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Battery-Less IoT Device

Final Report

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1.2 List of Definitions

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, Dr. Jiming Song, Praveen Gurrala, and Scott Melvin for providing solutions and resources to some of the technical challenges faced in this project.

2.2 Problem/Project Statement

We created 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. The MCU will periodically start up, perform a function, and shutdown.

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. 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

The device’s ideal use is for collecting readings such as temperature/voltage and transmitting them into a more usable format i.e excel sheet. Such demos will allow further research into low-power devices. The device will initially be used by EE and CprE faculty for more in-depth research topics.

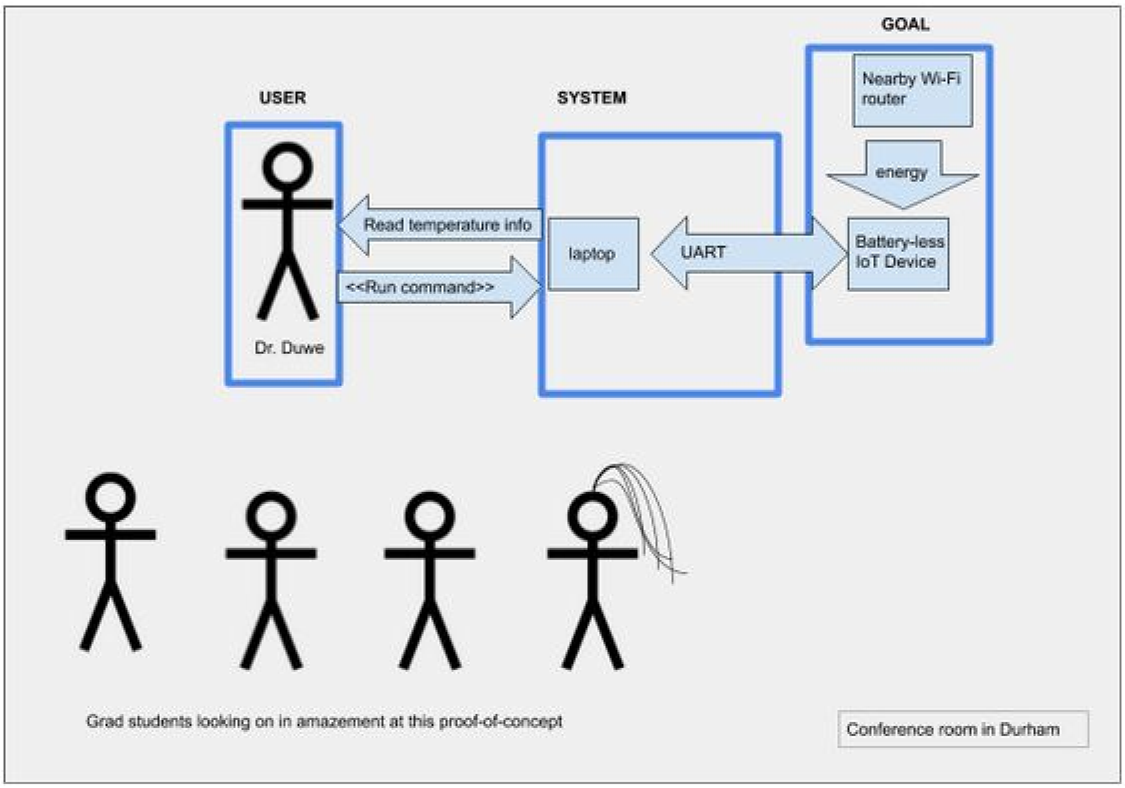


Figure 00: User-case diagram

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.

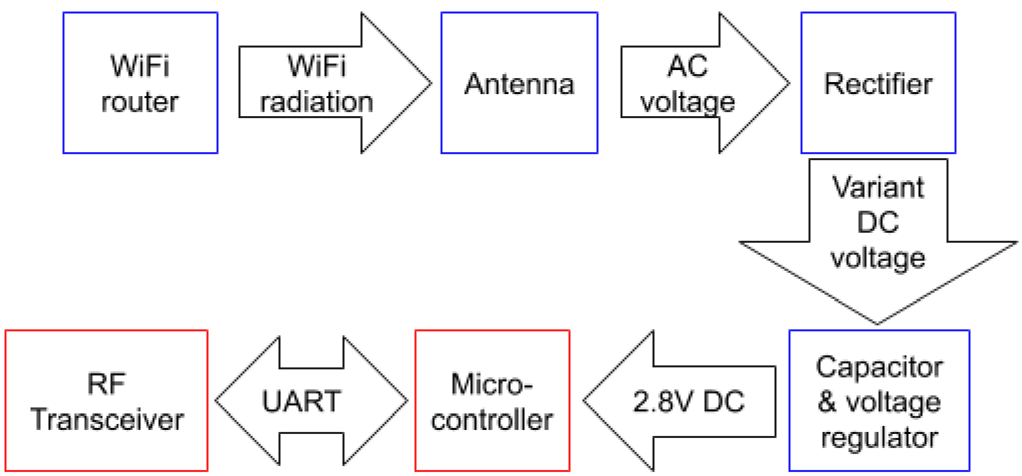


Figure 01 : Design diagram

3.2 Design Analysis

3.2.a Antenna

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]

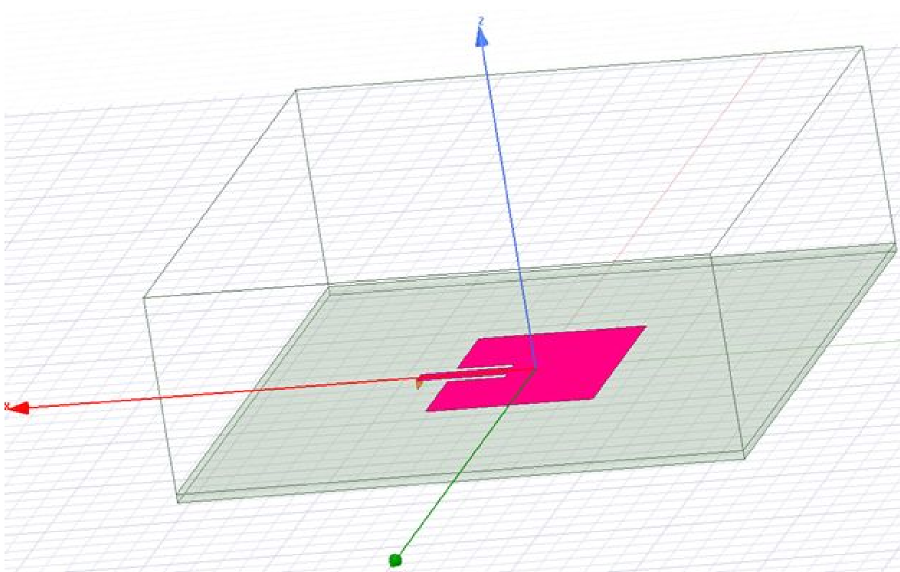


Figure 02: HFSS simulated patch antenna

This design was superseded by our purchased 8dB Patch Antenna.

Figure 03: EMRSS 8dB 2.4GHz Articulated Patch Antenna

3.2.B Rectifier Circuit & Voltage Regulator

- **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.

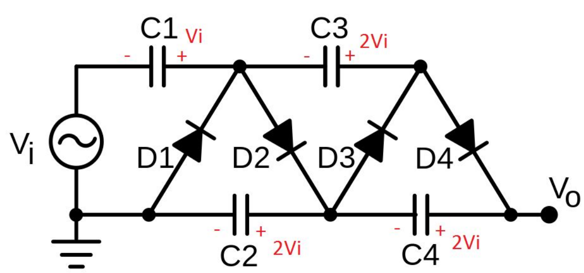


Figure 04 : 2-Stage Cockcroft-Walton Multiplier

This was the circuit we initially decided on. This is a voltage multiplier with stages of 2 capacitors and 2 Schottky barrier diodes each. With the small parts and short lengths of metal between components, its power losses are minimal. The output voltage is based on the distance the antenna is from the router and the number of stages in the voltage multiplier. From Test 2 we realized that the power losses from the components mean that the DC voltage supplied does not increase linearly with the number of stages. After enough stages, the losses accrued will negate the voltage added by that stage. For our final rectifier design we decided to go with 5 stages which outputs sufficient voltage to power the MSP430.

Following shows the PCB layout and the schematic for our 5 stage rectifier design. It uses 10uF capacitors and Schottky diodes.

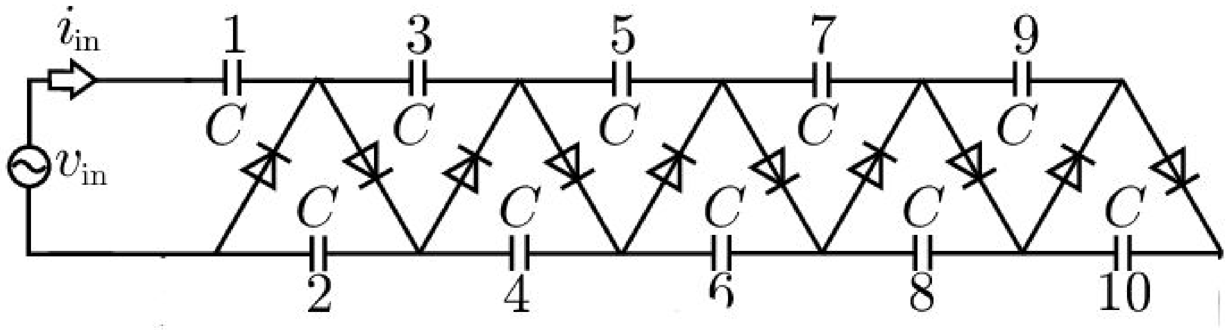


Figure 05 : 5-Stage Cockcroft-Walton Multiplier

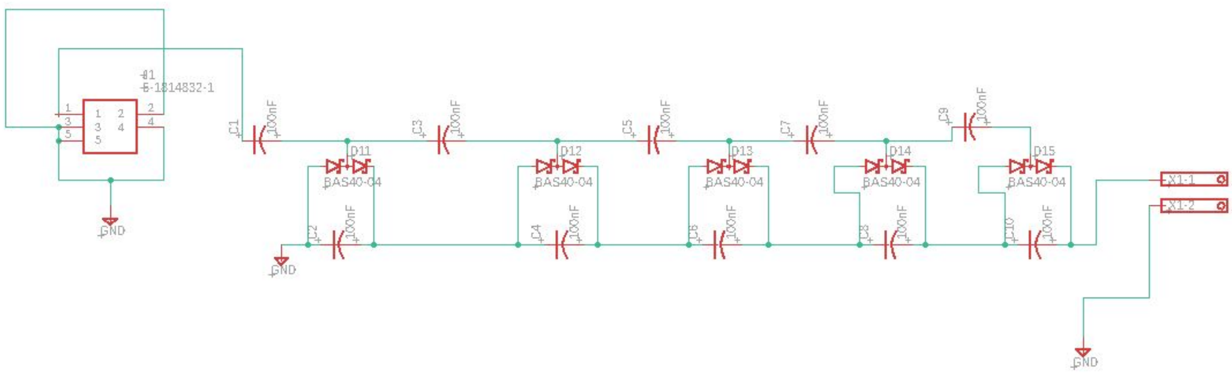


Figure 06: PCB schematic of the 5-stage rectifier

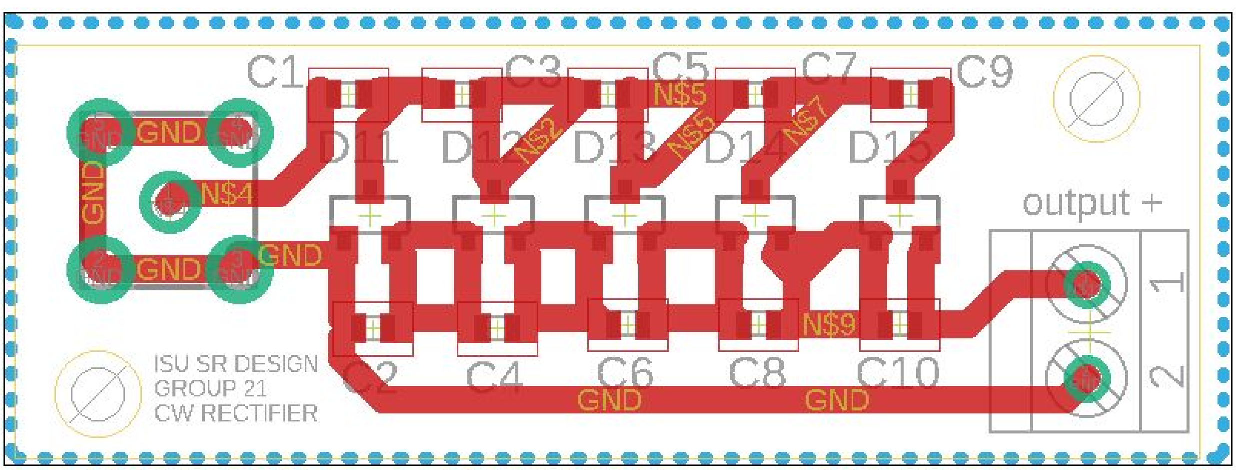


Figure 07: PCB layout of the 5-stage rectifier

- **Voltage Regulator Circuit**

The MSP430 microcontroller requires a steady DC voltage of at least 2.8V. To achieve this we require a voltage regulator. The rectified voltage output from the 5 stage rectifier is fed into the voltage regulator to result a steady DC voltage of at least 2.8V. The design options for the voltage regulator is either a switching regulator or a linear regulator. Our initial design consisted of a step-up switching regulator but our Test 9 showed that this regulator produced a fluctuating voltage output. The output voltage was not constantly steady to power the MSP430 microcontroller. Therefore for our final design we decided to use a linear regulator. Although the linear regulator is not as power efficient as the switching regulator, it produced a steady voltage of 2.8V. Following shows the circuit schematic, PCB schematic and PCB layout of the linear voltage regulator. The regulator used Linear voltage regulator IC ADP150AUJZ-2.8-R7 and the capacitor values uses were 10uF to achieve an output voltage of 2.8V.

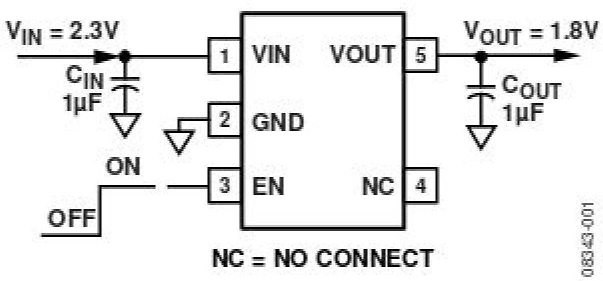


Figure 07: Linear voltage regulator schematic

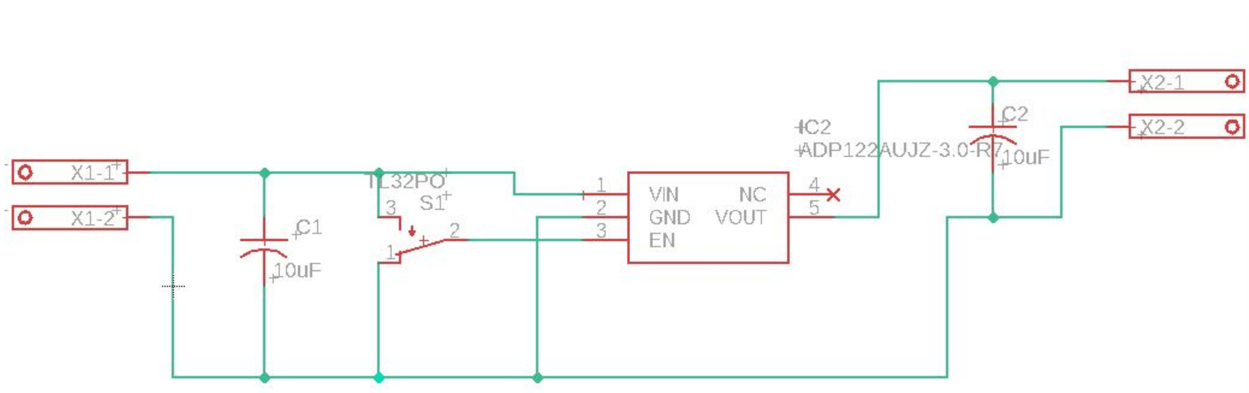


Figure 08: Linear voltage regulator PCB schematic

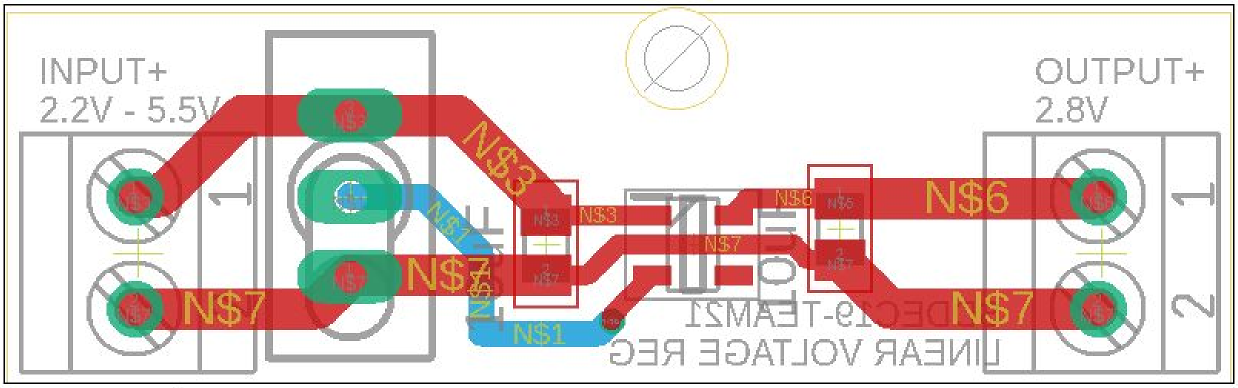


Figure 09: Linear voltage regulator PCB Layout

3.2.c 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. 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 subsequent 2.4GHz WiFi antenna will connect to the rectifier circuit through a 50 Ohm SMA connector. After the rectifier circuit converts the 2.4GHz wave into a DC voltage the output will connect to a capacitor bank through 2-pin screw terminal blocks on each PCB, one pin connected to the positive terminal of the capacitor and one pin to ground. Between the capacitor bank and the microcontroller there is a voltage regulator, it also has 2-pin screw terminal blocks for its input and output. Once enabled the voltage regulator will output a 2.8V DC voltage to the microcontroller. The energy collected will be used to power a microcontroller (MSP430) and a feedback communication circuit. These can be connected by female-to-female headers. Using an MSP430 with non-volatile F-RAM memory to store the data measurement collected by ADC sensor. Since we expect power levels to be insufficient at times, the MSP would use a lower power mode after taking each set of temperature readings. Finally, a serial connection is used to communicate the temperature readings stored to present them to our users.

4.2 Hardware/Software

Testing the design prototype of our IoT device will include both hardware and software tests which includes testing the antenna, 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

- Keysight 34470A 7.5 Digit Multimeter
- Keysight InfiniiVision DSO-X 2024A D.A. Oscilloscope
- Agilent Technologies E5071C Network Analyzer
- Tektronix RSA6114A Real-Time Spectrum Analyzer

Software

- Advanced Design System
- Code Composer Studio
- RealTerm : Serial/TCP connection
- Energia
- MSP430-GCC
- Eagle PCB
- Ansys HFSS
- National Instruments LabVIEW

Hardware Descriptions

- Digital Multimeter

Figure 10: 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

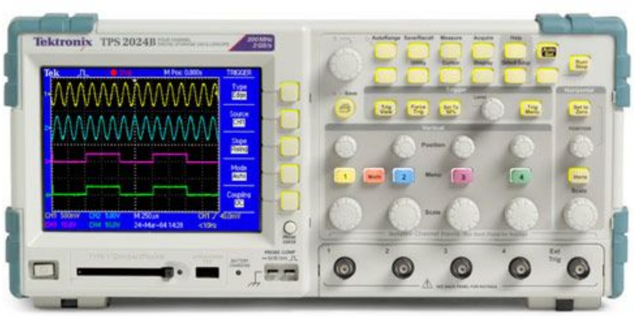


Figure 11: Digital Oscilloscope

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.

- Network Analyzer

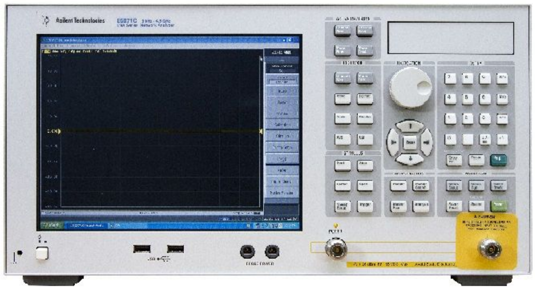


Figure 12: Network Analyzer

The network analyzer allows us to collect S-parameter values from various components in our circuit. Using a test board we can sweep a components S-parameters versus frequency to serve as the basis for a parasitic model. The network analyzer is also used to find the S11 values for our antenna. This determines the amount of power loss in the antenna itself.

- Spectrum Analyzer

The spectrum analyzer will allow us to determine the frequency bands that the router is broadcasting at as well as the power provided by each band. We used this in our project to determine the possible power received by our antenna from a basic Coover Hall WiFi router.

Figure 13: Spectrum Analyzer

Software Descriptions

- Keysight Advanced Design System

ADS is an electronic design automation software system owned by Keysight. ADS will be used to model our Cockroft-Walton rectifier circuit 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. Moreover, code composer studio has a this able to use EnergyTrace Technology for the microcontroller to analyze and display our programs current energy consumption levels. This helps optimize and improve our consumption of energy.

- RealTerm

Software used as a tool to capture our temperature readings from the MSP430 to a computer using serial communication.

- Energia

A high level programming 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.

- NI LabVIEW

LabVIEW is used to program test equipment such as multimeters or power supplies for complicated test procedures that can take a human significantly longer to complete. We used this program for DC testing our Schottky Diode.

5. Testing

5.1 Testing Process and Testing Results

Test 1: Strength of Wi-Fi signal and Power Output

- Purpose:

is 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 (during low WiFi traffic time). 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. 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 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

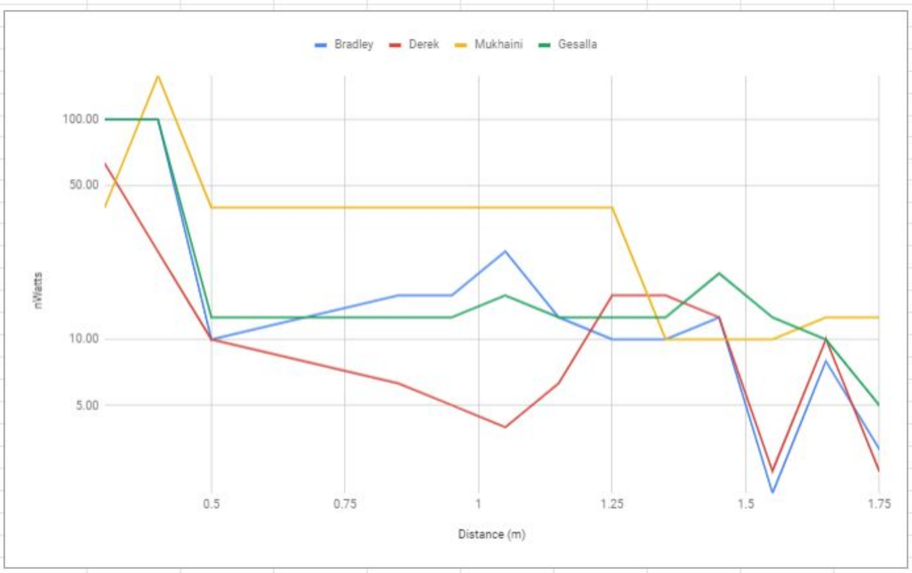
Limitations of the Apps: -40 dB Maximum Value for App

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 14: 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 15: Linear plot for nanowatts vs. distance

- Results:

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.

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.

Test 2: Simulate the Rectifier

- Purpose and Procedure:

Using ADS, we simulate 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 simulated in ADS, and the diodes and capacitors will have models made for them for use in ADS. We will also be examining the thickness and material of the connectors and the substrate of the board.

- Results:

The results from our simulations weren't as helpful as we originally believed. There were many mistakes made in planning and testing the components that pushed back many goals and ended up causing the simulations to have little impact on the prototype.

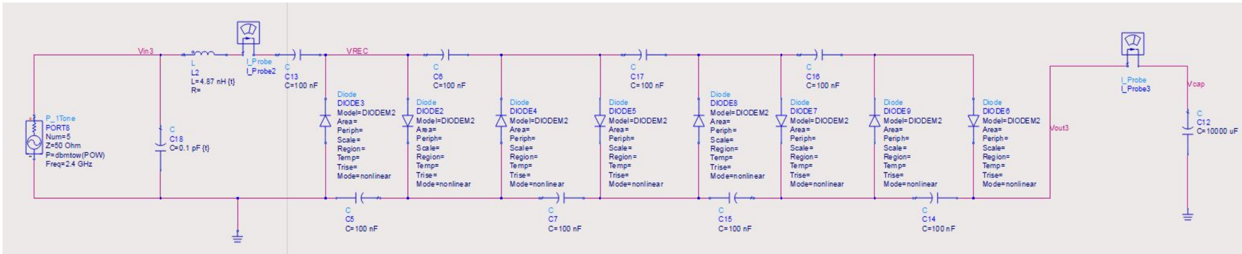


Figure 16: 5-Stage Cockroft-Walton rectifier schematic with a basic matching circuit

Our rectifier presented a few challenges we weren't able to overcome. Because the device was non-linear and the output changed based on the power provided at the input we weren't sure how to analyze the circuit.

That being said we were able to simulate the circuit and see that at some power levels, it was operating.

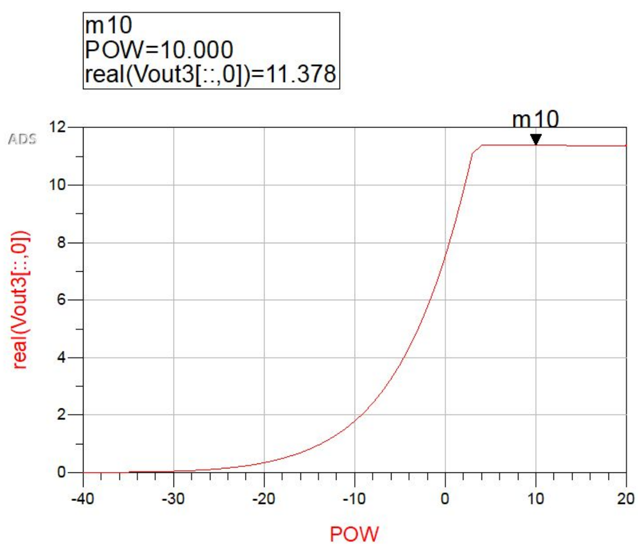


Figure 17: Output voltage(V) of the rectifier based on the input power(POW) in dBm

To attempt to match the rectifier we used a structure similar to that of an L-Match. We quickly realized due to the non-linear nature of the device we couldn't match it correctly. We attempted to tune the device to get us closer to a 50 Ohm input impedance but we were not able to get exactly the value we required. Our final input impedance for a target power of 10dBm was approximately 29 + j*1.9 Ohms. This gives us a relatively small mismatch loss of 8%. The input impedance of the rectifier deteriorates very quickly when lower powers are received which causes the mismatch losses to skyrocket to ~90%.

Test 3: Code Functionality and MSP430 Operating Modes

- Purpose and Procedure:

Testing was done on our code throughout development to ensure components were functioning as expected. To simulate intermittent power we used the integrated supercapacitor on the Launchpad: A jumper enabled the capacitor every time we wanted the MSP430 to power on and was then removed to simulate power loss. In this way we did not need to have the rest of the prototype working to verify code functionality. We obtained energy consumption measurements during these tests with EnergyTrace++.

Additionally we wanted to observe the energy consumption characteristics of the Launchpad, particularly around the brownout voltage for the MSP430. However the MSP430 must be connected to a computer to use EnergyTrace++ and therefore is continuously powered, which makes this task difficult. To measure the behavior of the MSP430 around its brownout voltage we used an oscilloscope. Specifically we focused on the rate of energy consumption, if any, after brownout. Additionally we tested how long we could stay above the brownout voltage within low power modes after measurements had been taken.

- Results:

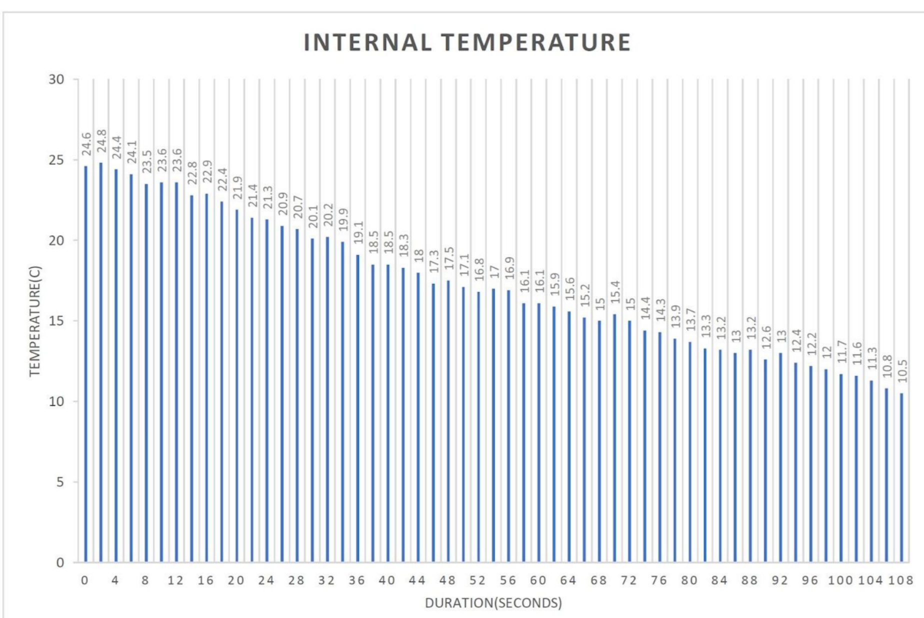


Figure 18: MSP430 Internal temperature readings

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.

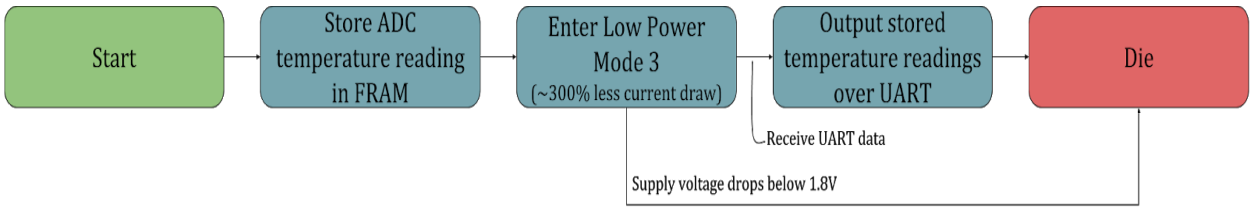


Figure 19: Flow control diagram for temperature-reading software

Test 4: Characterization of Schottky diodes

- Purpose and Procedure:

Using Spectrum Analyzer, this test was done to examine the Schottky diodes by DC testing them to see their IV characteristics. The purpose of this test is to validate our simulation diode models. The schottky diode function gave very similar results to the datasheet. Contrary to what we thought going into this, the IV characteristics were not exponential. Due to the way schottky diodes are made, there is an ohmic contact that causes the diode to have linear characteristics after its knee voltage.

- Results:

Results are shown on the graph below

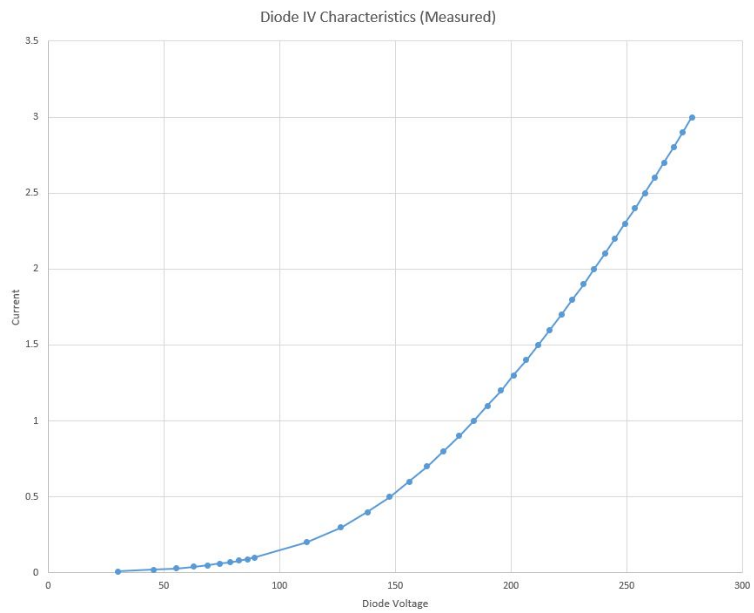


Figure 20: DC Test of the Schottky diode

Test 5: Measuring Wi-Fi signal Strength using Signal Analyzer

- Purpose and Procedure:

This testing was done to measure the power received by the antenna from a 2.4 GHz WiFi router. Using Signal Analyzer to take those measurements, the antenna was plugged into the signal Analyzer and placed directly below the WiFi router. At two meters directly underneath the router, our signal analyzer is showing that the antenna receives approximately -43dBm of power. WiFi routers are designed to radiate signals when a request for signal is initiated by a connected device. To ensure that the router was giving away signals, we connected out phones to the same WiFi router and started streaming videos. The spike seen on the figure below is a result of high signals withdrawal from the WiFi router when a video was being downloaded on a connected cellphone. This power is from channel 11, which is furthest away from the antenna's center frequency at 2.4GHz.

- Results:

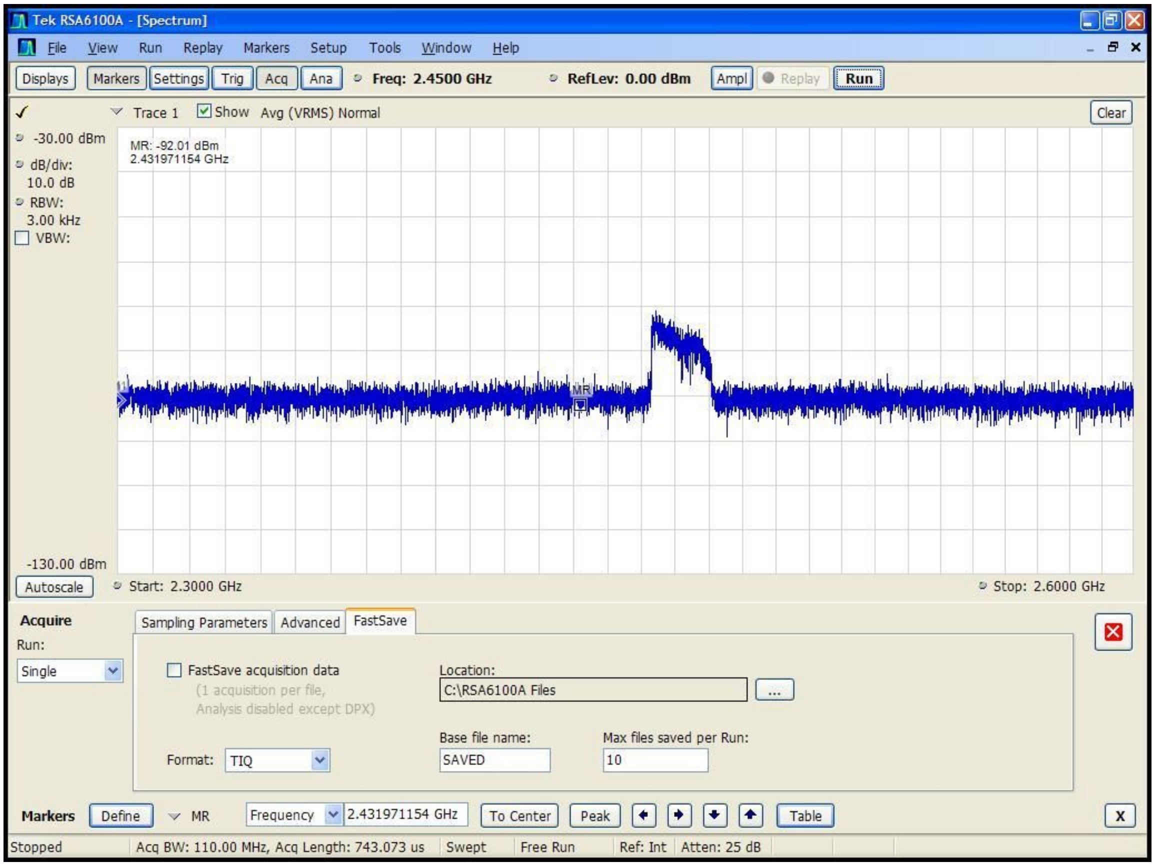
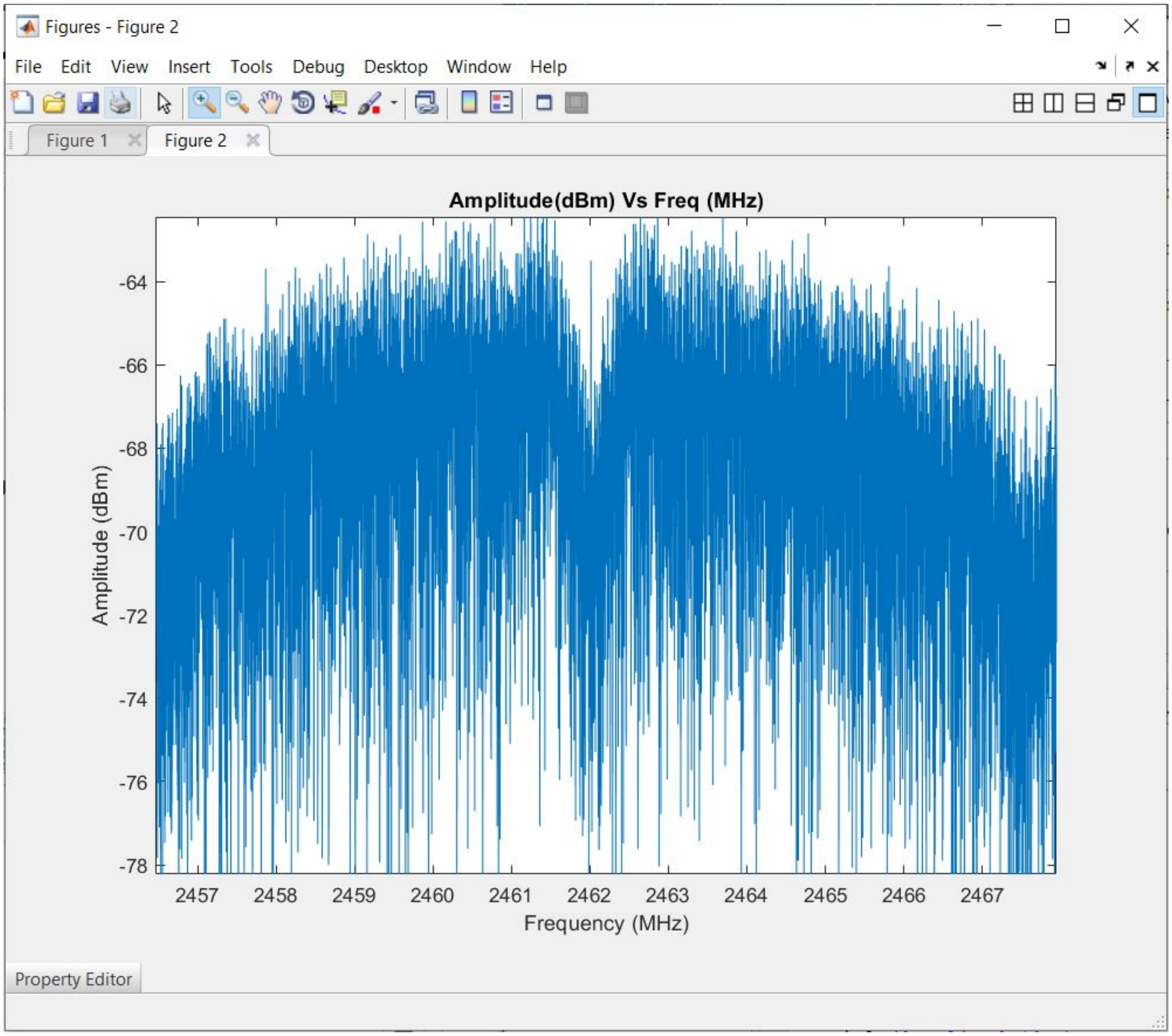


Figure 21: Results of spectrum analyzer measurement over 2.3-2.6GHz. Pictured is CH11



TEST 6: 2-STAGE RECTIFIER FUNCTIONAL REQUIREMENTS

- Purpose and Procedure:

This testing was conducted to determine three requirements: the resistor load required for the 2 stage Cockcroft-Walton Multiplier/rectifier, the power output of the 2 stage rectifier and the capacitor resulting the lowest voltage drop.

Following figure shows the schematic used for the 2 stage rectifier.

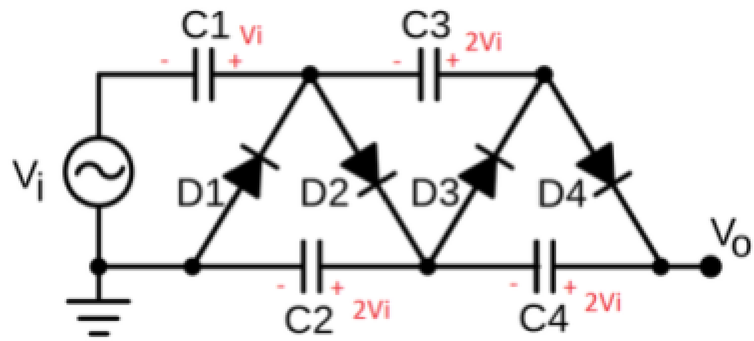


Figure 22: Schematic of the 2 stage Cockcroft-Walton Multiplier/ rectifier used for Test 6

For this testing we used two conditions for the capacitors C1,C2,C3,C4.

Condition 1: C1,C2,C3,C4= 0.1uF

Condition 2: C1,C2,C3,C4= 10uF

D1,D2,D3 and D4 are schottky diodes. The input AC voltage was a 25MHz wave with an amplitude of 0.6V (1.2Vpp). Test was carried out under these two capacitor conditions with different resistor load values ranging from 10 ohm to 1Mohm. The output voltage from the rectifier was measured using a multimeter. The power was calculated using P=V*I.

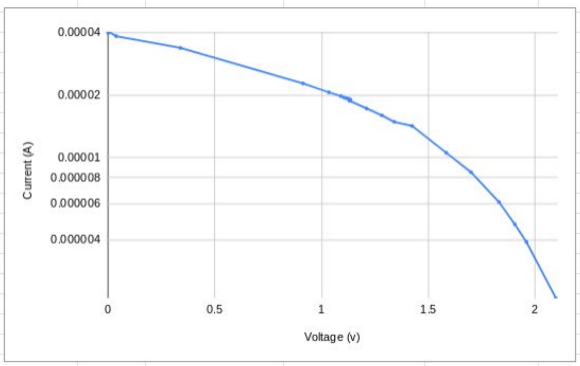
The ideal condition for this Cockcroft-Walton Multiplier is infinite capacitance. 0.1 uF was recommended by the scholarly articles we researched on. This is because 0.1uF is large enough to smooth lower the voltage drop and it is affordable. We decided to use a second set of capacitors of 10uF to test if increasing the capacitance does a better job in lowering the voltage drop.

- Results:

Following shows the results for the test condition 1 and 2.

Rectifier 1 (0.1uF)

Resistor (ohm)	Voltage (V)	Current(A)	power(w)	max power
Inf	2.22	0	0	0.00002169267752
10	0.0004	0.00004	0.000000016	
100	0.004057	0.00004057	0.00000016459249	
1000	0.03865	0.00003865	0.0000014938225	
10000	0.339	0.0000339	0.0000114921	
40000	0.913	0.000022825	0.000020839225	
50000	1.034	0.00002068	0.00002138312	
55000	1.09	0.00001981818182	0.00002160181818	
56685	1.105	0.00001949369322	0.000021540531	
57670	1.117	0.00001936882261	0.00002163497486	
58655	1.128	0.00001923109709	0.00002169267752	
59638	1.135	0.00001903148999	0.00002160074114	
60000	1.13	0.00001883333333	0.00002128166667	
70000	1.21	0.00001728571429	0.00002091571429	
80000	1.281	0.0000160125	0.0000205120125	
90000	1.34	0.00001488888889	0.00001995111111	
100000	1.423	0.00001423	0.00002024929	
150000	1.583	0.00001055333333	0.00001670592667	
200000	1.699	0.000008495	0.000014433005	
300000	1.83	0.0000061	0.000011163	
400000	1.904	0.00000476	0.00000906304	
500000	1.958	0.000003916	0.000007667528	
1000000	2.096	0.000002096	0.000004393216	



Rectifier 2(10uf)

Resistor (ohm)	Voltage (V)	Current(A)	power(w)	max power
Inf	2.0577	0	0	0.000018972013
10	0.0004	0.00004	0.000000016	
100	0.004061	0.00004061	0.000000164917	
980	0.037084	0.000037840816	0.000001403288	
9996	0.312	0.000031212484	0.000009738295	
50718	0.974	0.000019204227	0.000018704917	
55700	1.027	0.000018438061	0.000018935888	
56685	1.037	0.000018294081	0.000018970962	
57670	1.046	0.000018137679	0.000018972013	
58655	1.05	0.000017901287	0.000018796351	
59638	1.057	0.000017723599	0.000018733844	
100000	1.315	0.00001315	0.00001729225	
1000000	1.947	0.000001947	0.000003790809	

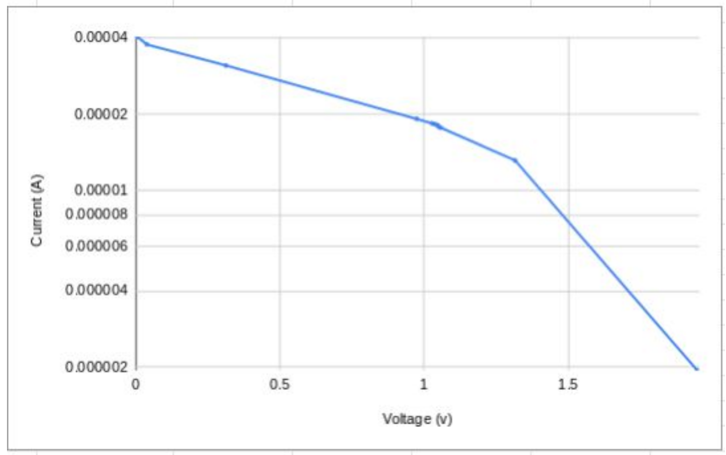


Figure 23: Test condition 1 and 2 results

With these test results we determined that 0.1uF capacitor results the best power output and the resistor load that we determined is 58kOhm which gives us a maximum power output of 21uW.

Test 7: 5-Stage Rectifier vs 2 Stage rectifier

- Purpose and Procedure:

This test was conducted to determine if increasing the number of stages in the Cockcroft-Walton multiplier/rectifier would increase the power output. Initially we thought that adding more stages to the rectifier would have more leakage although it would result in an increased voltage output. This test was to clarify the effect of adding more stages to the power output.

For this testing we used 2 conditions

Condition 1: 5-stage rectifier (Schematic in Figure 05)

Condition 2: 2-stage rectifier (Schematic in Figure 04)

In addition we also tested both these conditions with 2 capacitor values 0.1uF and 10uF. This was to find out which capacitor would result in the maximum power output depending on the number of stages.

We used the testing prototype below to conduct this test. For the two conditions we connected the 5 stage and the 2 stage rectifiers right after the Patch antenna and measured the voltage output from the rectifier using a multimeter. The power was calculated using $P = \frac{V^2}{R}$.

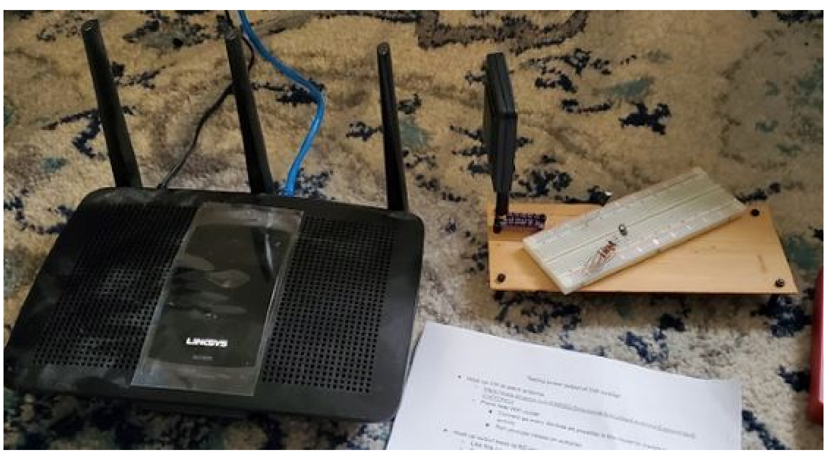


Figure 24: Testing prototype used for Test 7

- Results:

Following shows the test conditions and results

Test 1: Testing for Best load resistance 5 stage Rectifier

Test Conditions

Router model: Linksys EA7300

Traffic: 4k Youtube videos playing on 7 devices

Angle from router: patch antenna parallel to x axis with the monopole antena in z axis

Distance from the router: 6.35cm

Test Results

Board Used: 5 stage with 0.1uF with load 100uf

with no load= 7V

Load resistance(ohm)	volt(v)	power(w)	power(mW)	max power(mW)
100	0.052	0.00002704	0.02704	0.4454545455
1000	0.443	0.000196249	0.196249	
9900	2.1	0.0004454545455	0.4454545455	
50000	3.8	0.0002888	0.2888	
100000	4.8	0.0002304	0.2304	
1016000	6.2	0.00003783464567	0.03783464567	

Board used: 5 stage with 10uF with load 100uf at 6.35cm

with no load= 10V

Load resistance(ohm)	volt(v)	power(w)	power(mW)	max power(mW)
100	0.09	0.000081	0.081	1.296
1000	0.7	0.00049	0.49	
10000	3.6	0.001296	1.296	
50000	5.9	0.0006962	0.6962	
100000	7.8	0.0006084	0.6084	
1000000	9.8	0.00009604	0.09604	

Figure 25: Test 1 conditions and results

Test 2: Testing for Best load resistance 2 stage Rectifier

Test Conditions

Router model: Linksys EA7300

Traffic: 4k Youtube videos playing on 7 devices

Angle from router: patch antenna parallel to x axis with the monopole antena in z axis

Distance from the router: 6.35cm

Test Results

Rectifier Used: 2 stage with 0.1uF with load 100uf

with no load=5.5V

Load resistance(ohm)	volt(v)	power(w)	Power(mW)	max power
100	0.14	0.000196	0.196	0.81
1000	0.9	0.00081	0.81	
9900	2.7	0.0007363636364	0.7363636364	
50000	3.8	0.0002888	0.2888	
100000	4.3	0.0001849	0.1849	
1016000	4.9	0.00002363188976	0.02363188976	

Rectifier used: 2 stage with 10uF with load 100uf

with no load= 5.2V

Load resistance(ohm)	volt(v)	power(w)	power(mW)	max power
100	0.17	0.000289	0.289	0.676
1000	0.81	0.0006561	0.6561	
10000	2.6	0.000676	0.676	
50000	4.3	0.0003698	0.3698	
100000	4.4	0.0001936	0.1936	
1000000	5	0.000025	0.025	

Figure 26: Test 2 conditions and results

With this testing we found out that 5 stage rectifier produced the maximum power output of 1.296mW with a 10uF capacitor. These results proved that adding extra stages did not have as much power loss as we thought. The 5 stage rectifier also satisfied the power requirement of the MSP430 microcontroller. In our final prototype we decided to proceed with the 5 stage rectifier design with a 10uF capacitor.

Test 8: Determining the Distance between the Antenna and Router

- Purpose and Procedure:

This test was conducted to determine how far our device can be from the router to have a sufficient power output. We used the 5 stage rectifier with the 10uF capacitor and the same test prototype in figure 24. The voltage output from the rectifier was measured using a multimeter and the power was calculated using $P = \frac{V^2}{R}$.

- Results:

Following shows test results

Test: Changing Distance from the router

Test Conditions

Router model: Linksys EA7300

Traffic: 4k Youtube videos playing on 7 devices

Angle from router: patch antenna parallel to x axis with the monopole antena in z axis

Board used: 5 stage with 10uF with load 100uf with load resistance of 10kOhm

Test Results

Distance(cm)	Voltage(v)	Resistance(ohm)	Power(w)	Power(uW)
6	3.8	10000	0.001444	1444
10	2.9	10000	0.000841	841
20	1.6	10000	0.000256	256
40	0.7	10000	0.000049	49
80	0.3	10000	0.000009	9
100	0.13	10000	0.00000169	1.69
130	0.1	10000	0.000001	1

Figure 27: Test results for distance from the router

With the above results we determined that our device can be as far as 20cm from the router to output sufficient power. But the further we get away from the router, the lesser the power output. For the final design we decided that the router will be about 10cm from our device.

Test 9: Testing the 5-Stage rectifier with the Voltage Regulator

- Purpose and Procedure:

This test was to determine the final voltage output from the voltage regulator after the input voltage has been rectified and stored in the capacitor bank. In addition, we used this test to find out the best load resistance and how long it will take for the capacitor bank to discharge.

Following figure shows the test setup we had for this testing

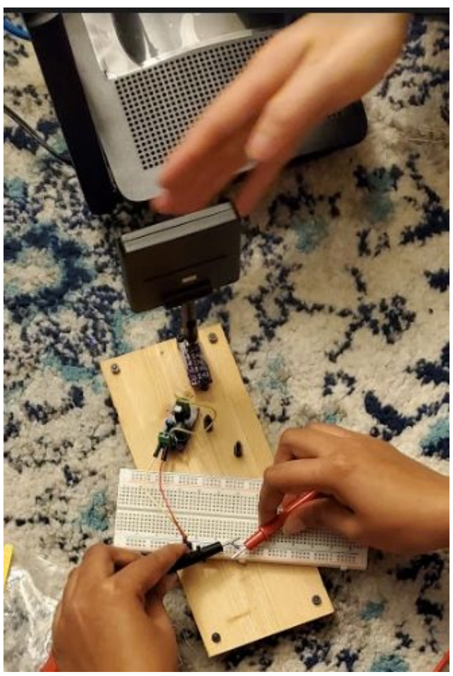


Figure 28: Test setup for Test 9

- Results:

Following shows the test conditions and results

Test: Testing the 5 stage with Voltage Regulator				
Test Conditions				
Router model: Linksys EA7300				
Traffic: 4k Youtube videos playing on 7 devices				
Angle from router: patch antenna parallel to x axis with the monopole antena in z axis				
Distance from the router: 13cm				
Board used: 5 stage with 10uF with capbank= 100uf				
Voltage Regulator input voltage : 0.7V - 3.0V				
Test Results				
		Load Resistance		
Time lasted	Voltage(v)	Resistance(ohm)	Power(w)	Power(uW)
for like 4 secs	3	100000		
5secs	3.3	200000		
10secs	2.97	250000	0.0000352836	35.2836
>5mins (less flucations in voltage)	3.02	300000	0.00003040133333	30.40133333
>5mins (flucation voltage between 3V-4v)	3.6	1000000	0.00001296	12.96

Figure 29: Test results for Test 9

From the above results we found out that our voltage regulator can output about 30uW for more than 5 mins before the MSP430 is connected. But we realized the switching regulator used in this design in not the best design for our design since the voltage output is fluctuating. The MSP430 requires a constant voltage, so we decided to change our voltage regulator design to be a linear regulator.

Test 10: Antenna S11 Measurement

- Purpose and Procedure:

To verify that our antenna is actually working efficiently as a power source we measured the S11 parameter with the network analyzer. From our results we can tell that at our operating spectrum there is very little reflected (wasted) power.

- Results:

The sides of the “valley” that contains our target band are between -17.6dB to -16.3dB. This represents a power loss of 1.7% to 2.34% at maximum from the antenna. The lowest loss portion of this band is approximately -28dB which represents almost a 0.16% loss in power due to the antenna. This validates our antenna and ensures that there isn’t needless power loss in the receiver.

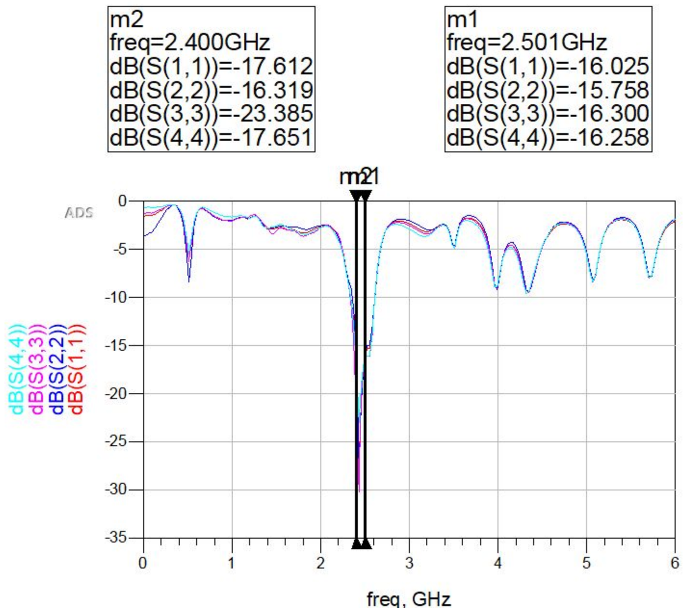


Figure 30: Antenna S11 sweep from 300kHz to 6GHz

Test 11: Component S2P Measurements

- Purpose and Procedure:

To test our components at high frequencies we need to create a test board for use with the network analyzer. This board will have two 50 Ohm SMA Ports and have a trace with two pads in the middle for soldering a singular component on. We will use the length and width of the trace to negate the transmission line effects and isolate the component under test.

Figure 31: Test board with surface mount component ready for measurements

We will use the network analyzer to get S2P measurements which we will import into ADS. Once this is done we will use an ADS tool, LineCalc, to negate the transmission line effects. Once this is completed we will be left with the S2P parameters of the component. This allows us to create a parasitic model based off of components from the same family.

- Results:

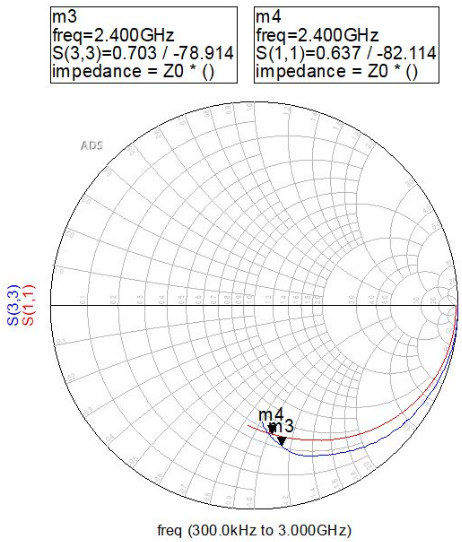


Figure 32: Smith chart representation of 1pF Capacitor S2P measurements

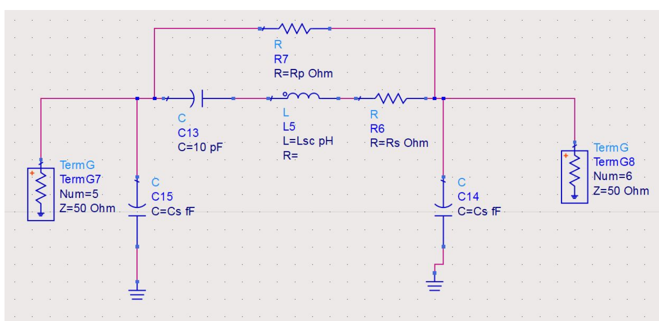


Figure 33: Capacitor Parasitic Model

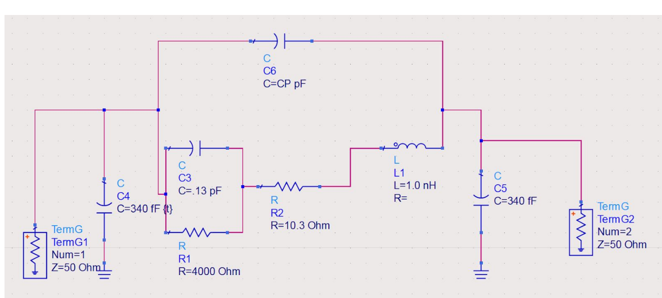


Figure 34: Diode AC/Parasitic Model

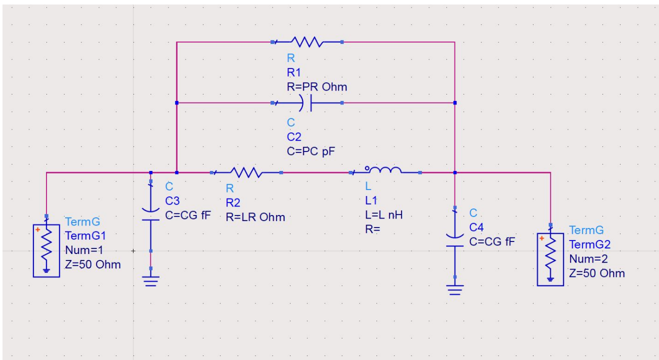


Figure 35: Inductor Parasitic Model

After gathering the S2P data we can match the measurement data to a stand-in parasitic model for each component. This allows us to approximate different values of devices in the same model family. It is helpful to measure a few different values for each component, that way we can synthesize a more accurate model.

5.2 Non-functional testing

The main non functional requirements of our device are

- Portability: the maximum size of the device should be the size of a breadbox
- Efficiency: reasonable operation and charging time
- Testability: reliable for demonstration
- Reasonable cost: under $100

To make sure the size of the device is not bigger than a breadbox we need to pay attention to how we size the antenna and the rectifier circuit. The efficiency of our device will be tested once the physical prototype has been assembled.

6. Operating Manual

6.1 Setup

Wifi Signal:

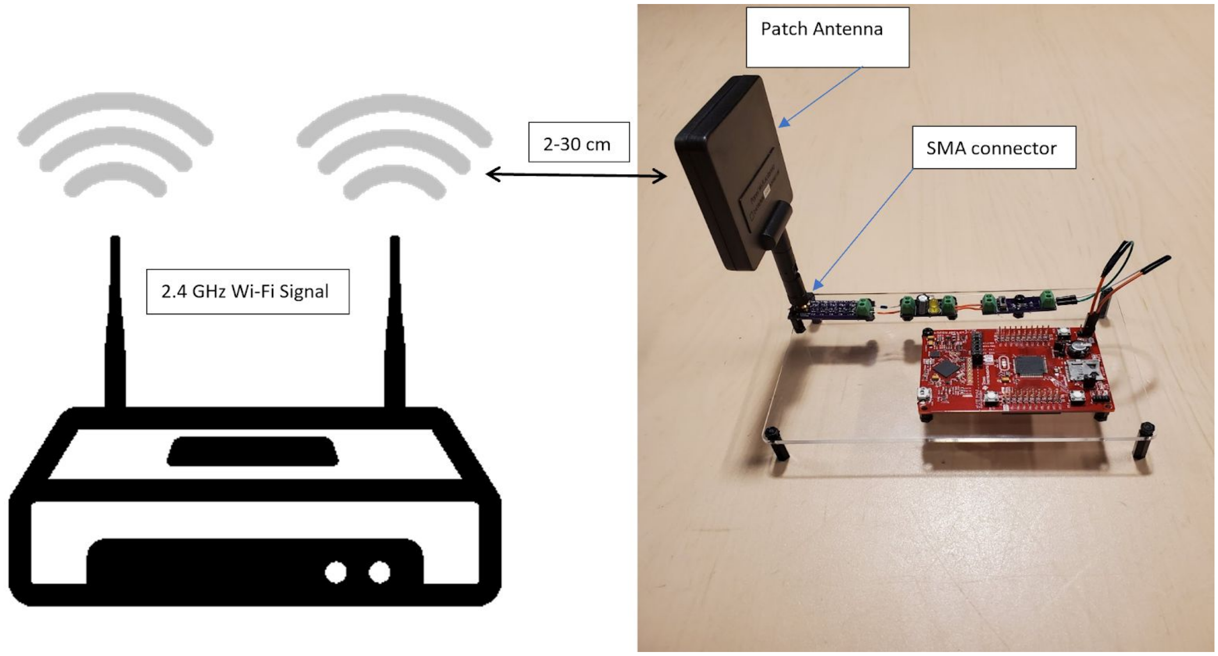


Figure 36: Final Device Setup

- Locate a wifi signal as perpendicular as possible from the patch antenna to ensure maximum energy transfer.
- Place the device around 2-30 cm away from the wifi. The WiFi signal weakens as you get further away from the WiFi source. For optimal levels of energy harvesting requires a connection with a maximum duty cycle try to stay as close as possible to the signal source with consideration that high signal might be damaging to the rectifier. Figure below shows how the WiFi source should be placed with respect to the antenna.

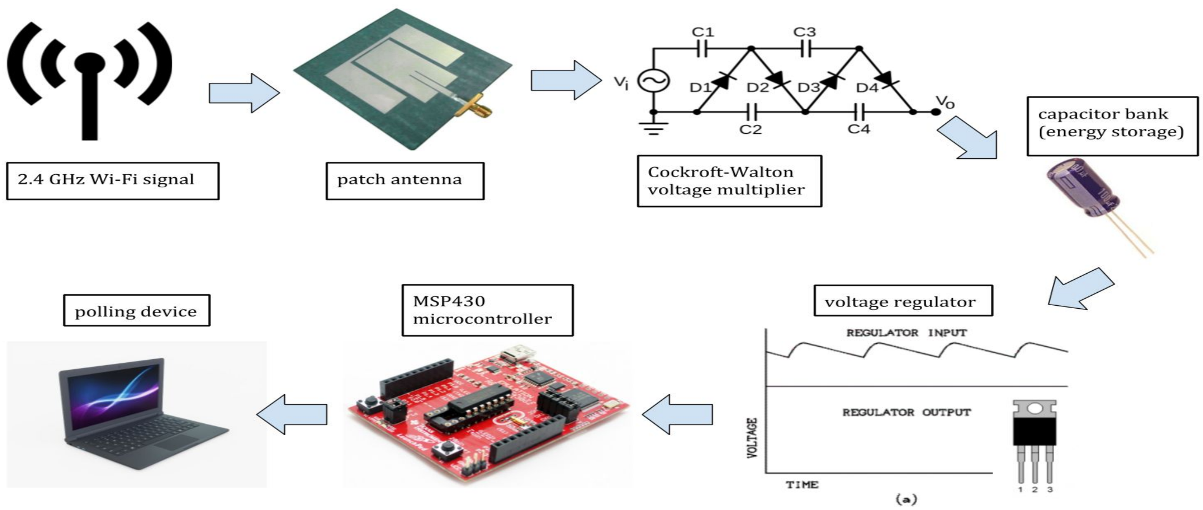


Figure 37: Device Flow diagram

Antenna:

- The patch antenna has an output port of type male-SMA connector. Screw the patch antenna end of the SMA connector to the rectifier female-SMA connector.

Closed Circuit:

- Using a male to male jumper wire to connect 2-pin screw terminal blocks between:
    - Rectifier and the capacitor bank (energy storage and discharge circuit)
    - Capacitor bank to the Linear Voltage Regulator
    - Linear Voltage Regulator to the ground and the power 3-volt power pin of the MSP430

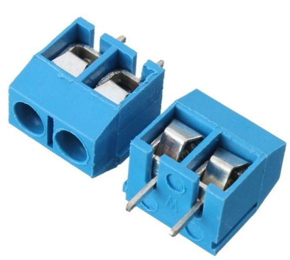


Figure 38: 2-pin Screw Terminal

MSP430 to a PC:

For getting temperature sensor readings which our MSP is programmed to do for this project. Using a micro-USB cable, connect the MSP430 to your laptop USB port

6.2 Demonstrate

1. The captured signal from the patch Antenna will be passed through a 5 stage Cockroft-Walton Voltage multiplier that converts the AC signal into DC
2. The DC output of the recifer will go into a 20 mF capacitor bank
3. The energy collected and stored in the capacitor bank will output a uniform 2.8 V using a Linear Regulator
4. The output voltage for the linear regulator is used to power on the MSP430 to perform it's computational operation. These values will be stored into a non-volatile F-ram memory.
5. Using a UART serial connection to display the outputs from the MSP to a PC via a micro USB cable. RealTerm software is used to determine and display recorded values.

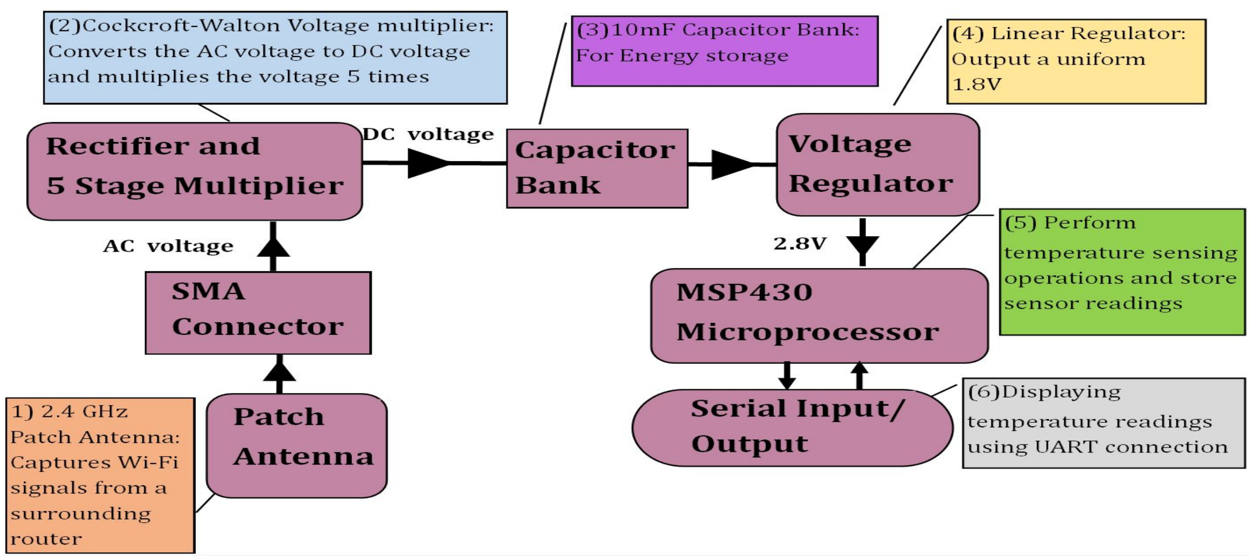


Figure 39: Device Block Diagram

6.3 Test

Hot and Cold:

1. To test the performance and validity of our device in collecting accurate temperature readings.

2. Placing a warm or cool object on the MSP for 20 seconds.
3. MSP uses it's ADC sensor to measure the temperature, these temperature changes should be reflected in our readings accordingly.

LED Light:

1. To demonstrate a quick way of showing that our system has harvested energy successfully. Turn on the LED switch on our device.

7. Alternative Designs

7.1 Rectifier Designs

The initial design of our rectifier was a 2 stage Cockcroft-Walton multiplier (Figure 23) with a 0.1uF Capacitor. After doing tests to determine the power output, we realized that the voltage output from the 2 stage rectifier is insufficient to power the MSP430. We decided to use a 5 stage rectifier for our final design because it produces the sufficient voltage to power the microcontroller.

7.2 Different Approaches to our Code

The code on the MSP430 is a proof of concept for using the harvested energy in a meaningful way. For that reason our clients requirements for the code was fairly general: take a temperature reading when enough energy has been harvested and store it for later retrieval. There were a number of notable scrapped ideas during prototyping.

One of our first ideas was to use flash memory as our method of non-volatile storage, but after researching other types of non-volatile memory we quickly settled on FRAM. FRAM is superior to flash memory in that it is much easier to write to and consumes less energy to read and write from.

The next approaches involved data retrieval from our IoT device. Currently the user must physically plug into the Launchpad via USB and send a character over UART to prompt the MSP430 to dump it's temperature logs. Initially we thought we may do this wirelessly, but due to the additional energy requirements of this method we focused on wired transmission. Either way the user would have to move next to the device. Additionally we planned to dump temperature readings over UART after the user pushed a physical button, but decided to go with our more elegant and compact current method of stimulating the device.

Finally, we prototyped code designed for a board that would run on continuous power. However this was quickly abandoned when we realized we would only be running off of intermittent power.

7.3 Voltage Regulators

We chose a linear voltage regulator over a switching voltage regulator for the final design. The switching voltage regulators showed fluctuating voltage output. There were voltage spikes and sometimes the regulators just wouldn’t work for a while. A linear voltage regulator, while less efficient, proved more stable.

The IC’s that we tried were:

- AP63203WU-7 (from Diodes Incorporated)
    - with SMD inductor and through-hole inductor
- REG710NA-3.3/250 (from TI)
- TLV61224DCKT (from TI)

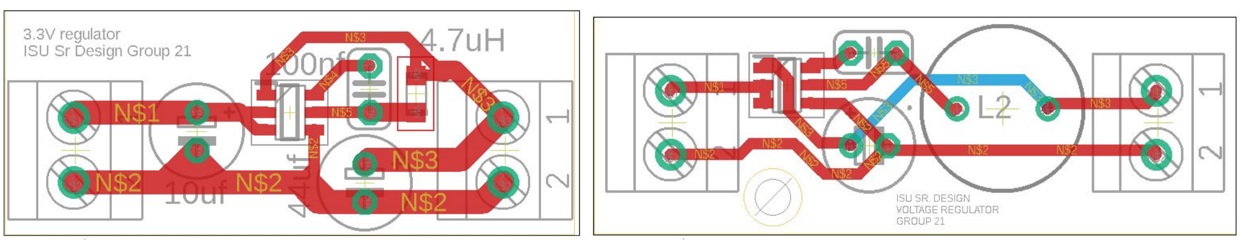


Figure 40: Voltage regulator boards featuring the AP63203WU-7, with SMD inductor (left) and through-hole inductor (right)

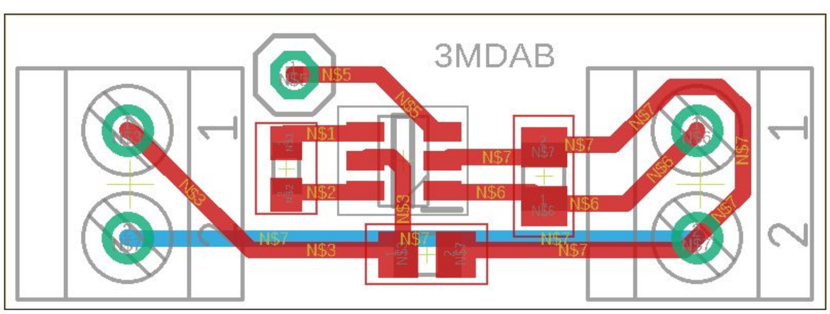


Figure 41: Voltage regulator board featuring the REG710NA-3.3/250

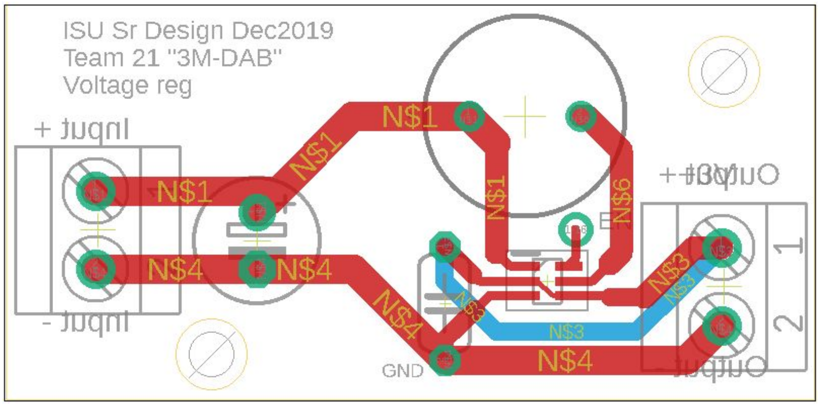


Figure 42: Voltage regulator board featuring the TLV61224DCKT

The fact that the IC would require memory to operate ruled out a lot of our options. Most voltage supervisors are simple: only the present input determines the output. They also don't usually have to meet multiple conditions. (A typical supervisor would output the function X > 3.5.)

A microcontroller could be used to perform the desired function, but it'd undoubtedly be so power-hungry that its integration into the design would nullify its purpose.

7.4 Antenna Alternatives

- 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.

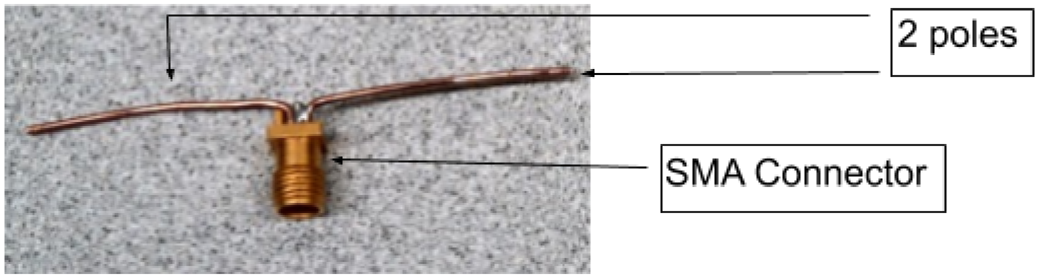


Figure 43: Dipole antenna

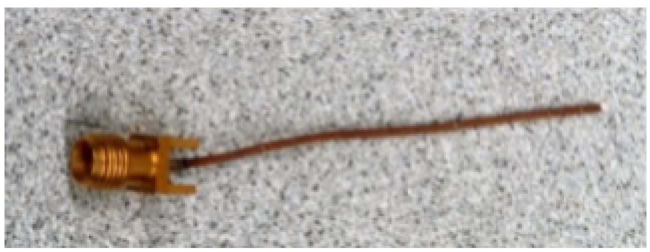


Figure 44: Monopole Antenna

- 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.

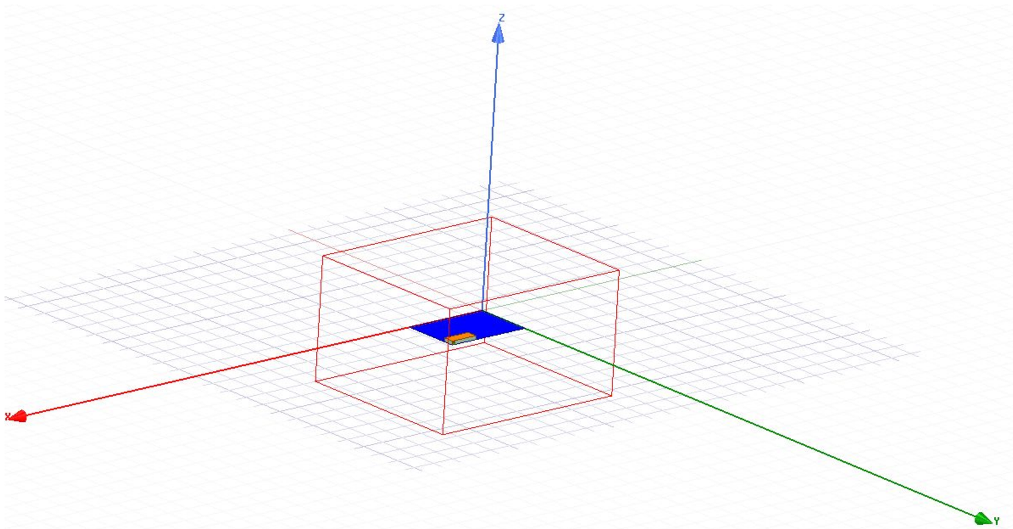


Figure 45: PIFA antenna modeled by ANSYS HFSS

8. Improvements

8.1 Rectifier Alternatives

Greinacher voltage doubler circuit.

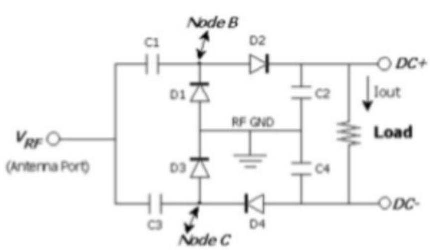


Figure 46: Greinacher voltage doubler circuit

It is very similar to the Cockroft-Walton multiplier. In fact, it is 2 CW multipliers in parallel. It gets double the output voltage, but its output low side is not connected to the common ground. In hindsight, we probably should've gone with the Greinacher model. We'd avoided this because we thought it 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.

Voltage multiplier featuring a transformer.

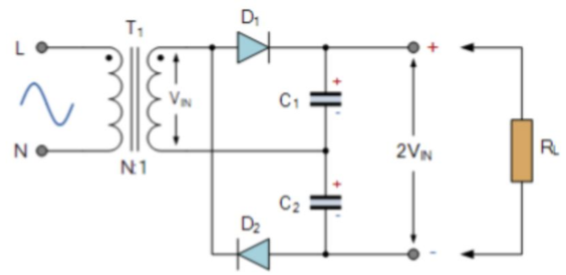


Figure 47: Voltage multiplier with a transformer

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.

8.2 Voltage Supervisor IC

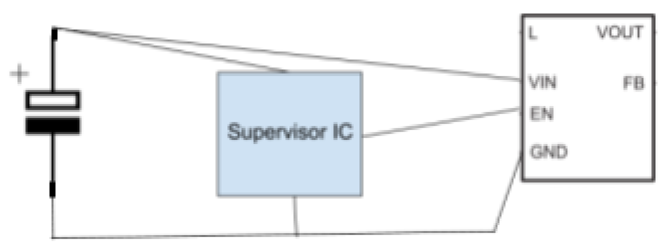


Figure 48: Voltage supervisor schematic

Under the model of periodic startup/work/shutdown for the MSP430, we could benefit from using a voltage supervisor IC. Its ideal functionality would be to:

1. Allow the capacitor bank voltage to reach a certain minimum value (say, 3.5V)
2. Pull to high the ENABLE pin on the voltage regulator, powering the MSP430
3. Turn the ENABLE pin back off when the voltage had dropped to below a certain value (say 2.9V)
4. Repeat

However, this functionality presents conflicting states: ON when X > 3.5, but OFF when X < 2.9. What happens when 2.9 < X < 3.5?

If X had reached 3.5V previously, ENABLE (ON)

If X is rising up from 2.9V, DISABLE (OFF)

8.3 Solar Panel

One alternative was to incorporate a solar panel into the device's power supply in order to supplant the RF harvester. To solve the problem of reverse current flow through the panel ("dark current"), we created the mechanical relay board below to:

- Only connect the solar panel to the shared capacitor bank if the panel was active
    - 150mW needed to keep the switch flipped on
- Only charge the capacitor bank if the panel's voltage was greater than V_{CAP} + 0.7
    - We put 2 diodes in the board because we were unsure about sizing

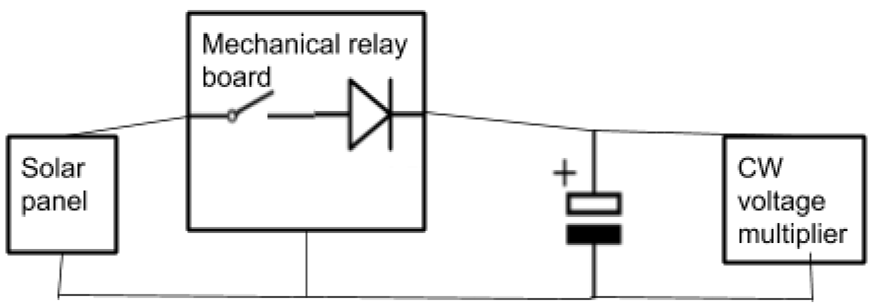


Figure 49: Conceptual sketch of solar panel incorporation

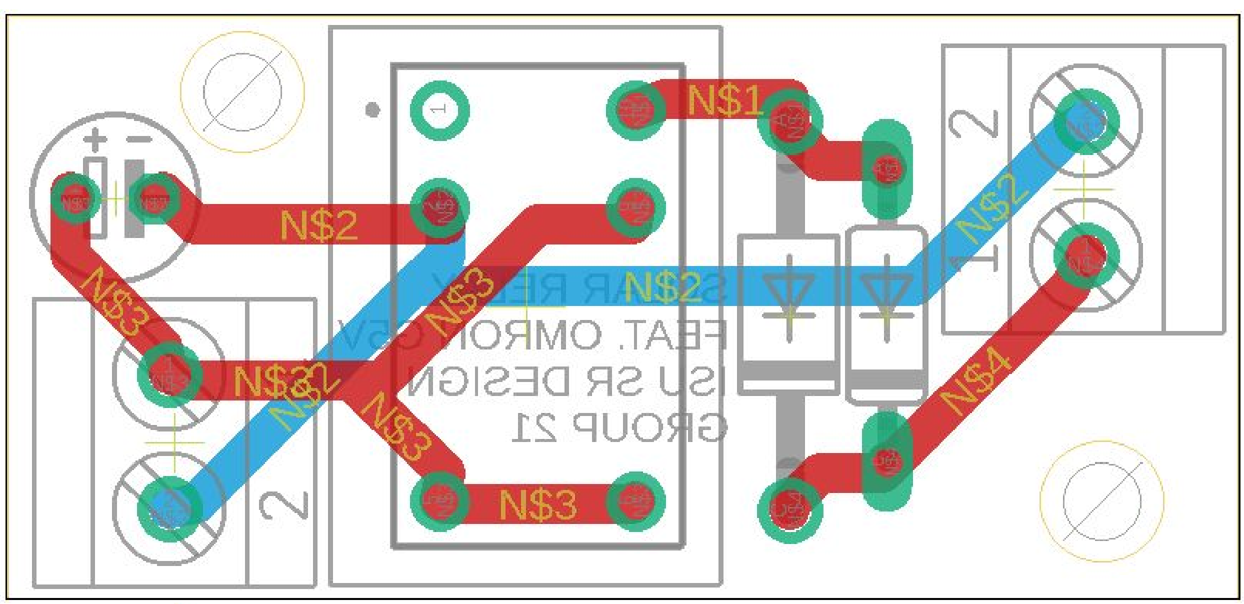


Figure 50: Layout of mechanical relay board

9. Code

The C program running on the Launchpad can be found here: https://pastebin.com/nHe0Tc6S

10. Other Considerations

10.1 Stabilising the Rectifier Output

Wi-Fi is not a steady sine wave, and the charge pump (CW rectifier) only works when it's being fed an input. We've observed that, if there's a pause, the charges in the series capacitors start to collapse on themselves. To keep these doldrums from reducing the voltage on the capacitor bank, we put a Schottky diode between the rectifier and the capacitor bank.

10.2 Choosing a Capacitor

The biggest issue to consider when choosing capacitors for long-term storage is the leakage current (or "insulation resistance"). The leakage current is proportional to the capacitance times the voltage (for example, .01CV). Supercapacitors have been used in the past for small energy-harvesting devices, but they are an order of magnitude more expensive than their same-size ceramic and electrolytic counterparts. Also, remember that $C = \varepsilon * A/d$, and $R = \rho * d/A$, which means that changing the area or distance between the plates causes a proportional change that negates any benefit we would receive from sizing the components differently. To pick a better capacitor in the future we would suggest comparing the ε_r and ρ values of the dielectric in the capacitor being considered. Electrolytic capacitors seem to have smaller leakage currents than their ceramic counterparts.

11. Closing Material

10.1 Conclusion

It is feasible to create a WiFi harvesting device. However, it is VERY limiting to have a circuit powered solely on ambient RF waves. In our attempts, we have been met with some successes and many failures.

We have found partial success under each of 2 models:

1. Periodic startup/work/shutdown method (operates when it can afford to)
   a. We can build up enough charge to run the MCU for a few iterations
   b. In lieu of a voltage supervisor, we'd have to manually turn on the voltage regulator each time
2. Constant runtime (periodic measurements & RTC)
   a. It may be possible to run the MCU like this, but the device will have to be very close to the Wi-Fi source
   b. Using a large capacitor bank, we can definitely sustain constant operation of the MCU in low-power mode

Either way, the physical structure of the device remains the same. Ambient RF waves are intercepted by a patch antenna. A 5-stage Cockroft-Walton rectifier turns the 2.4 GHz wave into a DC voltage, which is stored in a capacitor bank. This voltage, which changes slightly, is regulated to a fixed value by a linear voltage regulator. The output goes to the microprocessor, which uses the received power to perform a task.

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