficulties in initially learning how to effectively operate CST, the long simulation times for parameter sweeps and the time spent researching there were considerable delays. This is best shown through my gant charts showin in my appendix. Figure A.1 is a gant chart tracking my progress throughout my thesis and figure A.2 is a gant chart outlining the initial planning and how the project was meant to move forward. One of the biggest uses in time came in properly designing the single element antenna due to negligence in understanding input impedance of an antenna was proportional to the width of the antenna, this resulted in a series of antennas with a width of approximately 130mm that had horrible farfield and E-field results. However as this research project shows it is important to improvise, adapt and overcome the challenges put in front, there will always be challenges

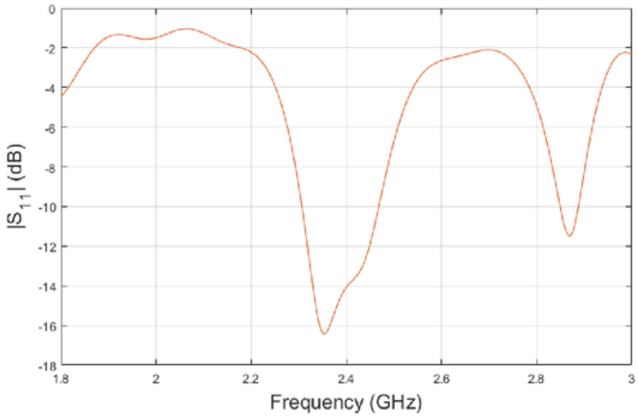

Figure 4.6: The simulated S11 results of the multistrip antenna.

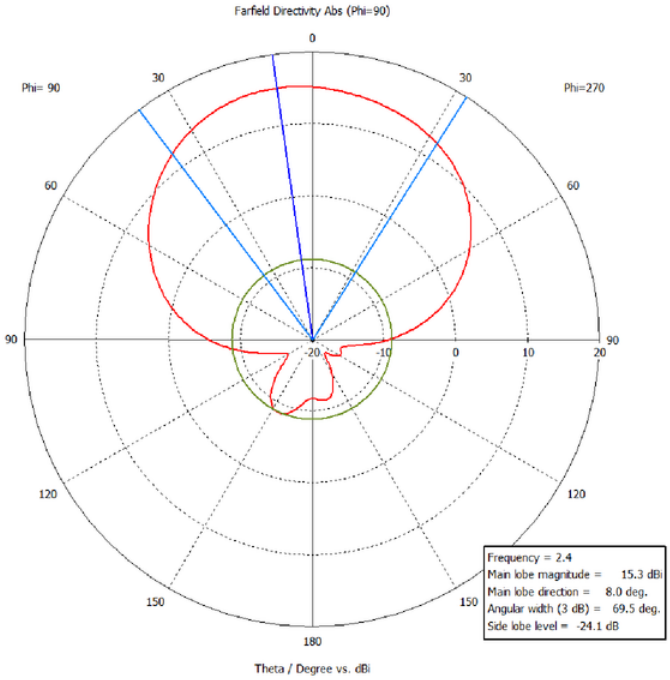

Figure 4.7: The simulated farfield results of the multistrip antenna.

but these challenges should be met head on. By continuing to research into antennas it eventually became clear that this issue was with the impedance matching

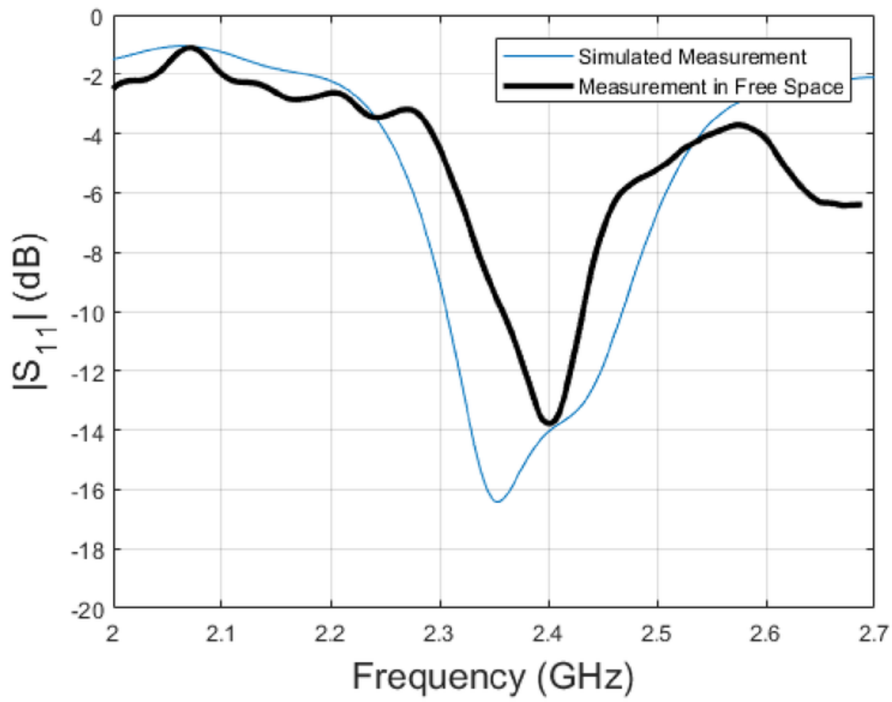

Figure 4.8: The simulated S11 results of the antenna compared with the measured S11 results.

The decision of which frequency to attempt to harvest was a relatively simple one. Due to wanting to test the final design on site at the university the waves needed to be easily received at the university. The obvious choices that were going to be readily available all over the university were the waves from mobile phones and the waves from Wi-Fi. Both mobile phones and Wi-fi operate with microwaves, that is they operate between a range of 300MHz and 300GHz. Due to the plethora of telecommunication companies and and available frequencies for the telecommunication companies to use there is a wide range of frequencies available for mobile phones within Australia to operate on. These frequencies are generally split into two categories, low band and high band. Low band operates between 700MHz to 900MHz while high band operates between 1800MHz to 2600MHz. Alternatively the vast majority of Wi-Fi routers and signals in Australia run on either 2.4GHz or 5GHz. At first it may seem better to attempt to harvest power from mobile phones, as all mobile phone signals would be reached with a bandwidth of 1900MHz (1.9GHz) while all Wi-Fi signals would be reached with a bandwidth of

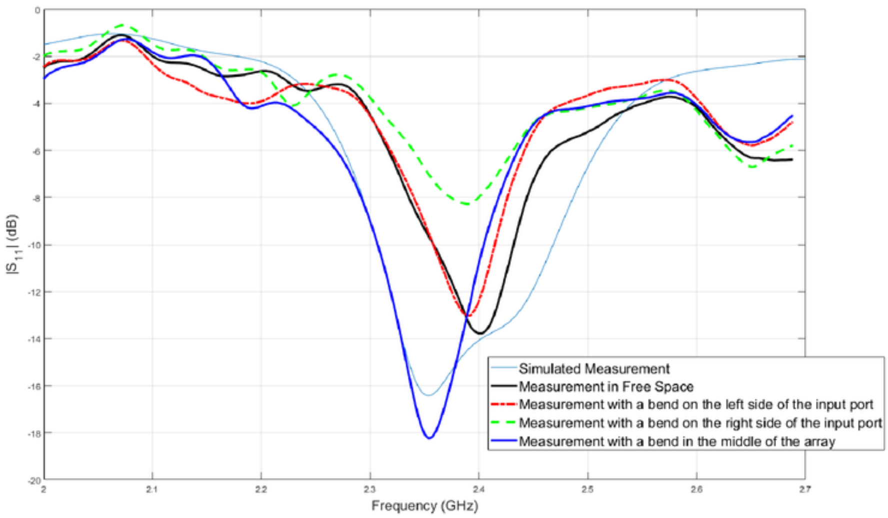

Figure 4.9: The simulated S11 results of the antenna compared with all measured S11 results.

2600MHz (2.6GHz). However it is unrealistic to attempt to design an antenna with an effective bandwidth of 1.9GHz, so instead it was concluded to attempt to design an antenna for one of the Wi-fi frequencies as it could cover approximately half of all Wi-Fi signals compared to a single mobile phone frequency which would cover approximately a quarter of all signals. Considering that the final design had a bandwidth of approximately 100MHz it is fair to conclude that the decision to only harvest at one frequency range, that point being half the possible Wi-Fi singals was a better option than attempting to harvest at one mobile phone singal frequency and that frequency being equivalent to a quarter of the potential mobile phone frequencies. [8]

Although we were forced to use a substrate with a height of 2.5mm because of the available felt at the university, there were still simulations held to see how adjusting the height of the substrate would effect the antenna. This is helpful for future research into a similar topic.

Knowing that a prototype of this antenna was eventually going to be made, physical constraints had to be taken into consideration. Due to these physical constraints optimum dimensions were not used for designs, this is because often the optimum design would not be feasible to make a prototype of optimum dimensions. For example the quarter wavelength of this unit was 28.527mm (3dp) however when modeled and simulated the quarter wavelength was treated as 28.5mm and when the prototype was constructed it would have been closer to 28mm.

When designing both the corporate fed array type microstrip antenna and the single element microstip antenna it was important to have an S11 where the bandwidth at -10dB included 2.4GHz. This is because -10dB is equivalent to receiving 90% of the potential microwaves at that frequency range.

For the initial array type antenna through deeper research it was eventually discovered the reason for the horrid farfield results was due to the spacing of the elements and did not require a complete redesign. The error was placing the elements too close to each other, the design initial had the elements centre point was a quarter wavelength away, however when this distance had the patches overlapping the two patches were put an arbitrary distance apart. Changing the design to have the distance of the edges of the elements to be a quarter wavelength away would have improved the farfield results considerably.

There was also a worry that the units were incorrectly fed. This initial feeding technique had a 50Ω tranmission line coming out of the patch leading to a 70.7Ω transmission line leading to a 100Ω bridge connecting the two 70.7Ω transmission lines together. This design was repeated to create the complete corporate feed as seen in figure 3.2. This design was replaced by a simpler design that had 100Ω feeds coming out of each patch, where each patch was also set to have an input impedance of 100Ω which led to a 100Ω bridge connecting two transmission lines, and then that bridge connecting the two 100Ω bridges had a 50Ω feed coming out of it, which had the another 100Ω bridge two 50Ω transmission lines, which finally led to the final 50Ω feed. Rectifying these errors was crucial in improving the antennas farfield and S11 results.

The results of S11, seen in figure 4.4 are quite nice for the initial design as there with a bandwidth of approximately 100MHz at -10dB. These results are similar to the final design seen in figure 4.6. The main difficulties of the initial array antenna was the disappointing and undesired farfield results. The fairfield results for the final design seen in figure 4.7 although slightly skewed looked quite good and considerably better than the farfield results of the initial array type design.

4.3.1 The Prototype

From the first instance there were going to be issues with prototyping. This is because having the exact dimensions cut out with copper tape would have been impossible, for example the 100Ω transmission lines were meant to be 3.8mm wide, these lines were made with a 5mm copper tape that had a thin strip cut of the edge, it is highly unlikely these feeds that were cut by hand were exactly 3.8mm.

The second issue with the prototype was a shortage of material, specifically a shortage in the felt provided by the university that was being used for the substrate. The prototype ended up needing to have the ground and substrate shorter by 2cm on each side. Fortunately this would affect the S11 minimally. The model was adjusted in CST and it was noticed that main change is the farfield result. Unfortunately this shortage meant that the single element microstrip antenna could not also be simulated.

From the graph in figure 4.9 it is evident that bending the antenna effects the S11 results of the antenna. Fortunately majority of the results are still good. All results except for the results with the bend on the bend on the right side of the input port have 2.4GHz covered at -10dB. This means that for the majority of conditions the antenna is receiving 90% of the possible waves to receive. However the bend on the right has a minumum magnitude of approximately -8dB which is less than the expected. This should be tested again to see if its due to copper tape connections or is an actual flaw in the design. If it is a flaw in the design more designs need to be tested to see why there was an error and how it can be rectified.

Following on from the success of testing the S11 of the prototype it would have been helpful to test the prototypes farfield results. Unfortunately due to time constraints we were unable to test the farfield of the prototype. The expectation for the farfield results of the prototype was not as good as the farfield results of the simulation, this is not due to losses, but rather due to inaccuracies in measurements, firstly as mentioned earlier due to a lack of material the substrate had to be 2cm shorter on each end and since the substrate was shorter so was the ground plane, on top of this the copper tape used to create the patches and the transmission lines would not have been as accurate as required, this also would have caused disruption in the farfield. With the farfield result being affected by the substrate size, patch sizes and transmission line sizes, it was expected to have the farfield results of the prototype not be as desirable as the farfield results of the simulation.

Chapter 5

Conclusions and Future Work

5.1 Conclusions

There are two main disadvantages of this research project. The first is that it is harvesting power from Wi-Fi routers, Wi-Fi routers transmit 50mW to 100mW this means that even with 90% efficiency which is what was goal that was achieved by having the S11 calculation be less than -10dB at the 2.4GHz range that in a best case scenario without any additional losses there is a possibility of receiving the equivalent of 45mW to 90mW of power. This means that the antenna is only suitable for use on low power applications. The other disadvantage is the harvested power is from a relatively low distance. The distance that power is harvested on depends on the antennas capability, for example POWERCAST, a company based in the United States of America who use more conventional materials for the substrate have power harvesting taking over 1.5miles or 2.4Km. This is with the best possible materials, with the substrate being made of felt it is unlikely to get results as positive as POWERCAST.

Even considering the disadvantages, this paper and project, through research and testing has shown that it is feasible to wirelessly harvest power using an antenna with a felt substrate. The simulations showed that array type antennas are indeed more effective than single element microstrip antennas at wirelessly harvesting power. This means it is possible to develop an antenna with felt as a substrate to wireless harvest power.There is plenty of room to grow on this research and to develop this antenna into a wearable device for wireless power harvesting. This research has a plethora of possible applications. Currently similar technology being used mainly for wireless sensor networks as this product is best for low power and battery free applications. As discussed, the clearest and the initial intention for the project was to implement the unit within clothing which is why as explained previously the substrate was chosen to be felt, as mentioned in the introduction this would best be used to provide power to small devices such as smaller biomedical devices and hand held devices.

5.2 Future Work

There is quite a bit of future work available on this topic. The multi-array antenna can still be refined and improved by using exact dimensions instead of taking into account how to feasibly make a prototype with felt and copper.

The design also requires a rectifier to be able to successfully convert the electromagnetic energy being received into DC electricity.

Another possible improvement which can be implemented into the design is to make the antenna a multi-band antenna to receive energy from both Wi-Fi frequency bands of 2.4GHz and 5GHz. This may be an opportunity to try and implement defective ground structure into the antenna. DGS attempts to use defects on the ground plane of the micro-strip to upgrade the antennas performance. DGS functions as a game in the resonance which disturbs the distribution of current in the ground plane of the antenna. This change in the distribution of the current affects the characteristics of the antenna by effecting the capacitance, inductance and resistance, because of this DGS can be provide multi-band operation and enhance bandwidth [9]

Another topic which must be looked into if this is to be implemented into clothing as the final design application is to find out the effects of radiation it produces onto the human body. The it needs to be ensured that the antenna is not harmful and does not in any way negatively affect the human body. While considering the effects of the antenna on the human body, it is also important to consider the effects of the human body on the antenna. The human body does have the potential to cause static electricity, this will effect the performance of the antenna and needs to be considered before the final product.

It is also be worth testing new and different substrates. Throughout the research and development during this thesis the only substrate used was felt as this is what was provided by the university. Similar to how in Salah-Eddine Adami, Plamen Proynov, Geoffrey S. Hilton, et al. paper titled "A Flexible 2.45GHz Power Harvesting Wristband With Net System Output From - 24.3 dBm of RF Power" various other materials can be tested such as wool, cotton, polyester, leather, etc.

When looking at different materials it is also worth looking into embroidering the antenna, particularly since the final goals main application is to be on clothing. [2]

Chapter 6

Abbreviations

DGS	Defective Ground Structure
CST	Computer Simulation Technology
HPBW	Half Power Band Width
DC	Direct Current
RF	Radio Frequency
VSWR	Voltage Standing Wave Ratio

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Appendix A

Project overview

A.1 Gant Charts

This gant chart shows initial timing outline designed to properly manage my team during my thesis.

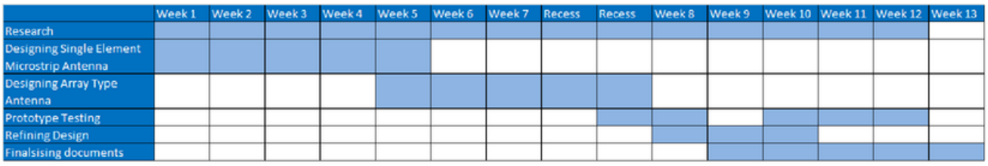

Figure A.1: Gant chart showing the initial planning for the project.

This gant chart showed the actual time taken to complete the project.

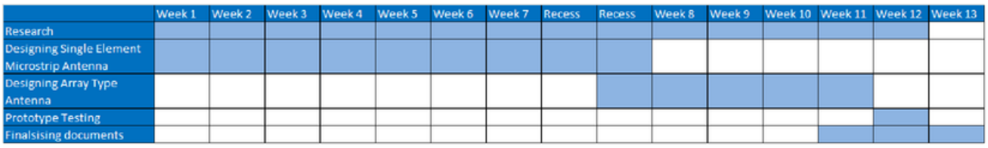

Figure A.2: Gant chart showing the time spent on objectives.

A.2 Project Approach

This flow chart represents the approach taken to the project.

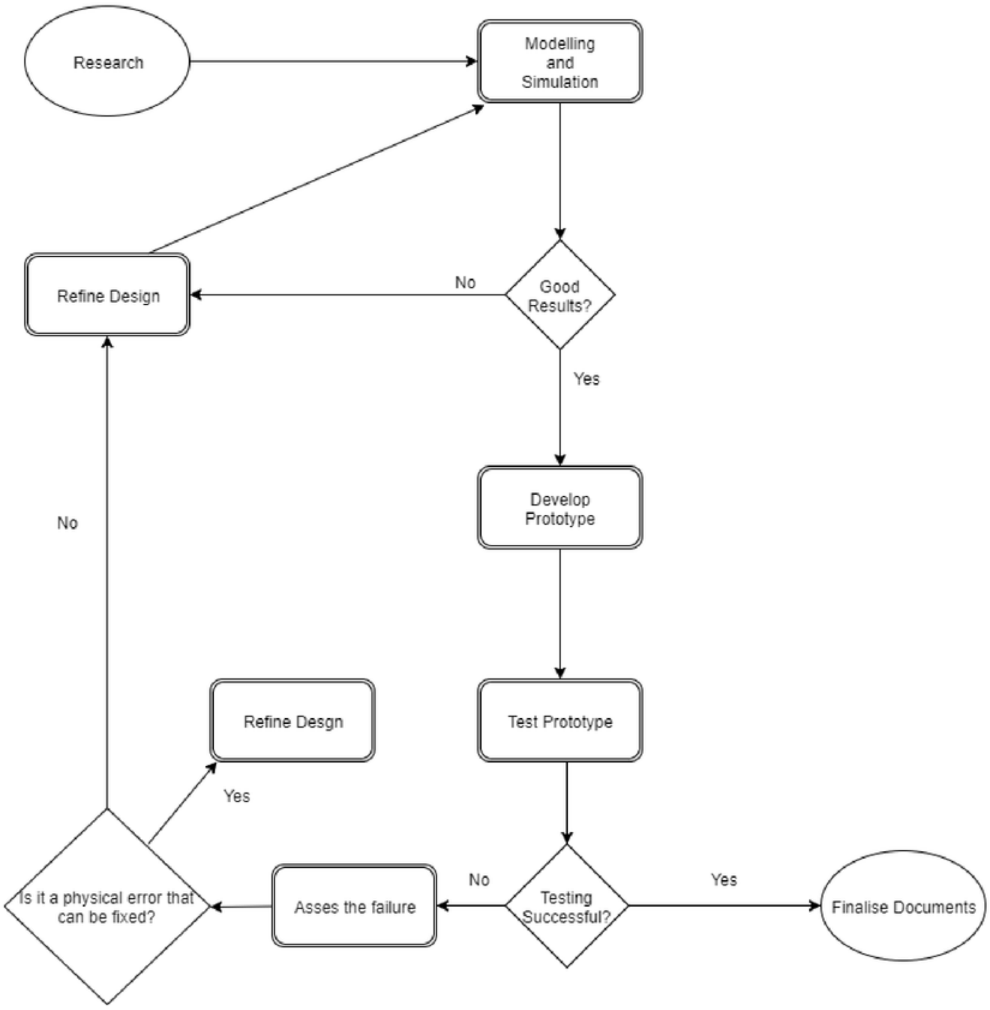

Figure A.3: Flow chart showing how the project will be undertaken.

A.3 Consultation Meetings

The meeting consultation form showing the history of most meetings taken throughout the project.

Consultation Meetings Attendance Form

Week	Date	Comments (if applicable)	Student's Signature	Supervisor's Signature
4	22/8/17		[illegible]	RM.
5	29/8/17		[illegible]	RM.
6	5/9/17		[illegible]	RM.
7	12/9/17		[illegible]	RM.
Recess	19/9/17	Semester 2 midsemester Break	[illegible]	RM.
Recess	26/9/17	Midsemester Break.	[illegible]	RM.
8	3/10/17		[illegible]	RM.
9	10/10/17		[illegible]	RM.
10	17/10/17		[illegible]	RM.
11	24/10/17		[illegible]	RM.
12	31/10/17		[illegible]	RM.
12	2/11/17		[illegible]	RM.

Figure A.4: The consultation meeting Form.