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Battery-Less IoT Device

Design Document

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ADS: Advanced Design System

CSS: Code Composer Studio

MCU: Microcontroller

2. Introduction

2.1 Acknowledgement

As team 21, we would like to sincerely thank faculty advisor Dr. Henry Duwe for providing valuable insight and guidance. We would also like to thank Dr. Nathan Neihart, Dr. Daji Qiao, and Dr. Jiming Song for providing solutions and resources to some of the technical challenges faced in this project.

2.2 Problem/Project Statement

We are creating a device that harvests ambient RF waves and converts the power received into a usable form. The problem behind harvesting and converting ambient RF waves is that the signal received will be much smaller than the signal broadcasted by the source. To obtain a usable amount of power from harvesting RF waves, the receiving antenna needs to be very close to the source or highly directive and pointed towards the source. Since the device will only have enough power to perform a few tasks until it loses power, the MCU will need to be specially designed to handle this type of situation.

Our solution is to create a device that efficiently harvests and converts ambient RF waves and uses them to operate a low-power MCU doing basic tasks. This will be achieved by charging a capacitor with the converted power and using that to provide a reliable source of power to the MCU.

2.3 Operational Environment

For initial purposes, this battery-less IoT device will be used in Durham and/or Coover buildings. The end product should be usable in zones of considerably strong WiFi signal. The device would not be ideal to use under rain/snow conditions or in extreme high temperature environments. This device is designed to use under normal room temperature and indoors.

2.4 Intended Users and Uses

Ideally, to collect readings such as temperature/voltage and transmit from MSP readings into a more usable interface i.e excel sheet, to conduct further analysis on collected data. The device will initially be used by EE and CprE faculty for more in-depth research topics.

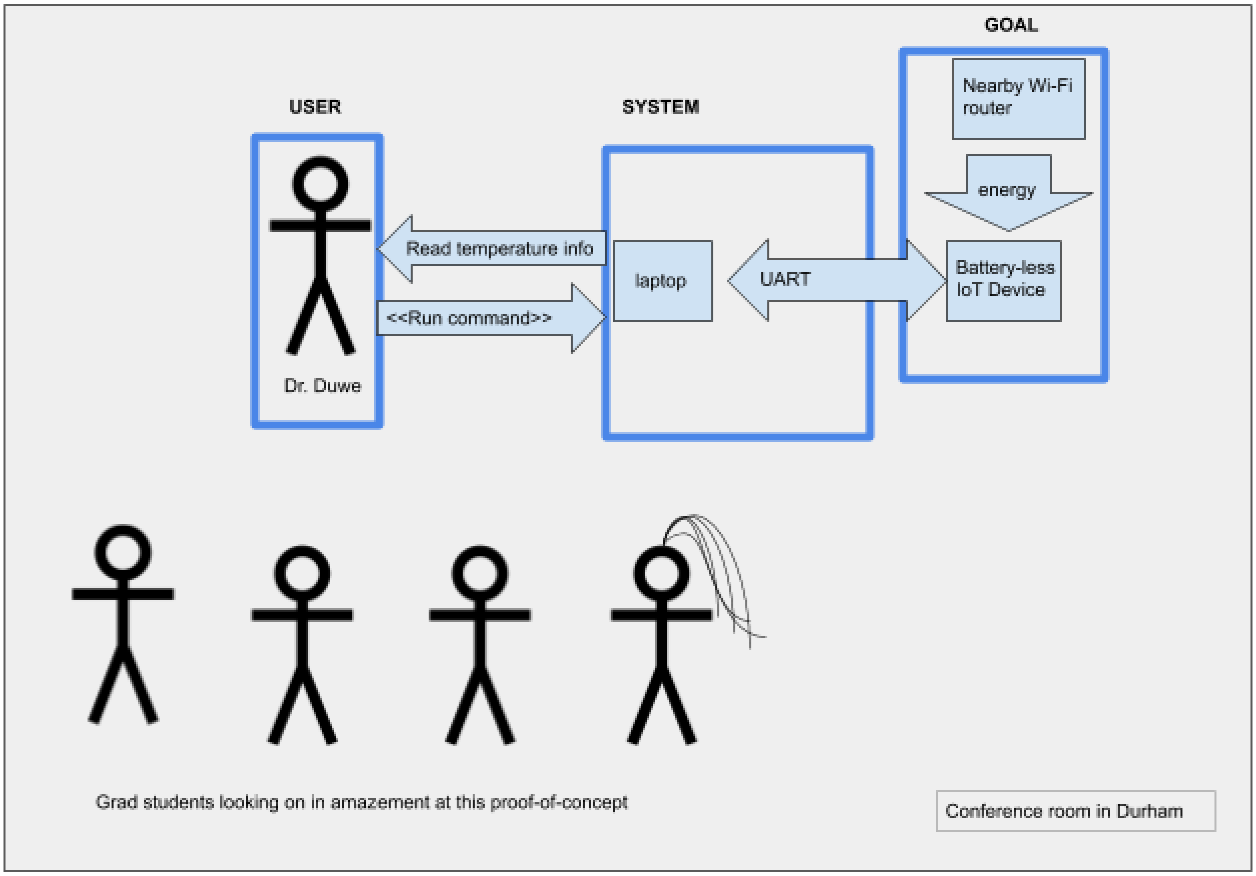


Figure 00: User-case diagram

2.5 Assumptions and Limitations

Assumptions:

- Wi-Fi router is in a close distance where the device is used to collect data
- Doesn't require high storage capacity

Limitations:

- Have to be used in areas with Wi-Fi routers
- Time of usage is approximately 2 hours
- Require approximately 30 minutes - 4 hours to power up the device

2.6 Expected End Product and Deliverables

The end product will be a battery-less IoT device powered through Wi-Fi to collect basic measurements such as temperature, light or voltage. It shall also transmit its measurements over RF. This device would eliminate the use of batteries and recharging batteries. The project is to be completed by December 2019.

3. Specification and Analysis

3.1 Proposed Design

- Functional Requirements:
  - Antenna(s) must be able to power the system adequately.
  - Antenna must be able to be adjustable to face the router.
  - MSP430 must be able to perform basic tasks and transmit the data to an external central system.
- Non-functional Requirements:
  - Antenna needs to gather power at a rate to supply the MSP430 for one measurement per hour or more.
  - MSP430 needs 1.8V supplied at a minimum to run correctly.
  - Supercapacitor needs to have significantly less power loss (leakage current) than the power generation.

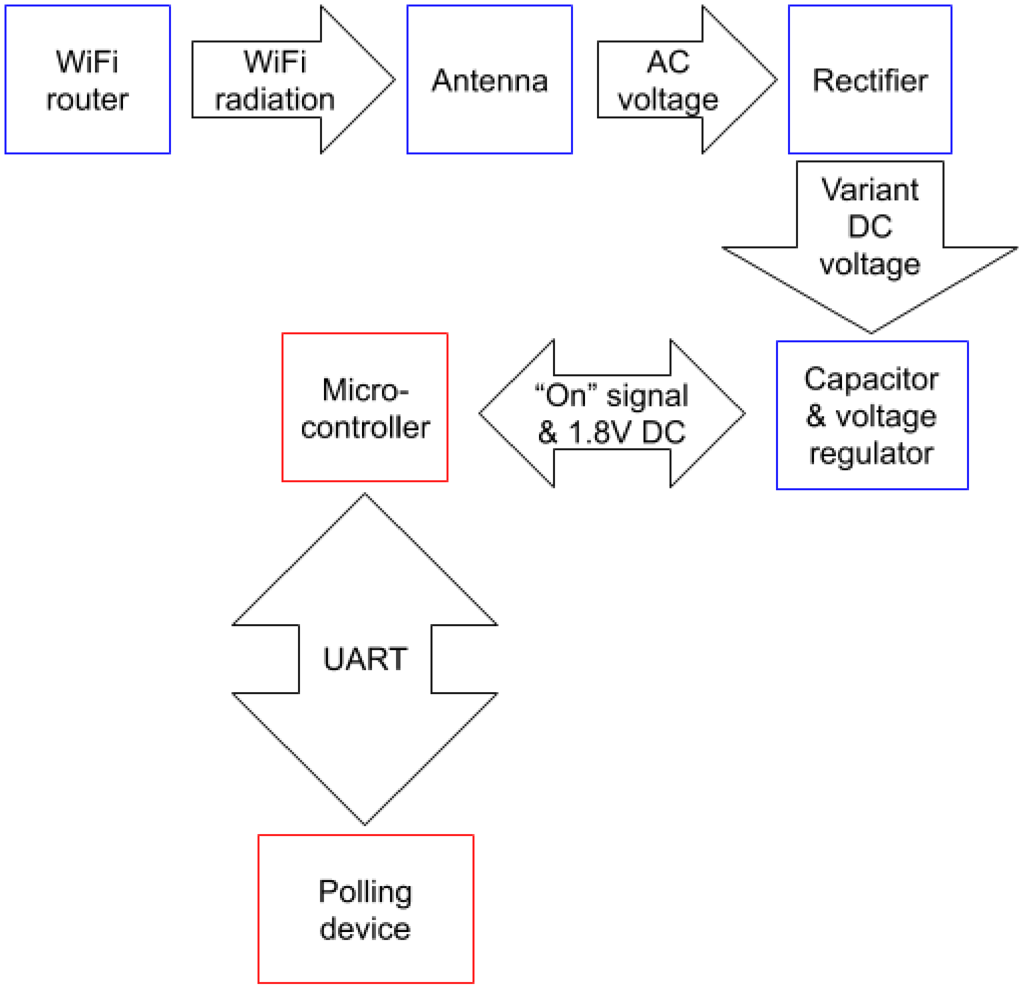


Figure 01 : Design Diagram

3.2 Design Analysis

Antenna

- Monopole and Dipole Antennas

We designed and built prototypes of monopole and dipole antenna using a coaxial cable and sma connectors. Theses design did not go into testing as we understood the limitation of our designs and their inability of delivering our requirements. The dipole antenna was facing impedance mismatching issues due to the ground plate of the sma connector working as a reflector. Also, our antenna is not a balanced system because the two ends of the dipole antenna have different lengths which will lead to difference in the current flow. The monopole antenna was not going to be able to capture enough signal to allow it to power our circuit. Given these facts, our team decided to move on with different designs such as PIFA and patch antenna.

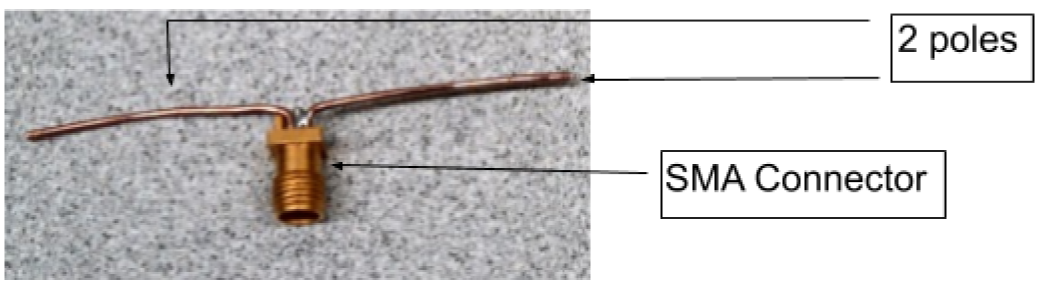


Figure 02 : Dipole antenna

Figure 03: Monopole Antenna

- PIFA (Planar Inverted F Antenna) [1]

For designing the PIFA antenna, our team used ANSYS HFSS. Using ANSYS HFSS we were able to control our design parameters which can allow us to design much more precise antennas as well as simulate them. We are attempting to create an antenna that fits onto the main board made of FR4 epoxy. FR4 Epoxy is a common PCB board, but it’s not made for antenna design, so there may be some issues with how the antenna performs. So far, the gain obtained from the simulation is 0dB, but it could be better. The gain doesn’t reduce by much at the edge of 2.4GHz, and the beamwidth is roughly 40-50 degrees across at the main beam. The advantage of this design is that it can fit on the board and takes up very little space. We've learned that the substrate and thickness of the board contribute greatly to the gain of the antenna. It seems that thicker substrates raise the gain of the antenna as well as contribute to an impedance effect that needs to be tuned away.

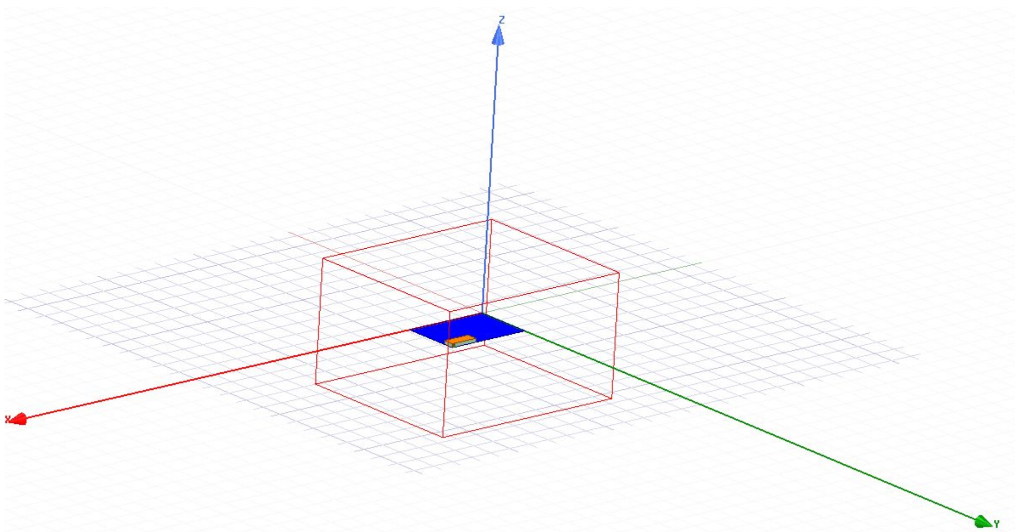


Figure 04: PIFA antenna modeled by ANSYS HFSS

- Patch Antenna

The patch antenna is a much simpler design compared to the PIFA, consisting of a rectangular "patch" that acts as the antenna. This type of antenna is the easiest option for use in an array of antennas. With an array, the power generation can potentially be multiplied, allowing for a much higher generation of power. The downside of using patch antennas is the extremely narrow bandwidth that fails to cover the entirety of the WiFi spectrum optimally. This downside can potentially negate any increased received signal gain we might achieve through an array. We plan to use a "corporate feed" configuration to reduce the amount of rectifiers we need to use. [2][Page 19]

Rectifier Circuit

In order to power the MSP430, we need to convert the AC RF wave into a DC voltage source. We also need to step the voltage up from the peak values provided by the RF wave. There were 4 main ways of going about this:

- Rectifier with a boost converter

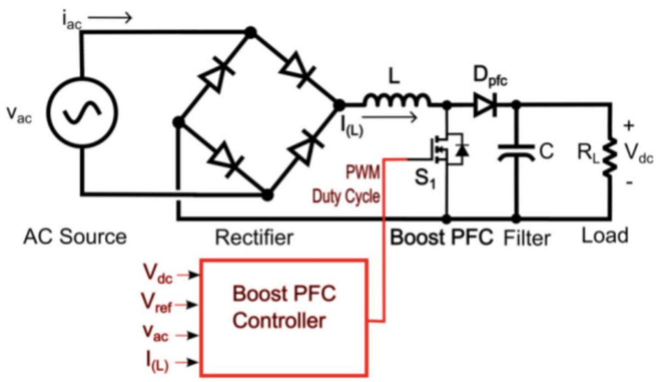


Figure 05: Full wave rectifier with boost converter

This idea was limited by the fact that a boost converter needs a timer circuit to operate. Uncertainty about what will control the timer circuit and how much power it will subtract from our finite supply are what ultimately tabled the idea.

- Voltage multiplier featuring a transformer

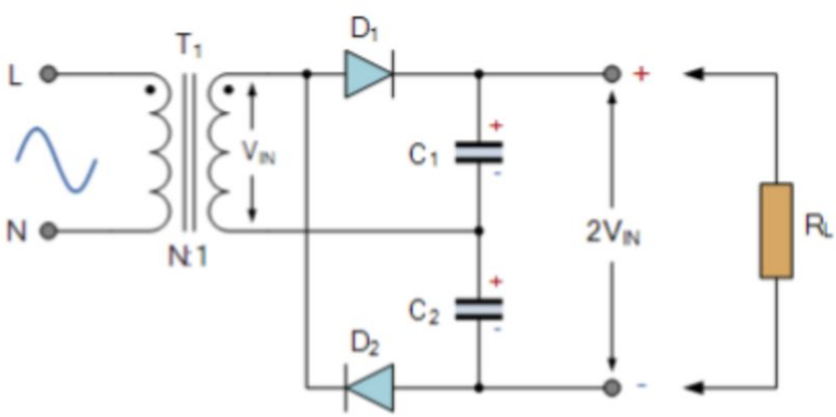


Figure 06: Voltage multiplier with transformer

The voltage multiplier is an appealing idea, but the transformer would make the design calculations more complicated, with regards to impedance matching. It would also have power losses in the coils, in quantities which may prove significant.

- Cockcroft-Walton Multiplier

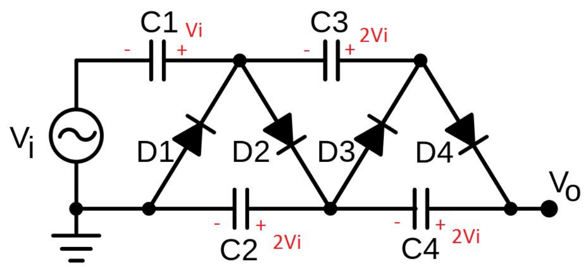


Figure 07 : Cockcroft-Walton Multiplier

This was the circuit we ultimately decided on. This is a voltage multiplier with 4 stages of 2 capacitors and 2 Schottky barrier diodes each. With the small parts and short lengths of metal between components, its power losses appear minimal. The output voltage is based on the distance the antenna is from the router and the number of stages in the voltage multiplier. One important note: the power losses from the components mean that the DC voltage supplied does not increase linearly with the number of stages. After 2 stages, the losses accrued will negate the voltage added by that stage. This is why we chose to leave it at 2 stages.

- Greinacher voltage doubler circuit

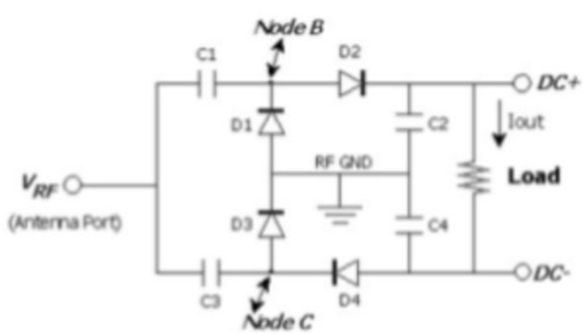


Figure 08 : Greinacher voltage doubler circuit

It is very similar to the Cockroft-Walton multiplier. However, it features 2 half-wave voltage doublers, so as to capitalize on the amount of RF energy received by the antenna. Each half-wave doubler has only 2 stages, so as to minimize losses. These qualities are excellent, but we decided to pass it up, in favor of the CW voltage multiplier. The output (DC+ and DC-) does not feature the same ground as the antenna. If we were to implement this idea, we would need 2 different ground planes; one for the rectifier(s) and one for the power control and the MSP430. It would be tedious to have to have multiple ground planes, whose size with respect to the rectifiers would have to be massive to approach ideal conditions. That is why we passed up on this design.

MSP430

Texas Instruments mixed signal microcontroller is considered one of our vital tools for this project. Due to it's inconsiderable amount of versatility and features, we should be able to use the energy harvested effective and efficient manner.

With a support low voltage range of 1.8 V to 3.6 V that can be customized to consume different Ultra power modes for different stages of our energy collecting process. Moreover, the active mode where our system is functioning at it's best manner this will be achieved after collecting enough power for our Wifi connection. As it's expected we are not always going to have enough energy to keep powering the MSP at our Active mode. For that, we needed to be read and use the 5 different low power modes.

4. Testing and Implementation

4.1 Interface Specifications

The input of the antenna is a 2.4 GHz Wi-Fi signal captured from a surrounding Wi-Fi router. The Antenna used in the design is of type patch antenna arrays that consists of a number of patch antennas. After each of the antennas captures a WiFi signal, the signal of each antenna will then be passed through its own rectifier that converts the AC signal to DC. In order to minimize impedance, the patch antenna and rectifier combinations will be part of the same PCB. The DC output of each rectifier will be added together in series to get maximum voltage, which then goes into an energy storage circuit. These can be connected by wires and a breadboard for now; ultimately, everything will be soldered to the same PCB. The energy collected will be used to power a sensor, microcontroller (MSP430) and a feedback communication circuit. These can be connected by female-to-female headers. The memory of the MSP430 will be used to temporarily store the measurement data collected by the sensor, which then will be transferred through the communication circuit to a data logger or a cloud system. The frequency and protocol for this will be based on minimizing the power required to transmit the measurement.

4.2 Hardware/Software

Testing the design prototype of our IoT device will include both hardware and software tests which includes testing the antenna and power circuitry and testing the software uploaded into the MSP430 MCU. To facilitate these tests, we will be making use of the hardware available in the engineering labs and the necessary software in the computer labs of Coover Hall.

Hardware

- Digital Multimeter
- Oscilloscope
- Signal Generator
- Signal Analyzer

Software

- Advanced Design System
- Code Composer Studio
- MSP430-GCC
- Eagle PCB
- Ansys HFSS

Hardware Descriptions

- Digital Multimeter

Figure 09: Digital Multimeter

Digital Multimeter would be used to measure resistances, capacitances, voltages and currents in our power circuitry which includes rectifiers and voltage doublers. This will give us an idea of how efficiently the AC voltage from the Antenna circuitry is rectified and how effectively the voltage is doubled.

- Digital Oscilloscope

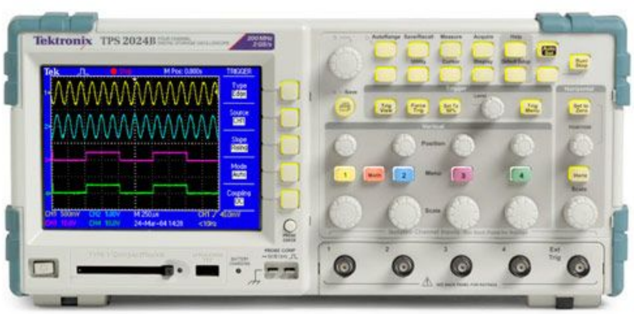


Figure 10: Digital Oscilloscope

The oscilloscope will be used to monitor the rectified voltage output from our rectifier circuit and voltage output from our voltage doubler circuit to make sure we are getting the expected results.

- Signal Generator

Figure 11: Signal Generator

Before using the voltage output from our antenna circuit, we will be testing our rectifier and voltage doubler circuits by sending in AC signals from the signal generator and observing the output using the oscilloscope.

- Signal Analyzer

Figure 12: Signal Analyzer

The signal analyzer would be used to validate the efficiency of the antennas by measuring the input signal magnitude and phase at a the Wi-Fi single frequency. This will allow us understand how much signal in dB units can be obtained from a 2.4GHz Wi-Fi signal source

<u>Software Descriptions</u>

- ADS

ADS is an electronic design automation software system produced by Keysight EEsof EDA. ADS will be used to model our rectifier and voltage doubler circuits before building them. This will give us an understanding of what capacitor values to use in our prototype to get the best results.

- Eagle PCB

Free software used to develop printed circuit boards (PCB's) for fabrication. This program will be used to design the rectifier board and possibly the antenna, which may all come as one piece together

- Code Composer Studio

An IDE developed by Texas Instruments which will be used to write and load temperature reading and storing software onto the MSP430 microcontroller.

- Energia

A high level programing language that allows us to communicate with various TI microcontrollers. It's important to note that Energia also arduino based language. This will be used as a backup and compare some reading and results from Code Composer Studio.

- MSP430-GCC

An open source C/C++ debugger and compiler toolchain for MSP430 microcontrollers. These tools will be used alongside CCS instead of the proprietary Texas Instruments C compiler to write, debug, and compile C and assembly code for our microcontroller.

- Ansys HFSS

An electromagnetics simulation program used for simulating a wide variety of RF applications. We will be using this specifically to create and simulate the antenna(s) for use in the circuit.

4.3 Functional testing

Test #1: Strength of Wi-Fi signal and power output

The purpose of this test was to understand the strength of the Wi-Fi and test the feasibility of using Wi-Fi to power our IoT device. This test was conducted in Coover in 1012 classroom after 9pm. For this test we used a mobile application called WiFi Analyzer to collect data.

Procedure: We used the WiFi analyzer app on our phones to measure the strength of the Wi-Fi signal in dbm (decibels with reference to 1mW). Data was collected at different vertical heights straight down from the router. Measuring vertically down from the router resulted the strongest signals. These results were recorded in an excel sheet to be converted to nanowatts and to be plotted for examining. To ensure the accuracy of the collected data, 4 mobile phones with WiFi analyzer apps were used.

Test #2: Simulate the rectifier

Using ADS, we will simulate the impedance, losses, and output voltage/current of the rectifier to test its feasibility. We will also be looking for ways to make it more efficient. If possible, we will also incorporate the antenna into the design and simulate the effect of RF waves on the whole circuit. The patch antenna can be easily drawn up in ADS, and the diodes and capacitors have files on the manufacturers' websites for use in ADS. We will also be examining the thickness and material of the connectors and the substrate of the board.

Test #3: MSP Operating Modes for Harvesting Energy

In an attempt to optimize the harvested energy we collect, we needed to figure out a way use our MSP at different power modes. Moreover, since we expect a discontinuity in the energy we receive. It meant that the MSP could be not operating at times, so we looked more into the different power modes. With a total of five different power modes, we attempted to use flash memory to story the temperature readings. These readings are collected from the MSP's internal system and would have to be tested at different constraints and limitations. The hope is that we can use our information stored in our flash memory operate sequentially with our collected power smoothly.

4.4 NON FUNCTIONAL TESTING

4.5 RESULTS AND CHALLENGES

Test #1: Strength of Wi-Fi signal and power output

Test to investigate the power output from Wi-Fi

Location of the test: Coover 1012
Tine of the test: After 9pm
Test date: 02/11/2019

Apps used to test the Wi-Fi:

Bradley	WiFi Analyzer
Derek	WiFi Analyzer
Mukhaini	WiFi Analyzer
Gesalla	WiFi Analyzer

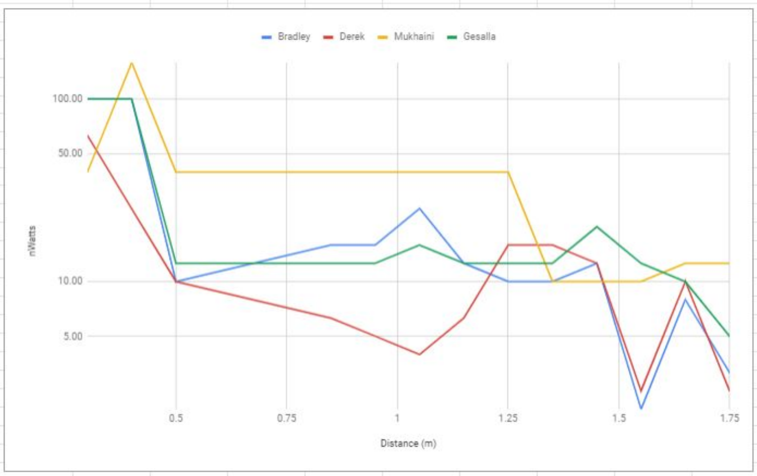
Limitations of the Apps: -40 dB Maximum Value for App

Angle from the router: vertically 90 degrees below the router

Convserion: dbm to nWatts

Distance(m	Wi-Fi strength in dbm				Power in nWatts			
	Bradley	Derek	Mukhaini	Gesalla	Bradley	Derek	Mukhaini	Gesalla
1.85	-55	-56	-49	-53	3.16	2.51	12.59	5.01
1.75	-51	-50	-49	-50	7.94	10.00	12.59	10.00
1.65	-57	-56	-50	-49	2.00	2.51	10.00	12.59
1.55	-49	-49	-50	-47	12.59	12.59	10.00	19.95
1.45	-50	-48	-50	-49	10.00	15.85	10.00	12.59
1.35	-50	-48	-44	-49	10.00	15.85	39.81	12.59
1.25	-49	-52	-44	-49	12.59	6.31	39.81	12.59
1.15	-46	-54	-44	-48	25.12	3.98	39.81	15.85
1.05	-48	-53	-44	-49	15.85	5.01	39.81	12.59
0.95	-48	-52	-44	-49	15.85	6.31	39.81	12.59
0.85	-50	-50	-44	-49	10.00	10.00	39.81	12.59
0.5	-40	-46	-38	-40	100.00	25.12	158.49	100.00
0.4	-40	-42	-44	-40	100.00	63.10	39.81	100.00
0.3	-40	-40	-44	-40	100.00	100.00	39.81	100.00

Figure 13: Recorded test results for Wi-Fi strength in dbm and nWatts



Conclusion:
As expected, the closer the phone antenna is to the router, the stronger the Wi-Fi strength resulting a higher power output.
Within 1.55m range the power output ranges between 5nWatts and 100nWatts

Figure 14: Linear plot for nanowatts vs distance

The results from this test show that we are only getting about 100nWatts of power when we are 0.3m away from the router. This is lower than we expected. After a discussion with Dr. Duwe and Dr. Neihart we realized that this test has to be conducted during times of high Wi-Fi usage densities.

We tested multiple cell phones with a Wifi Analyzer app to determine the power of the wifi signal at different distances from the phones. Each phone was placed under the router with the screen facing it. The orientation played a huge role in how much power the signals were received with. Since our phones were placed with the screen facing up, the main beam wasn't facing the router, causing the results to be skewed by -15dBm to -20 dBm less. When we re-tested at different angles to validate the data it became apparent that something was wrong with our initial experiment test. The challenge to taking measurements like these are orientation issues, as the main beams of antennas aren't always obvious and there is no way of seeming them normally, especially under black box circumstances.

Test #3: MSP Operating Modes for Harvesting Energy

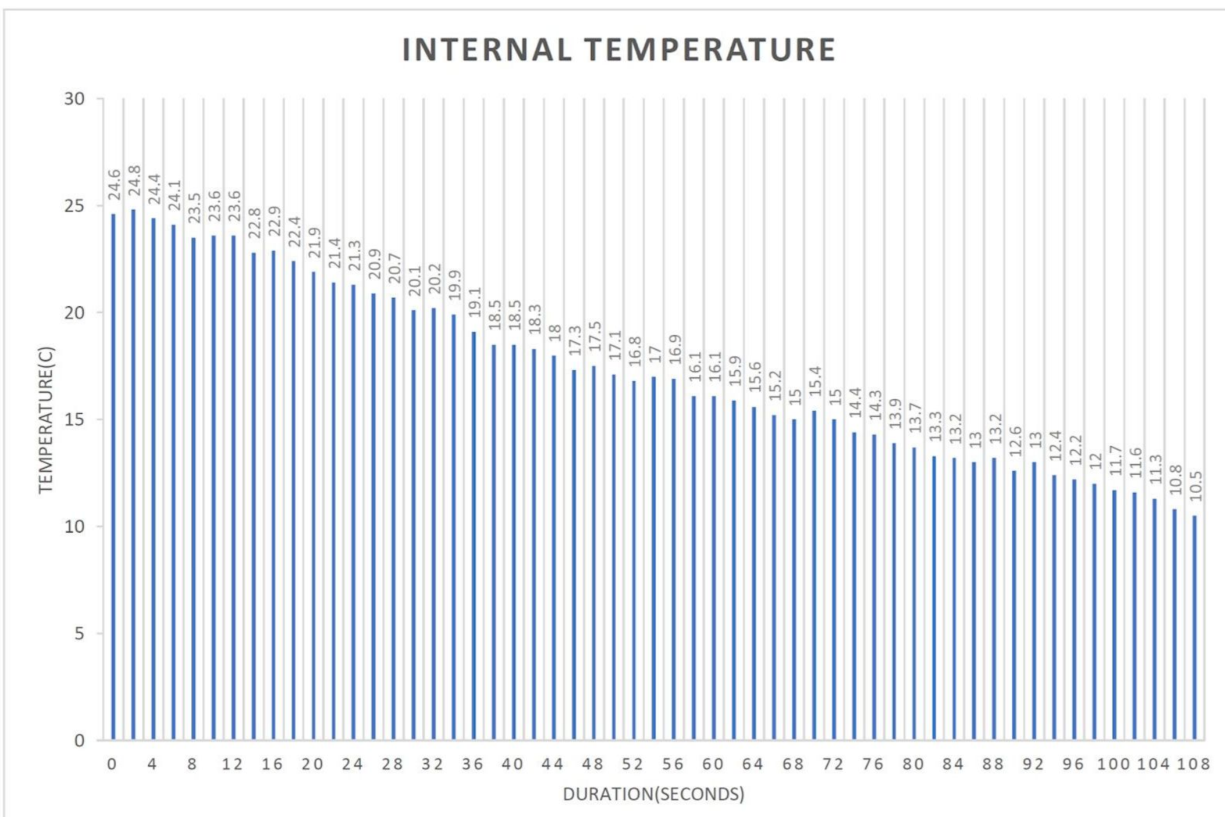


Figure 15: MSP430 Internal temperature readings

Knowing how lengthy this process is, we managed to successfully program our MSP to be able to read internal temperature. We tested this in two different platforms (Energia and Code Composer Studio) where similar readings were observed. Figure 15 shows a temperature drop observed through the MSP430 as we moved from inside to outside. Figure 16 below shows the basic flow control of our final program.

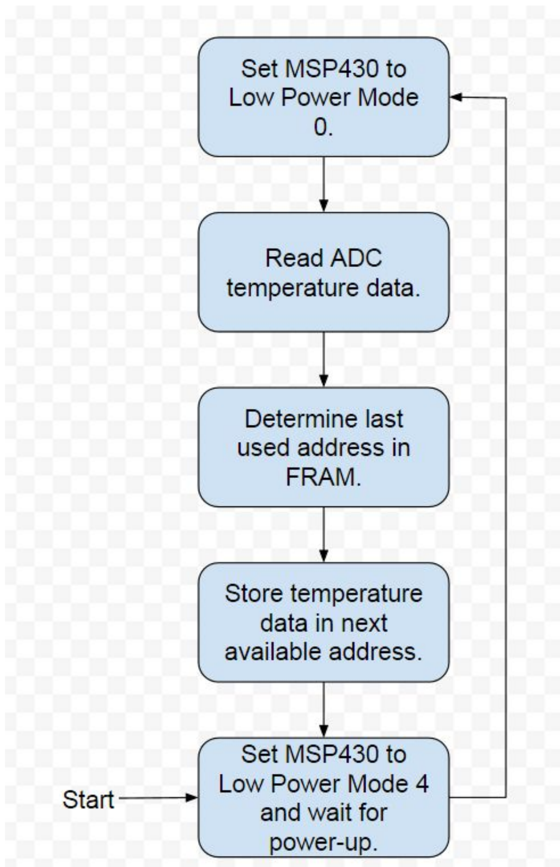


Figure 16: Flow control diagram for temperature-reading software

5. Closing Material

5.1 Conclusion

So far we have come up with multiple ideas for antenna designs, rectifier designs, and possible methods of using the MSP430. We have done basic feasibility testing and we have determined that it is feasible to create a WiFi harvesting device. We have done basic simulations and we are close to prototyping.

Our current short-term goals are to create and simulate an array of patch antennas, finalize a design for the rectifier circuit, and create code to allow the MSP430 to operate under ultra low power conditions. Mid-term goals include simulating the rectifier connected to the antenna array and prototyping the analog portion of the board.

Our solution is to create an array of antennas which will heavily increase the power generation compared to singular antennas. We plan on using a Greinacher circuit to rectify and double the AC Voltage into DC Voltage, from the articles we've read [3] it is used on almost all RF harvesting circuits. We will use a supercapacitor with a voltage regulator to store energy and to provide a constant voltage to the MSP430. The MSP430 itself is optimal due to its ultra low power usage.

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