Wireless Energy Harvesting

FINAL REPORT

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Introduction:

This is the final design, results and operational manual for the senior design project: wireless energy harvesting device. The purpose of this project was to create a device capable of capturing radio frequency signals given off by wireless access points, routers, microwave ovens and other wireless devices, and then converting that energy into usable power for small electronics such as sensors or light emitting diodes. This project was proposed as a research project with the guidance of Dr. Jiming Song for December, 2022 senior design.

Standards Used:

- IEEE 211-2018 - IEEE Standard Definitions of Terms for Radio Wave Propagation. Terms and definitions used in the context of electromagnetic wave propagation relating to the fields of telecommunications, remote sensing, radio astronomy, optical waves, plasma waves, the ionosphere, the magnetosphere, and magnetohydrodynamic, acoustic, and electrostatic waves are supplied. This applies to our project because it sets out a standard definition for all of the various vocabulary surrounding Radio Wave propagation. Because we are using Wi-Fi which is a radio frequency it is necessary that all the terms we are using are being used correctly.
- IEEE 149-2021 - IEEE Recommended Practice for Antenna Measurements. Provides standards and recommendations for measuring antennas properties such as their propagation fields, patterns, and testing facility setups. This applies to our project because a large part of our job is to design and test an antenna to meet the requirements set out by our client. With this standard we will have better guidelines for testing and the common practices used by antenna designers.
- IEEE 145-2013 - IEEE Standard for Definitions of Terms for Antennas. Definitions for antennas and for systems that incorporate an antenna as a component of the system are established in this standard. Terms and definitions used to describe systems using antennas, as well as that of any associated interfaces and components. This applies to our project because of the application of antennas in conjunction with some form of power conversion circuit. Knowing industry standards for antenna test ratings, interfaces and values is key to designing our solution effectively.

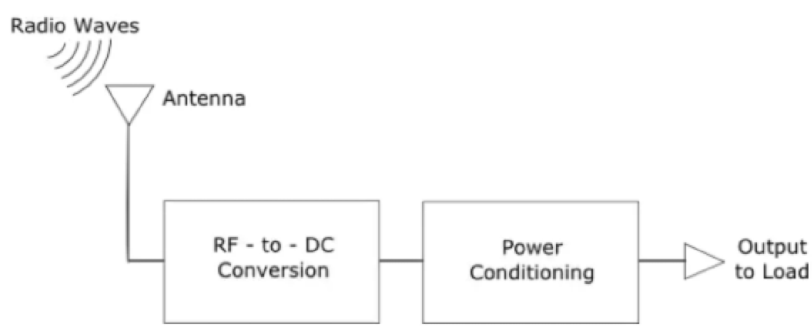
Project Design:

Functional Requirements:

- Function at or around 2.4 GHz frequency
- Convert radio energy into direct current
- Handheld/portable for testing purposes
- Represent power produced via voltmeter or powered LED

Device Block Diagram:

Below is the block diagram for the wireless energy harvester. On the left side there are incoming radio waves, next these waves will be collected by an antenna, next our harvesting board will convert these radio frequencies into a direct current signal. Finally, this power can be used on a load of choice.

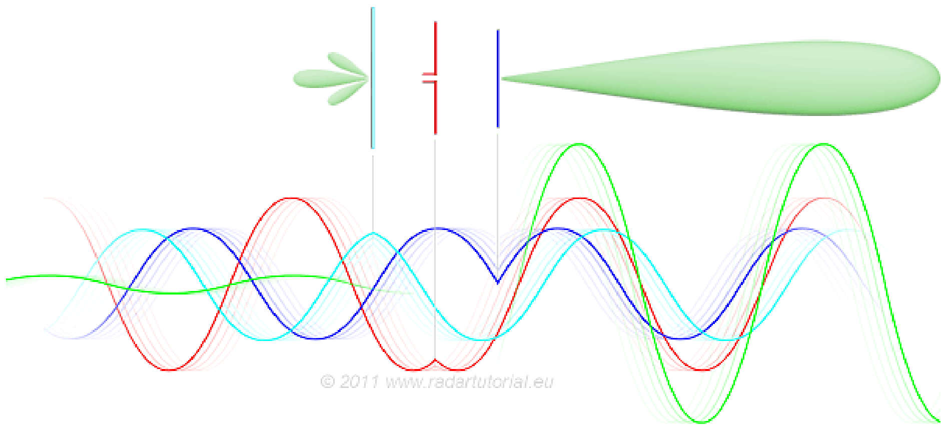


Design Decisions:

- Operation Frequency. We decided to focus our efforts on 2.4 GHz. We made this decision because it's one of the primary frequencies used for Wi-Fi and microwave ovens
- Size. One major concern of ours is size. We could create an antenna that completely envelopes a Wi-Fi router therefore supplying us with all available power being produced by the router but this would not be cost effective, would render the router useless for other devices and would take up a lot of space. We plan on creating a device that is small enough to be handheld
- Build vs Buy antenna. We decided we are going to build our own antenna. This decision was made because it allows us to create a device that exactly meets our criteria. Initially we will test with a store bought antenna but the final product will use a homemade Yagi-Uda antenna which will allow us to get a much higher gain while also taking up much less space

Antenna Selection:

For our project we decided a Yagi-Uda antenna would be the best fit criteria for our device. There are a number of different types of antenna designs that have very specific use cases and pros and cons. Dipole antennas, for example, are very simple to make, however they have a very low gain. The Yagi-Uda style however is more complicated, involving more components and parts, it is also extremely directional which means it is necessary to point it at the source of radio frequency in order to capture them. This directionality makes it possible to use constructive and destructive interference to drastically increase the gain of the driven element and therefore increase our power output. Below is an image showing how the directors and reflector on the Yagi-Uda antenna work together to increase the signal gain at the driven element.

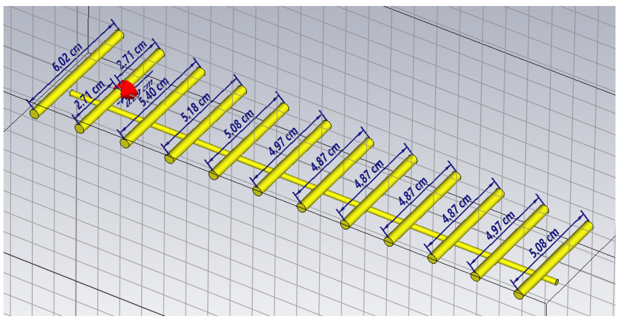


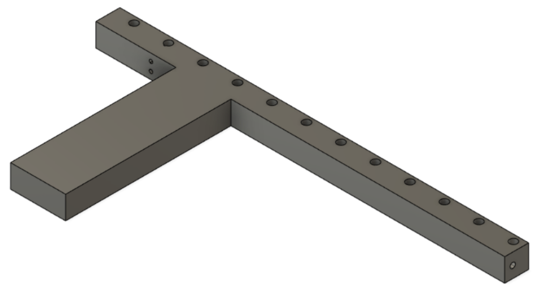
Initial Design Plan;

Our initial design for our device consisted of a 6 element Yagi-Uda antenna. The size of wire used, the length of elements, and expected output were all calculated using very basic calculations. After inputting the values for this design into our simulation software we quickly found that it would be an ineffective design. It would have had a very low gain and not worked very efficiently. Next, a new antenna was designed directly in the simulation software that met our specifications. After construction of this new antenna we quickly discovered it would not work. We were unable to effectively connect our coaxial cable to our driven element and the housing we had 3D printed was not perfectly straight.

Final Design Plan:

Our final design plan was to construct a 12 element Yagi-Uda antenna, the elements would be made of 6 AWG copper wire because it is nearly a perfect conductor. The length of the elements were simulated using CST Studio and are listed below. The housing was designed to be 3D printed out of PLA plastic and be 9 inches long. We connected our antenna to our harvesting board using a coaxial cable designed to operate up to 6 GHz which is well within our operational frequency. For our final product we also created a portable voltmeter that utilized an arduino nano, a voltage sensor and an LCD screen. We could hook our harvesting board up directly to this and test our antenna in the field. Below is the design for our antenna.





Implementation:

This project is useful more as a research based tool but if applicable there are a couple ways it could be implemented into the real world. A couple high end physical implementations for our project, if enough power is able to be generated, could be the ability to give power to devices embedded in concrete. Devices in low light areas where solar power will be less effective. Also in small household items like TV remotes and other items that don't need a lot of power to operate. Mainly this is a research tool to test antennas and how well they pick up RF signals.

Testing and Results:

We are testing the output voltage and current from the test board with the use of a multimeter. We are connecting the two output prongs on the test board to a breadboard and measuring the voltage over a closed and open circuit. We are expecting to have an output of 20 mW to power an LED, and hopefully have overhead to allow for higher load applications such as small electronics. We will also be implementing the use of directional antennas like Yagi-Uda to increase the amount of gain.

We conducted testing by first running RF simulations of our Yagi-Uda antenna design within CST Studio, and recorded a gain value of 15 dBi in ideal perfect conditions. Once a baseline target was determined, we began our experimental lab control testing. To do this, we used a software-defined radio (SDR) by the name of ADALM-Pluto to generate a 2.4

GHz signal that was transmitted from the Pluto's dipole antenna and received by the 12 elements of the Yagi antenna. Distance between the radio and antenna was in the range of 6 inches to 5 feet with the Yagi pointed directly at the power source and level to the ground.

Real world testing was conducted on and around the Iowa State University campus and involved measuring voltage produced from various sources. The first source tested was Wi-Fi routers found throughout ISU. This proved to be a problematic method of experimentation, as wireless access points (WAP) do not run at full load at all times. Therefore under minimal load (few to no devices connected to the router), only a small fraction of power is being sent from the source and very few useful voltage readings can be obtained. In order to bypass the limitation of Wi-Fi routers, we then attempted to use a mobile phone cellular hotspot as an analogue. Finally, we ran similar tests near the front door of common 1000W microwave ovens.

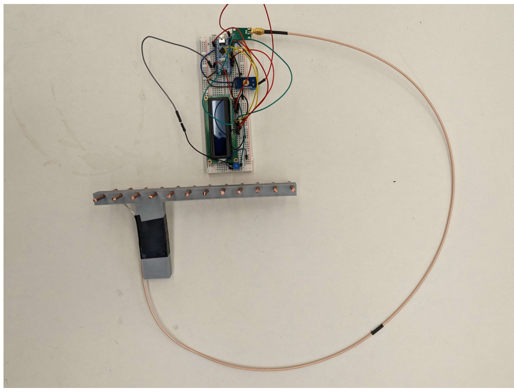
After testing was completed, we compiled the results and determined the microwave oven to be the best power source of everything compared to it. From a distance of roughly 1 foot, we detected a maximum voltage of 420 mV. Although relatively inconsistent, this provided the highest average output of any source. Both the Pluto and Wi-Fi routers generated measurable values, however voltage readings were barely high enough to overcome the detection voltage of the harvesting board (24 mV). The Pluto had better results overall, with an average reading of around 30 mV, while the WAP and wireless hotspot generally could not be relied upon for useful data as there was little to no voltage detected.

Finally, we compared how the harvesting board performs with the signal generated from the Pluto SDR being fed directly to the circuit board. To do this, we disconnected the harvesting board directly to the Pluto and detected a steady voltage reading of 70 mV.

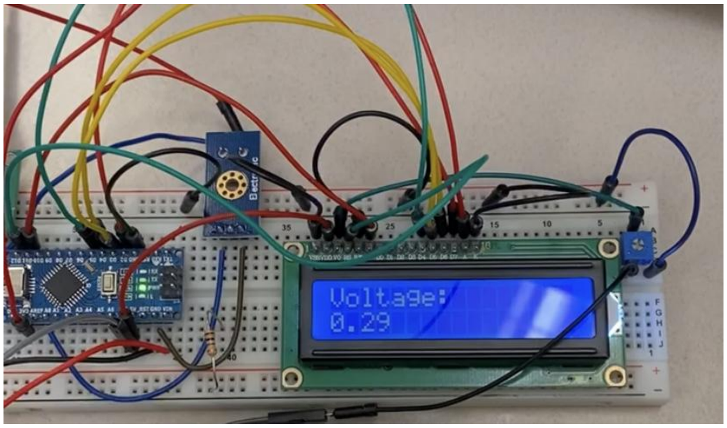
Appendices:

Appendix I: Operational Manual

Set-up:
To set up our project, we first need to grab the antenna and plug the coaxial cable into the RF-DC rectifier. Then, plug the chip into the voltage detection board. The final step is to plug in the 9-Volt battery and point the antenna at a Wi-Fi router or any other RF source.

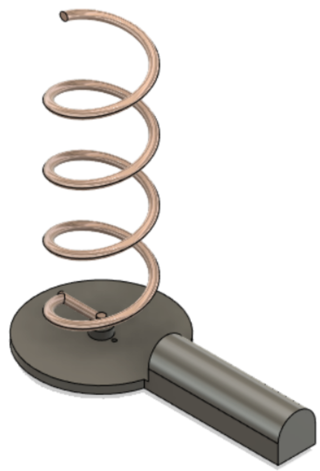


Demo/Testing:
To demonstrate the project, you simply have to point the antenna at a Wi-Fi router. The O-LED display will show the voltage the antenna and chip are harvesting.



Appendix II: Alternate Designs

During our design process we created the design for another antenna in case our Yagi-Uda antenna did not function properly. It was a helical antenna, designed to function at 2.4 GHz. Below are some images of the design and the first prototype we constructed. We did not end up pursuing this antenna type however because it had lower gain than our Yagi-Uda design and was much harder to create an accurate prototype because of the need to coil thick copper wires to a very specific diameter.



Appendix III: Other Considerations

Cost:

- Energy harvesting test board - $50
- 6 & 10 gauge copper wire - $30
- Coaxial SMA cables - $20
- Arduino (Atmega328) - $11.59
- Voltage sensor - $5.49
- OLED display - $7.19
- 3D printing filament - $10
- Total - $134.27

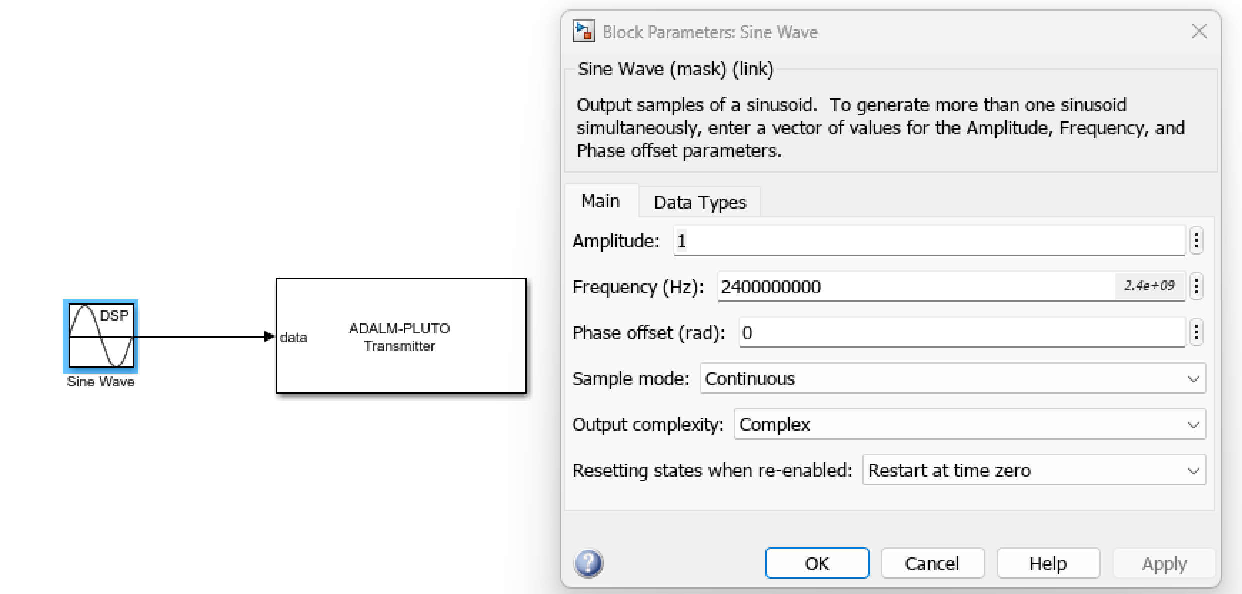
Hours:

Antenna Design	• Antenna selection • Research into selected antenna • Software simulation familiarity • Simulation Design • Physical Design	25 Hours
Circuit Design	• Circuit research • Designing some sort of antenna port • Circuit for RF to AC • Filter design • AC to DC rectifier circuit design • PCB modeling and ordering	10 Hours

Testing	● Initial dipole antenna testing ● Determining testing parameters such as distance from WAP, and load to test on ● Yagi-Uda antenna test ● Test with different frequencies	40 Hours
Cosmetic Design	● Designing Enclosure for final device ● 3D modeling enclosure ● 3D Printing	20 Hours

Appendix IV: Software Code

Matlab/Simulink program for generating 2.4 GHz signal from the Pluto SDR:



Arduino Code:

Below is the code that was written for the voltmeter functionality. Our voltmeter utilizes an arduino nano as the brain of the device so the code is written in arduino's version of C. It sets up certain pins as input or output and then allows us to detect the voltage coming from the voltage detector and then display it on the LCD screen.

```
#include <LiquidCrystal.h>

#define ANALOG_IN_PIN A0
const int rs = 12, en = 11, d4 = 5, d5 = 4, d6 = 3, d7 = 2;
LiquidCrystal lcd(rs, en, d4, d5, d6, d7);
// Floats for ADC voltage & Input voltage
float adc_voltage = 0.0;
float in_voltage = 0.0;

// Floats for resistor values in divider (in ohms)
float R1 = 30000.0;
float R2 = 7500.0;

// Float for Reference Voltage
float ref_voltage = 5.0;

// Integer for ADC value
int adc_value = 0;

void setup()
{
  lcd.begin(16, 2);
}

void loop()
{
  adc_value = analogRead(ANALOG_IN_PIN);

   // Determine voltage at ADC input
   adc_voltage  = (adc_value * ref_voltage) / 1024.0;

   // Calculate voltage at divider input
   in_voltage = adc_voltage / (R2/(R1+R2)) ;

   lcd.print("Voltage:");
   lcd.setCursor(0,1);
   lcd.print(in_voltage);
   lcd.setCursor(0,0);
   // Print results to Serial Monitor to 2 decimal places
  //Serial.print("Input Voltage = ");
  //Serial.println(in_voltage, 2);

  // Short delay
  delay(500);
}
```