# WIRELESS POWER TRANSMISSION USING MICROWAVE TECHNOLOGY

**Undergraduate Student Authors: Robert Fuller, Ryan Nastase, Kaoru Elliott, Anas Salhab, Jonathan Campbell**
**Faculty Advisors: Hao Xin, Michael Marcellin**
**University of Arizona Tucson, AZ 85721**

## ABSTRACT

As part of the Senior Capstone class held at the University of Arizona in the College of Engineering, the team was tasked to build a prototype that could power a simple electronic device wirelessly. The team succeeded in doing so and has proven that wireless power transmission could be a valuable tool for future use. There are a few difficulties to note and specifics will be given in the body of the report.

## INTRODUCTION

As part of the Engineering 498 Senior Capstone class at the University of Arizona, the team was required to produce a system that wirelessly powered a simple electronic load. This topic was chosen as a project because of its possible applications. One application is to supply personal electronic devices with power without the use of cables. For many devices the power cable is the last cable that must be attached. To remove the need of the cable would make the device truly wireless. It would remove the cumbersome clutter of cables that cause many unsightly sights. In short this application is the logical progression for home electronics if the technology proves capable. The second application is of a much larger scale. In the effort to find renewable energy, or green energy, comes the idea of harvesting solar energy from space for use on the Earth's surface. Such an idea needs wireless power transmission to deliver the power; however, the transmission of that amount of power must be safe and practical. The report will be structured as follows. First, the design process will be discussed with emphasis on the antennas and receiving circuitry, which the team had to design and build. The transmitting circuitry, except for the transmitting antenna, was all commercially bought. For this reason only a discussion of the needed parts for the transmitting circuitry will be given. The simulation results will be reviewed after the design discussion. Simulations were used to verify that the designs were valid enough to build and test. The discussion will continue by presenting the results of the prototype. In the conclusion the questions will be answered as to whether or not this project had proven that the previously mentioned applications are plausible.

## TOP LEVEL OVERVIEW OF PROTOYPE

The design process for the project involved breaking down everything into three primary units: the receiver, transmitter, and the antennas. These units were given specific requirements for inputs and outputs needed so that an entire system could be created that would meet all of the functional requirements. The requirements that the team was given were simple. It was required that the prototype transmit power wirelessly a minimum distance of 1 cm in order to power a simple electronic load. To simplify the design it was decided that microwave technology would be used at 2.45 GHz because it is a frequency range in which many components are made to work and it is within a range that the FCC allows for scientific research.

A top-level overview of the prototype can be seen in Figure 1. In the figure it can be seen that the transmitter circuit creates a signal that is inputted into the transmitting antenna. The signal then propagates out into free space, is received by the receiving antenna, and converted into a DC signal that is used by the LED load.

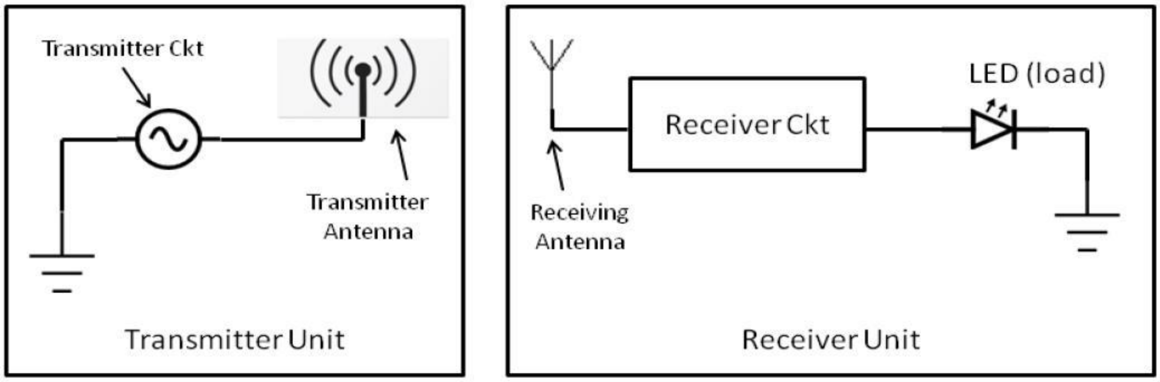


Figure 1- Functional Overview

The transmitter circuitry designed for this prototype consists of borrowed or commercially bought components. The power supply was borrowed from the University of Arizona Electrical and Computer Engineering (ECE) Department, the voltage controlled oscillator (VCO) and 5W output amplifier were commercially bought. The transmitter circuitry receives power from a DC power supply, the VCO uses the power to create an oscillating signal at the desired frequency and the amplifier ensures that the signal to the antenna is 5W in strength. The only time the prototype was transmitting its limit of power was when it was tested in an anechoic chamber at a lab at the University of Arizona (ECE) Department.

## RECEIVER

The receivers’ job is to take in high frequency energy and convert it DC energy to operate the simple electronic load. To accomplish this there are multiple important parts included in the receiver design. These parts are the simple electronic load, low pass filter, rectifying circuit, DC blocking capacitor, matching network, and the antenna. The simple block diagram below shows how the receiver looks at the top level.

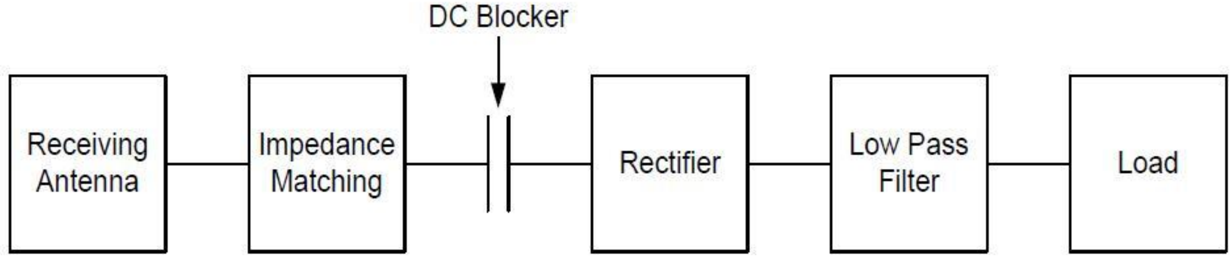


Figure 2 - Top level Diagram showing major components in the receiver circuit.

The functional requirements state that the prototype is to power a simple electronic load by wireless power over a distance of at least 1 cm. An LED (Light Emitting Diode) was chosen to be the simple electronic load to simplify testing. This device can operate on low power, and since it emits light it is easy to tell when the circuit is working. The chosen LED is red and needs only 60mW of power in order to operate at maximum luminosity.

A rectifier was needed to generate the DC energy from the high frequency energy. The rectifier chosen was a Schottky diode. Diodes are non-linear, and when a high frequency signal comes into contact with a non-linear device the signal is broken up into its harmonics including DC. The Schottky diode is necessary because it switches faster than a regular diode. In order for the rectifier to work, it must be able to switch faster than the highest frequency you want to rectify.

Since the rectifier allows more than DC energy to pass, and the LED can’t handle the high frequency energy, a low pass filter (LPF) needs to be added between the rectifier and LED. For the design a two pole LPF using lumped elements was used. This circuit was chosen due to its simplicity and sufficient rejection for the LED. This is one area where the design could be improved upon—it is possible that other filters or components can provide better results.

The remaining parts needed are the DC blocking capacitor and the input matching network. The DC blocking capacitor is placed just before the rectifier in order to ensure that all DC energy created by the rectifier flows toward the load. The matching network is used to ensure a maximum flow of power from the antenna into the receiving circuitry. Various circuits were tested, but again simplicity won out, producing a mixed lumped element and transmission line circuit to do the matching and a separate DC blocking capacitor to direct the DC energy.

The diodes and DC blocking capacitor were relatively easy to figure out, but the LPF and matching network involved more thought and consideration. As stated there are many usable circuits and the best one was found by research and simulation. The restrictions upon both circuits proved to be similar. If too much transmission line was in either circuit it had the effect of reducing the efficiency by increasing the line loss. On the other hand finding lumped elements that worked reliably at 2.45 GHz was surprisingly difficult. There are only a small number of values of capacitors and inductors that can be found to work at that frequency. This meant that a balance had to be found between the use of transmission line and the lumped elements that the team was able to find. Much of the design time was spent on trying different combinations of transmission lines and lumped elements until the final design was achieved.

The final circuit, shown in figure 3, was obtained through simulation in Agilent Design System (ADS). The software was used to confirm the most efficient LPF and also to find the input matching network that gives the circuit the highest efficiency. For the LPF the circuit was built and simulated by means of an S-Parameter simulation. This was used to find the frequency response of the LPF. Several iterations were required to find a design that used components that we could find and exhibited a good amount of rejection at higher frequencies. The matching network proved more difficult because care had to be taken to make sure that the matching network didn't affect the input signal. Matching networks also affect the frequency response of the circuit. After simulating and researching, the final circuit was found to have 58.6% efficiency (DC power at LED divided by RF power at input) and less than 1mW of high frequency energy. These results were found acceptable and the prototype board was produced by the students using chemical etching in a clean room in the ECE department at the University of Arizona.

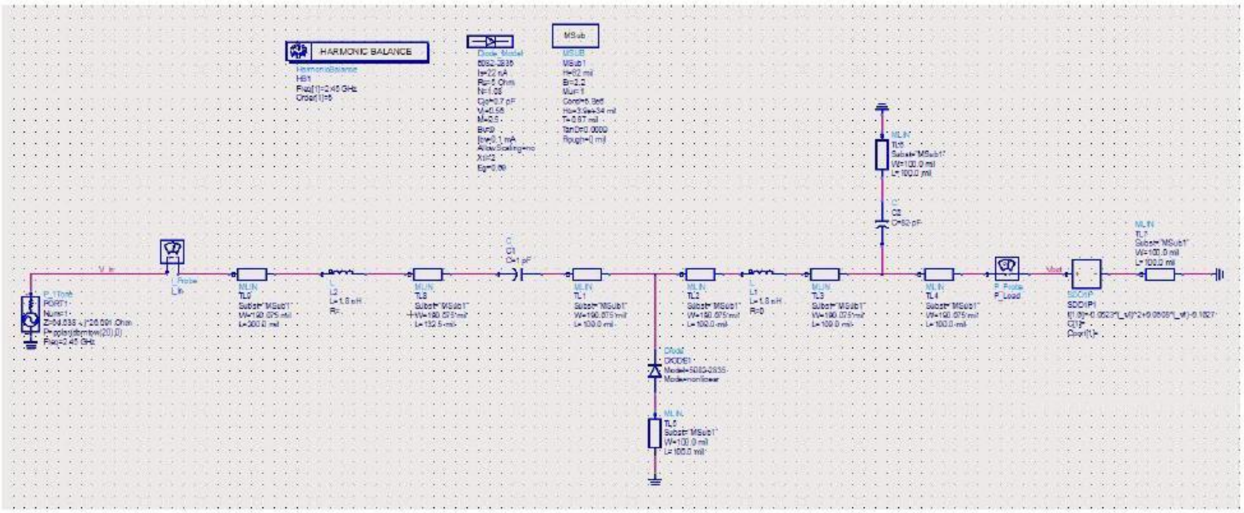


Figure 3 – Shows receiver circuit used in the final design.

## ANTENNAS

A multitude of factors were considered when deciding on a final antenna design. Some of the most significant factors included directivity, size, ease of manufacturing, robustness, and efficiency. The patch antenna was used for our antenna design because if designed correctly it fulfills all low level requirements of transmitting and receiving microwave energy.

A feed-line is the trace of conductor, in our case copper, which connects the transmission circuitry to the copper patch. This is where the energy enters or leaves the transmission and receiving antennas, respectively. There is a plethora of different antenna feed-lines that can be used in microwave transmission. Some of the issues that were considered when choosing the feed-line type were ease of manufacturing, effects of bandwidth, and efficiency at 2.45GHz. By using the microstrip the gain is sufficient and its bandwidth is fairly broad. This is important because it is easier to manufacture two antennas within the wider bandwidth restrictions. This in turn means more gain.

The design of the antenna was done first by using a detailed set of equations that governed the parameters of the rectangular patch antenna. The initial variables that were needed prior to using these design equations were frequency, permittivity, and height of the dielectric. The design equations were taken from Antenna Theory and Design, Edition 3, Balantis [1].

HFSS stands for High Frequency Structure Simulator and was used to model and simulate RF and microwave circuits. HFSS is a 3-D program that allows one to model all aspects of a circuit, in our case the antenna, to see how it responds to different signals or frequencies. The most important parameters that were simulated were center frequency, reflection coefficient, Voltage Standing Wave Ratio (VSWR), directivity, and gain.

The final design in HFSS is illustrated in Figure 4. As we have shown in the previous paragraphs our antenna design is a good design with acceptable losses and gains. The design is simple and can be etched in the ECE building at the University of Arizona.

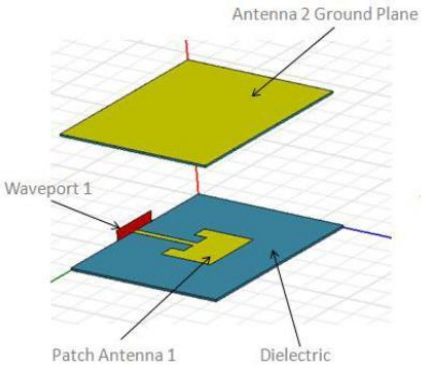


Figure 4-HFSS Final Design

The simulations showed that we achieved a center frequency of 2.45GHz. A plot of the S(1,1) VS frequency can be observed in Figure 5. It should be noticed that the S(1,1) at 2.45GHz is -15.36 dB. This means according to the simulation less than 3% of the power going in to “port 1,” or the transmitting antenna, is reflected.

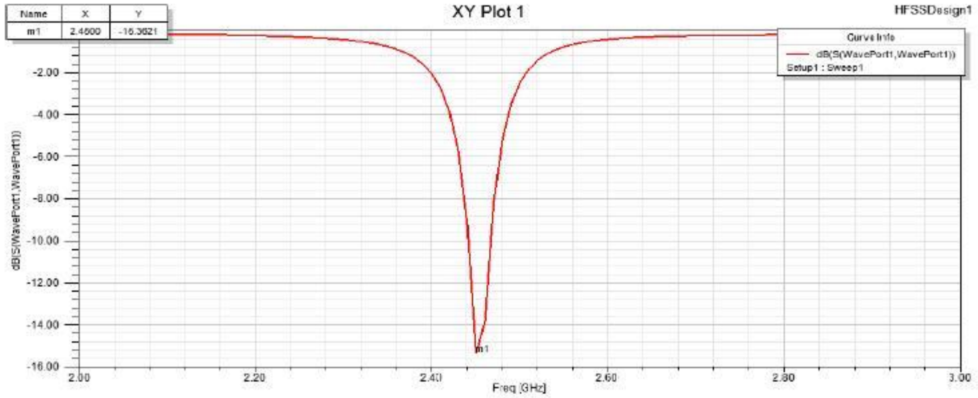
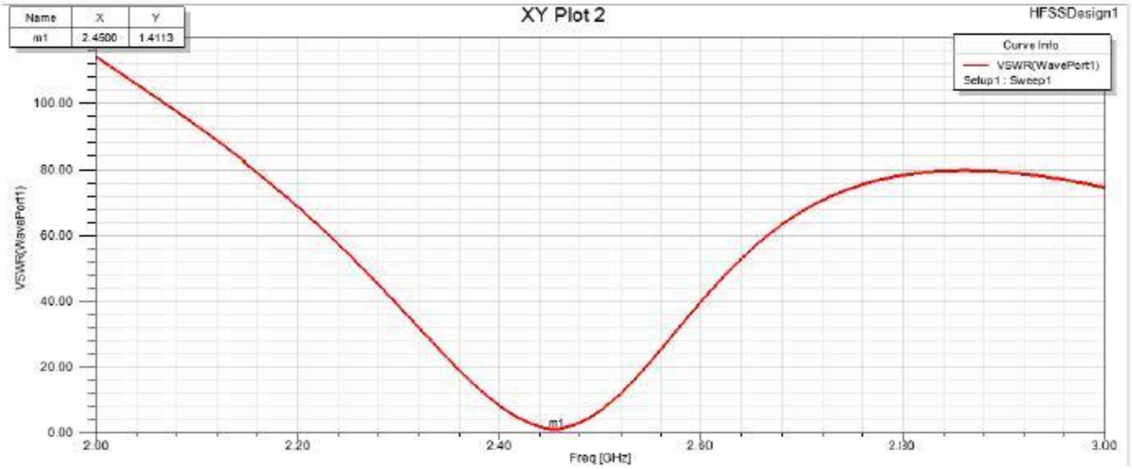


Figure 5-S11 Reflection Coefficient at 2.45GHz

It can be seen in figure 6 that the resulting VSWR (Voltage Standing Wave Ratio) is at 1.41. This means there is about 16% reflected power from inside of the antenna. From the VSWR we calculated the reflection coefficient to be 0.16 and the return loss to be 16.36dB.



The radiation pattern can be observed in figure 7. This is helpful to look at prior to building because it lets the designer know where the power is being radiated. The goal is to have the mainbeam, the highest power point, to be radiated in a direction normal to the surface of the patch. This is exactly what is happening in the simulation below.

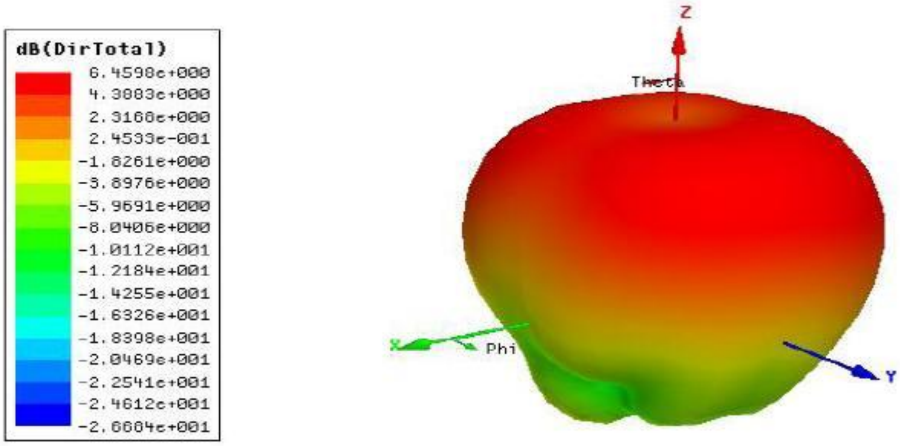


Figure 7- Radiation Pattern

When the design was finished a study of coupling versus distance was performed. The goal was to find out what level of power was coupling between the two antennas. This was performed using HFSS to simulate distance as parameter. Then each time the distance was changed, the S(2,1) parameter was plotted. This allowed us to observe how much power was coupling between the antennas. Figure 8 shows that at a distance of approximately 20cm the power coupled is about 1/10th of the power that is sent.

Figure 8- Coupling as a Function of Distance

The patch antenna is constructed on a RT Duroid board. The board has a permittivity of 2.2 and a height of 62 mils. The board consists of a ground plane on the bottom of the board made of copper and an additional layer of copper on the top. They are separated by a nonconductive dielectric material. This allows a current to radiate on the surface of the patch. The patch is fed with microstrip line that is used to match the 50 Ohm line to the approximately 330 Ohm patch.

The antennas are etched in order to get rid of the copper on the top to form our patch. Then a SMA connector is soldered onto the board by soldering the center conductor to the microstrip feed and the outer part of the connector to the ground of the board. This will ensure that there exists common ground between our patch antennas and our SMA connectors.

Coaxial cable is connected to the SMA connectors that are attached to the patch. The coaxial cable is used to transfer power from the amplifier to the transmitting antenna on the transmitting side. Coaxial cable is also used on the receiving side to transmit power from the receiving antenna to the receiving circuitry.

## TESTING

Testing the receiving unit was simple. The design requirements only required the receiving unit to power a simple load. The LED was chosen because it is easy to tell when it is working. The voltage across the LED was measured using a digital multi-meter. With the voltage and the I-V curve an accurate approximation was made as to the amount of power dissipated across the LED. This output power was then divided by the input power in order to see the efficiency of the receiving circuitry. Due to some strange behavior noticed while running the tests, the testers decided to try two variations of the receiving circuitry. The first was the normal design discussed in this paper and the second was the same design but with the matching network removed.

Figure 9 shows the results of the testing. It should be noted that the simulation results showed a 58.6% efficiency when 100mW is placed at the input of the receiving circuit. The results of the testing show that the efficiency of the circuit is about 40%. A drop was expected though it is a larger drop than expected.

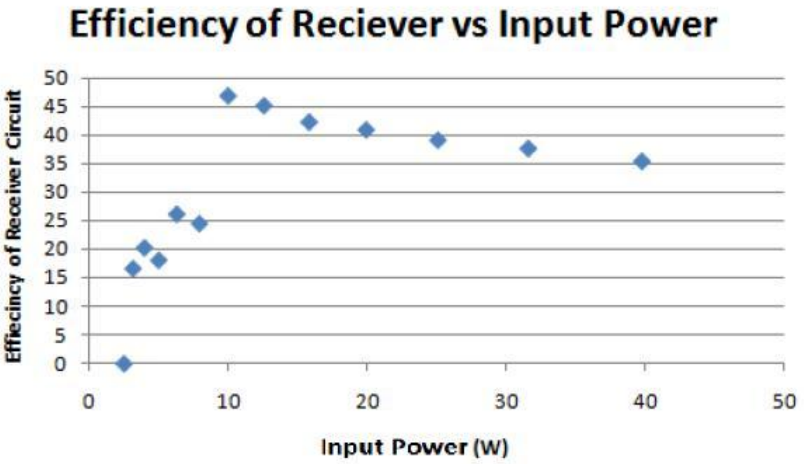


Figure 9- Shows test data of the receiving circuit with & without the matching network.

FCC regulations prevent the broadcasting of high frequency, high powered devices unless the tester is licensed or the tests are performed in an anechoic chamber. Due to these regulations all of our transmitting was done in an approved anechoic chamber. The setup included the following: calibrated horn antenna, power amplifier, attenuator, coupler, network analyzer, and signal generator.

The antenna under test (AUT) is initially tested by transmitting a known frequency through a calibrated horn antenna to the AUT and then the signal is read using a network analyzer. The initial signal of 2.45GHz is created by a signal generator. The signal generator is then connected to a power amplifier. An attenuator was used to bring the power down to 5 Watts. The coupler allowed us to know how much power is getting to the transmitting horn and therefore allow us to make minor changes in amplitude using the signal generator. Finally, the signal was transmitted through free space and the AUT received the signal. The AUT was then connected to the network analyzer so that the frequency could be verified.

Close attention is given to the distance between the horn antenna and the AUT. This is to ensure there is not too much power received and fed into the network analyzer.

By using the Friis Transmission Equation it was concluded that the receiving antenna must be at least 15 cm away from the transmitting antenna to ensure safety of all equipment. The initial test was done at 50cm to see how much of a signal is received on the patch antenna. This distance was then reduced by 5cm and the test performed again. This process continued until the network analyzer showed a power level between 100mW and 120mW. When the antenna was verified to work as simulated, the transmitting patch antenna replaced the horn antenna. The power was then adjusted to accommodate for a smaller gain antenna (the patch antenna).

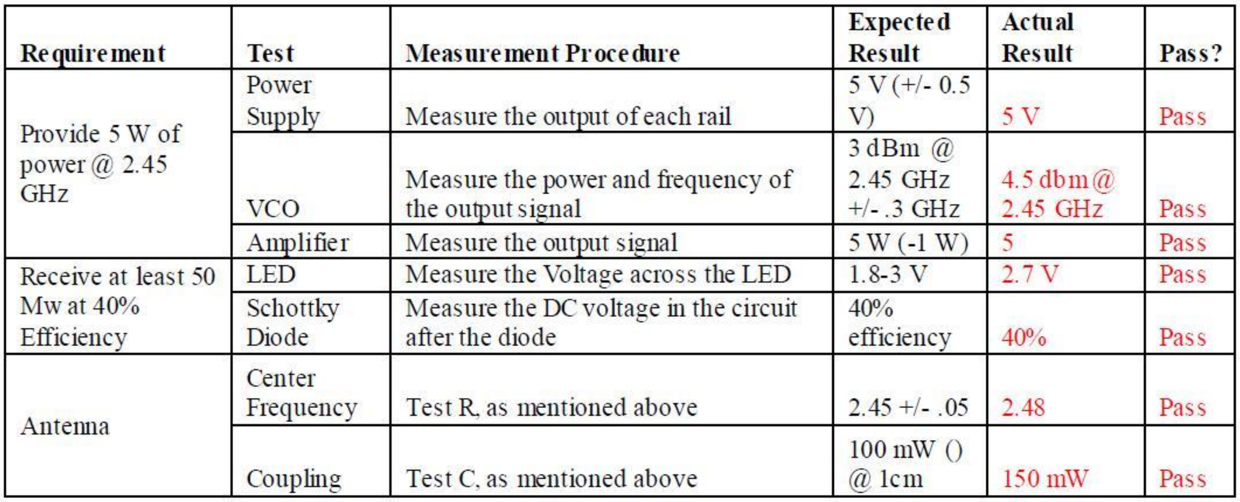
The test was performed again so that observation of the coupling antennas could be made. By performing this test we have verified that the antennas can couple energy. Performing this test also allowed us to determine the ranges of distance at which the circuit receives enough energy to power the LED.

# RESULTS

After performing the above test procedures we were able to measure the amount of power transmitted at 1cm and find the distance at which there was not enough power to turn on the LED. The measured power at 1cm was approximately 150mW. The maximum distance at which the LED would turn on was 55cm, which far exceeded our goal of 1cm.

The tables below show the results of various tests performed to determine whether our prototype functioned as designed. Table 1 is the result of testing the low-level functional requirements, while Table 2 shows the results of the top-level functional requirements. When testing the prototype, the distance between the transmitter and receiver was set at 50 cm. We performed testing, then reduced the distance by 5 cm, and repeated the process again.

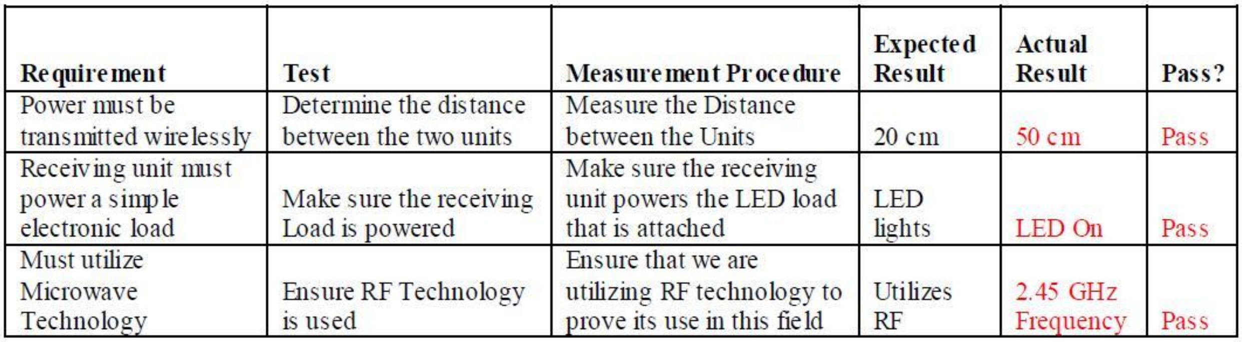
Table 1- Verification Matrix



| Requirement | Test | Measurement Procedure | Expected Result | Actual Result | Pass? |
|---|---|---|---|---|---|
| Provide 5 W of power @ 2.45 GHz | Power Supply | Measure the output of each rail | 5 V (+/- 0.5 V) | 5 V | Pass |
| | VCO | Measure the power and frequency of the output signal | 3 dBm @ 2.45 GHz +/- .3 GHz | 4.5 dbm@ 2.45 GHz | Pass |
| | Amplifier | Measure the output signal | 5 W (-1 W) | 5 | Pass |
| Receive at least 50 Mw at 40% Efficiency | LED | Measure the Voltage across the LED | 1.8-3 V | 2.7 V | Pass |
| | Schottky Diode | Measure the DC voltage in the circuit after the diode | 40% efficiency | 40% | Pass |
| Antenna | Center Frequency | Test R, as mentioned above | 2.45 +/- .05 | 2.48 | Pass |
| | Coupling | Test C, as mentioned above | 100 mW () @ 1cm | 150 mW | Pass |

In conclusion all of the components passed the tests that were assigned for them, verifying the lower function requirements are met.

Table 2 - Validation Matrix



| Requirement | Test | Measurement Procedure | Expected Result | Actual Result | Pass? |
|---|---|---|---|---|---|
| Power must be transmitted wirelessly | Determine the distance between the two units | Measure the Distance between the Units | 20 cm | 50 cm | Pass |
| Receiving unit must power a simple electronic load | Make sure the receiving Load is powered | Make sure the receiving unit powers the LED load that is attached | LED lights | LED On | Pass |
| Must utilize Microwave Technology | Ensure RF Technology is used | Ensure that we are utilizing RF technology to prove its use in this field | Utilizes RF | 2.45 GHz Frequency | Pass |

As can be seen from the table, all three of the functional requirements were passed, validating that the project not only met the requirements but exceeded them.

## CONCLUSION

In completing this project, it was observed that this technology is one that could be used for powering small electronics, or transmitting power from solar satellite. There are certain points that must be considered before being implemented in the large-scale, the first of which is safety. If power levels get too high, it will be difficult to stay within the limits set by the FCC for safe human interaction. These limits are specific to frequency, so care must be taken in choosing the frequency of use. The second consideration is components. It is difficult to find inductors and capacitors that are capable of working at higher power levels. However, new technologies emerge often and it is possible that the needed components could be made. More research will tell whether or not these concerns will prevent microwave technology from being used to transmit power wirelessly.

The goal of this project was to create a wireless power transmission system that could provide enough power to a receiver, which would power an electronic circuit. Using microwave technology provided some hurdles, but the team was able to meet and exceed the established requirements. At 20 cm the team was able to supply close to 50 mW of power to the load, which exceeded the requirements. This project, having met and exceeded all requirements, was a success.

## RECOMMENDATION

This project was a proof of concept that power can be transmitted wirelessly using microwave technology. Many lessons were learned on how to design, simulate, and analyze the components in the design as were discussed previously. Some recommendations for future iterations: improved antenna designs via better matching to inputs and changing parameters of the inset; Increasing the antennas' gain and bandwidth via better substrates with greater height and better fabrication of the antennas; producing various receivers dependent on application of the project.

## REFERENCES

[1] Balanis, Constantine A., ―Microstrip Antennas,‖ Antenna Theory and Design, 3rd, John Wiley & Sons, Inc., Hoboken, New Jersey, 2005, pgs 811 – 876