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Battery-Less IoT Device

Project Plan

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IoT : Internet of Things

MCU : Microcontroller unit

RF : Radio Frequency (AC signal at 10 Kilohertz to 1 Terahertz)

Wi - Fi : 2.4 GHz Frequency

DC : Direct Current (0 Hz)

AC : Alternating Current (f>0 Hz)

ETG: Electronics Technology Group

UART: Universal Asynchronous Receiver/Transmitter

1 Introduction

1.1 Acknowledgement

Team 21 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 also providing valued intelligence in overcoming technical challenges faced in this project.

1.2 Problem Statement

Team 21 is trying to create 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. The device will only have enough power to perform a few tasks until it loses power, so the MCU will need to be specially designed and programmed to handle this type of situation.

Team 21's 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 periodically providing sufficient power to the MCU.

1.3 Operating Environment

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

1.4 Intended User(s) and intended use(s)

Fundamentally, this device will be used to collect readings such as temperature/voltage and transmit these 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.

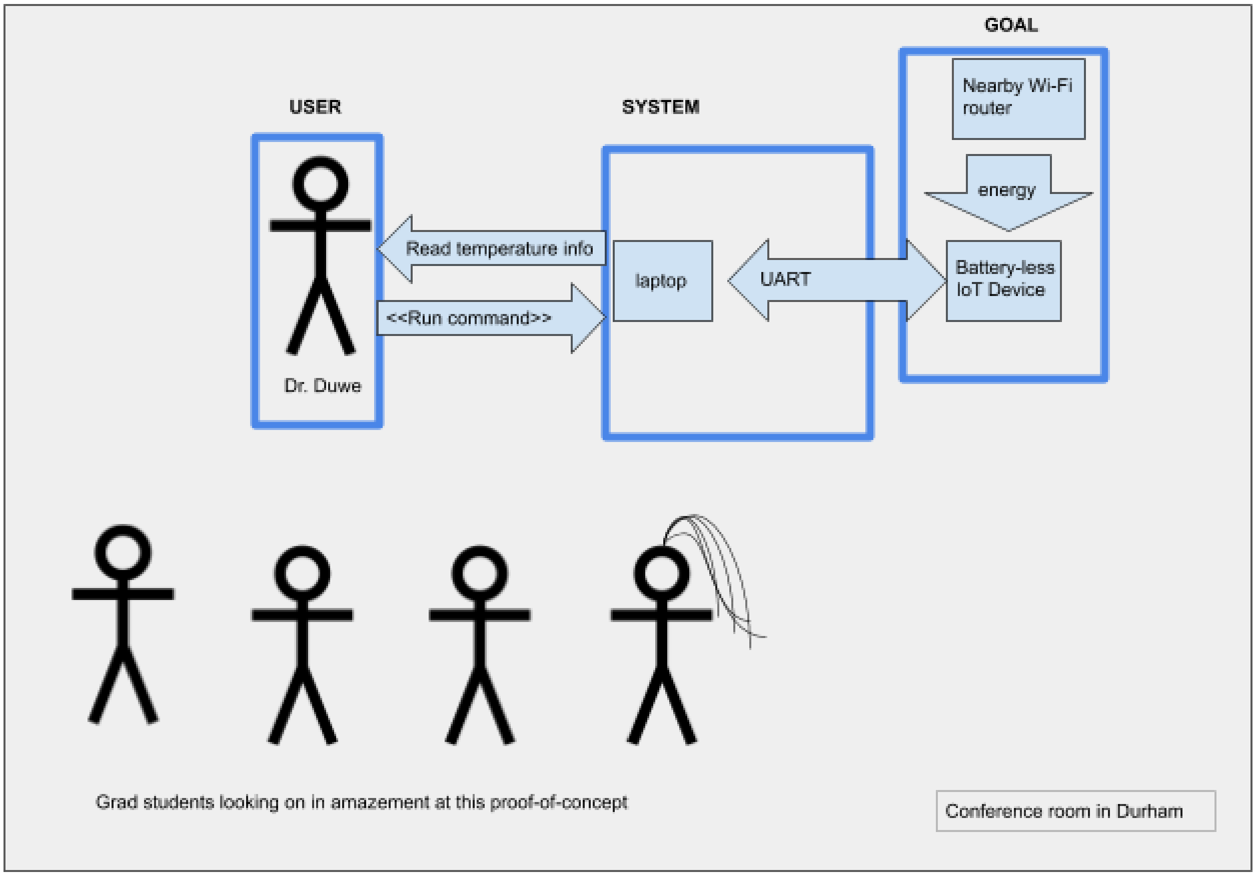

Figure 01: User-case diagram

1.5 Assumptions and Limitations

Assumptions:

- Wi-Fi router is in close proximity to where the device is used to collect data
- The device is low-power, and doesn't require a high storage capacity

Limitations:

- Have to be used in areas with Wi-Fi routers
- Time between uses is roughly 2 hours
  - Requires 30 minutes - 4 hours to power up the device
- Non-linearity of diodes requires the antenna to be at a fixed location from the source

1.6 Expected end product and other deliverables

This semester, we are working on coming up with weighing alternatives and choosing the most optimal design for our final product. As mentioned previously, our device consists of a few major parts, harvesting circuit for capturing Wifi signal, rectifier circuit and an MSP430 MCU to log and record sensor data.

- Harvesting Circuit:

The team has made multiple attempts on the antenna design starting with a monopole and dipole antennas. We had issues with those two antennas such that the monopole antenna had a lot of signal reflecting from the ground plane. The half-wavelength dipole antenna had an impedance mismatching issue due to imperfect design and being an unbalanced circuit.

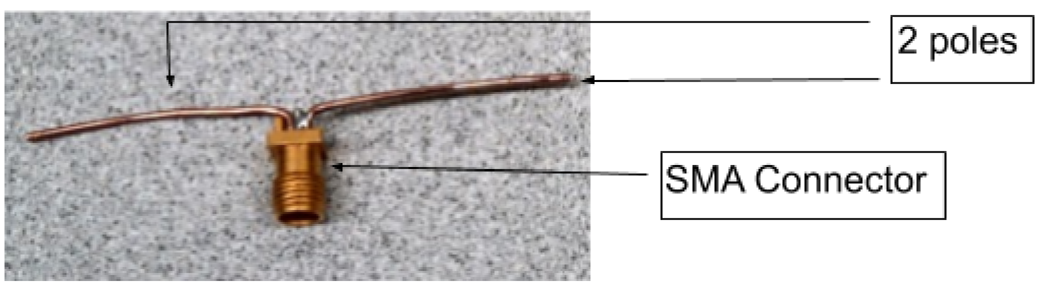

Figure 02: Dipole Antenna

Figure 03: Monopole Antenna

Next, the team considered Patch and Planar Inverted-F Antennas (PIFA), designing these antenna using HFSS allowed us some flexibility on the design parameters where we were able to get a reasonable gain of 1-3 dB while the center design of the antenna 2.4GHz. In the future we would like to be able to fit the harvesting circuit as well as the rectifier on one PCB board.

We designed a rectangular patch antenna that radiates at 2.4 GHz. This antenna is low on cost, can easily be etched on a PCB board and provide easy access for troubleshooting as well as it is small in size which makes is easy to have an array of antennas.

Moving forward, the team will start the etching process of the patch antenna. Currently, we are considering doing the etching process in house.

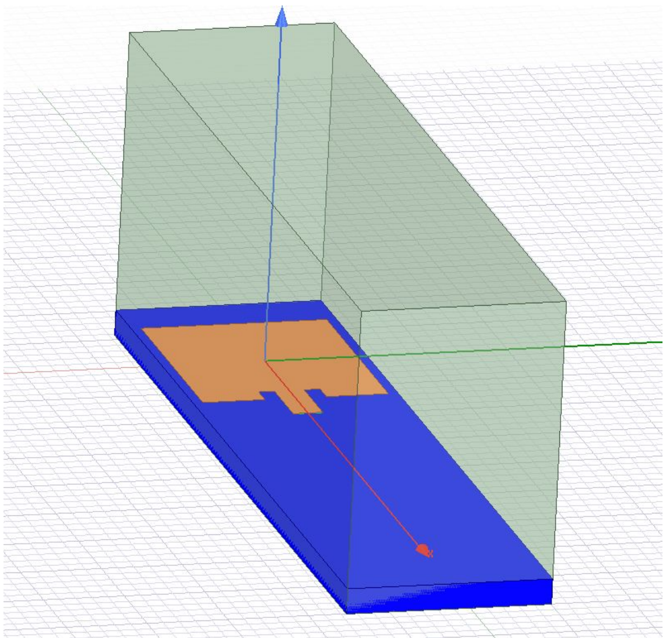

Figure 04: Patch antenna designed in ANSYS HFSS

Going forward, the antennas team plans on creating multiple test circuits to characterize the parasitics of the rectifier components to better match the circuit to the antenna. This will allow maximum power transfer and gives better control of the voltage supplied by the antenna.

- Rectifier Circuit:

The team has been looking at multiple designs for the rectifier circuit. As a team, we spent a lot of time finding the right rectifier design as well as diodes with a low voltage drop and instantaneous recovery time (time it take to switch from forward to reverse biased mode). The Schottky diodes we found had very low voltage drop and instantaneous recovery time.

The first rectifier design that the team considered was the Greinacher voltage doubler. The team tried to model this design using ADC but there were few issues where the design files were not properly integrated into the ADC component library. Also, this design was a two sided rectifier which increases the voltage but would be shifting the ground form the common ground to the negative terminal of one circuit.

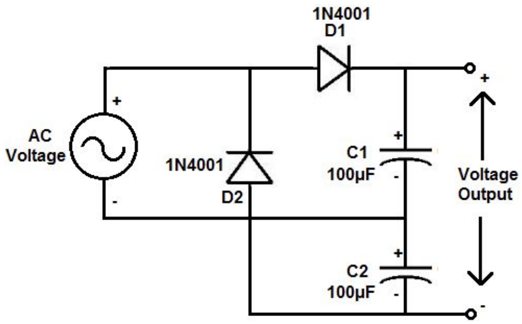

Figure 05: Greinacher voltage doubler

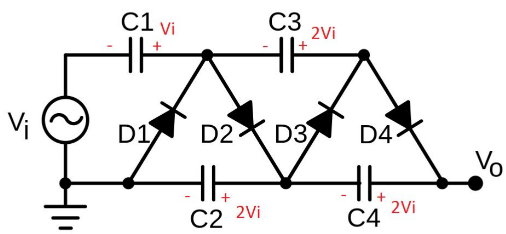

Figure 06: Cockcroft-Walton voltage multiplier

Currently the team is considering Cockcroft-Walton voltage multiplier, which is a more plausible design for two reasons. A 2-sided multiplier would increase the voltage, but we would be shifting our ground from the common ground to the negative terminal of ONE circuit (we plan on possibly having multiple CW multipliers). If we plan on adding more rectifiers, then they can all share a common ground, which will save space and simplify the design.

The Cockcroft-Walton voltage multiplier is currently 2 stages. This is because it's believed to be a happy medium between stepping up the voltage and the output voltage drop.

$2nV_{MAX}$ this is ideal voltage output
$2nV_{MAX} \triangle V_0$ this is real voltage output

$$\Delta V_o = \frac{(4n^3 + 3n^2 - n)}{6} \frac{I_o}{fC}$$

n = number of stages

Next semester, the team will simulate the Cockcroft-Walton voltage multiplier using ADS to validate design, making the final design using a cad tool and etch the design on a PCB board.

- MSP430 MCU

After looking at a number of MSP430 models, the team has selected the MSP430FR2100 MCU for the final design. This model is one of the cheapest models available that retains the required features and functionality for our MCU. These features include:

- 1 KB FRAM: The FRAM on the FR2100 will be used to store program code, and will leave us with more than enough storage to take multiple readings in-between data transmissions
- 10-Bit ADC: The ADC embedded in this MCU is the source of our temperature readings, which will be sufficient for our proof-of-concept device.
- UART: A UART connection will be used to transmit recorded temperature readings off of the MCU.

Early in the semester we realized that we want to use an MCU with FRAM instead of standard flash memory. We reached this decision when we discovered the power-saving benefits of FRAM over flash. After acquiring a TI Launchpad with FRAM, the team has spent the semester developing software that will be run by the MCU when supplied with sufficient power.

One of the most important benefits of using MSP430 is the property of using and accessing various Low Power Mode. We examined the different Low power modes to determine the most fitting operating mode that suits our experminant. Active Mode was vital for operating the microcontroller in its more maximum and fundamental characteristics needed to store and access FRAM for our temperature readings. However, Active mode consumes the most power out of all other modes. Hence, just before we run to keep on powering our microncoller we would have to access LMP4. This will act as a catalyst to determine if we have enough energy harvested to use Active Mode. Figure 7 shows the changes in power consumption between each low power mode.

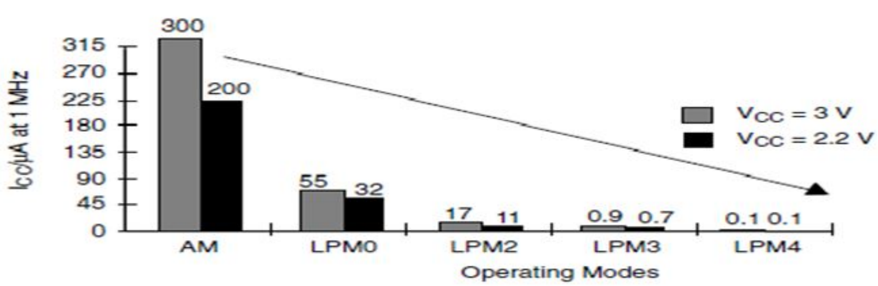

Figure 07: Current consumption vs Operating Modes

Figure 8 shows the relationship between the current vs voltage for the different operating frequencies while in active mode. From this data we observed that operating at the highest frequency will be the most energy efficient. Therefore our MCU will be operating at 16 MHz.

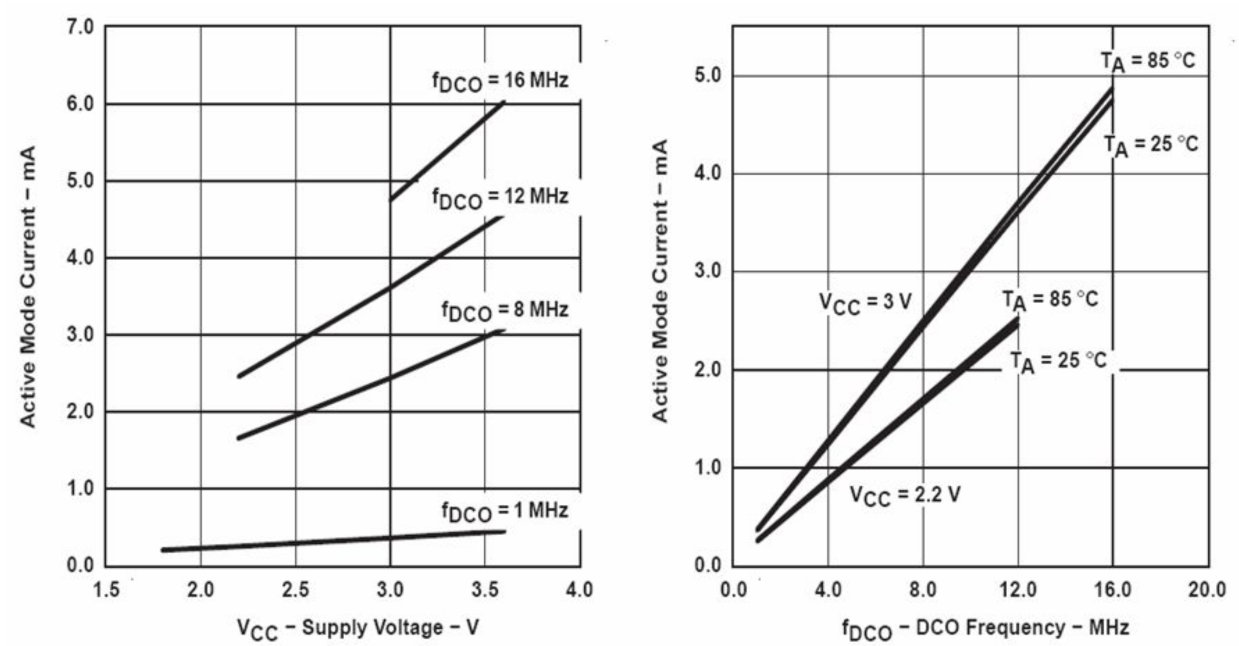

Figure 08: Active Mode Supply Current

Our software will wait in LPM4 until the X circuit triggers a GPIO interrupt. This interrupt will occur when the capacitor powering the MCU has enough energy stored to completely power one “run” through the software. After code completion, the MCU will place itself into LPM4, allowing the capacitor to charge again. Currently the team is recording power and energy measurements for “sleeping” in LPM4 and operating in active mode to supply the power systems team with energy requirements. Figure 9 shows a basic representation of how the MCU will move between power modes.

When in active mode, the program will follow the flowchart detailed in figure 10. We will use a GPIO pin as an output enable pin, which will be tied to a button. This button will be pressed when a recorder comes to the device to extract the logged temperature readings.

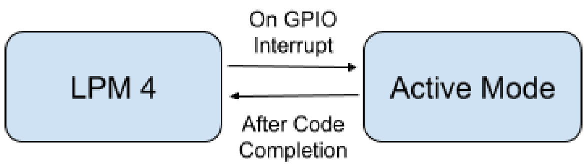

Figure 09: Waking up from LMP4

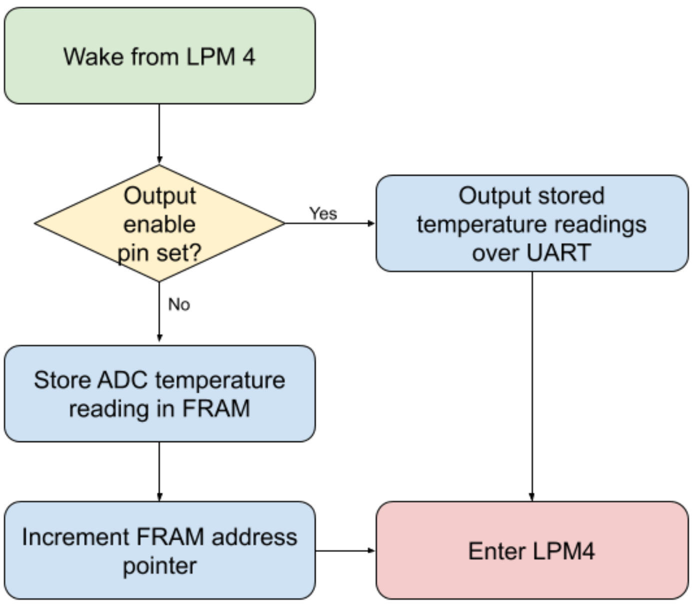

Figure 10: Flowchart of LMP4

2 Proposed Approach and statement of work

2.1 Functional Requirements

In general, this IoT device will be able to harvest energy from Wifi signals, measure quantities such as temperature/light, and transmit the measurement over RF to be read by the user. This can be categorized in four major functional components: circuit to harvest energy through Wi-Fi, rectify the voltage output from the energy harvesting circuit, microprocessor to collect and process data, and circuit to transmit data collected. The following diagram illustrates how these 4 major components combine to build the battery-less IoT device.

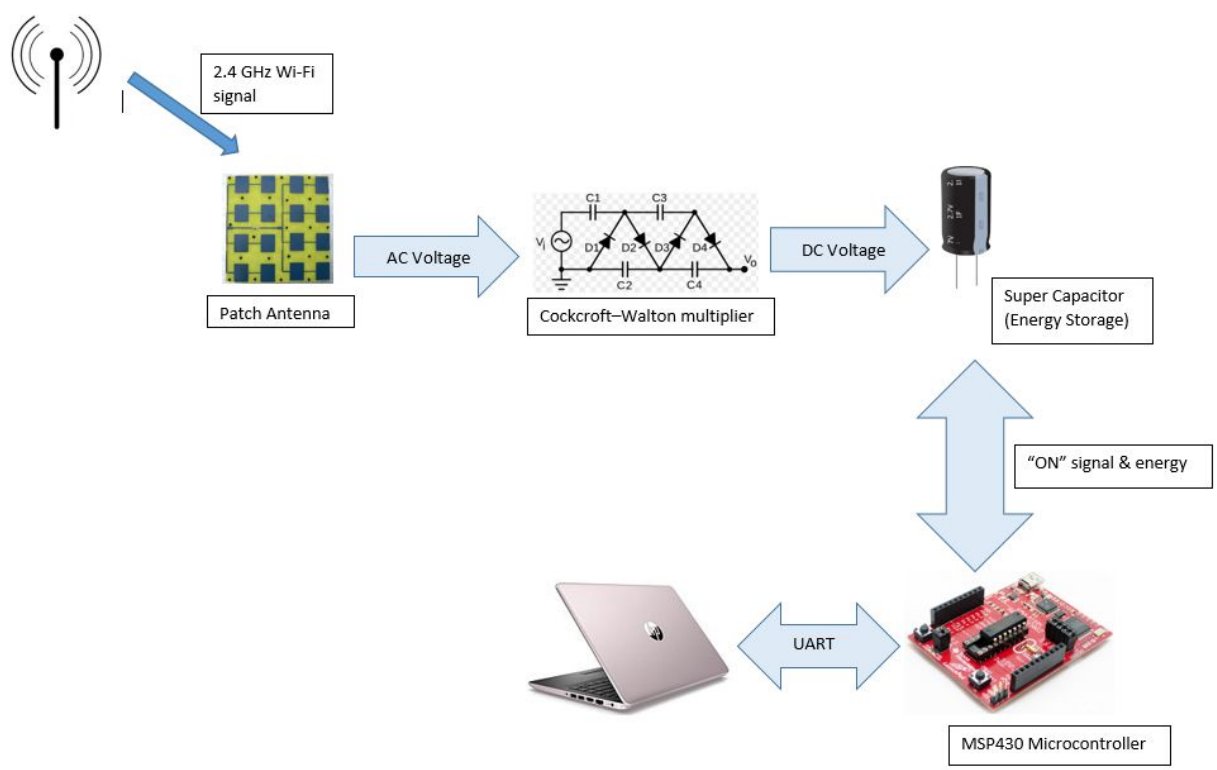

Figure 11: Block diagram of the battery-less IoT device

As shown in figure 07, the patch antenna will harvest Wifi signal to generate a very low AC voltage output. Patch 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. Since the microcontroller requires constant DC voltage of about 1.8V to 3.3 V. To meet this requirement, we require a rectifier and a multiplier circuit. The Cockcroft

Walton multiplier does both rectifying and multiplying. The low AC voltage output from the patch antenna circuit will be rectified to a DC voltage and will be multiplied by the Cockcroft Walton multiplier. This DC voltage output will be stored in the super capacitor to be used whenever the microcontroller calls for it. The MSP430 microcontroller supports 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. As it's expected we are not always going to have enough energy to keep powering the MSP430 at our Active mode. For that, we needed to be read and use the 5 different low power modes. In our IoT device MSP430 will be used to collect sensor data such as temperature and light intensity. The data collected by the microcontroller will be transmitted to a laptop through UART, which is basically in the microcontroller.

2.2 Non Functional Requirements

Data Security: One of the main concerns with IoT devices is data security. The software programmed to our MSP430 needs to be protected against potential cyber attacks. Safeguards needs to be put in place for the data collected and transmitted by our IoT device to prevent cloud attacks.

Data Privacy: If our IoT device is used to collect sensitive information such as health data, care should be taken to make sure we do not violate user privacy.

2.3 Constraints Considerations

The device needs to be about the size of a breadbox, or smaller. It cannot use batteries or be powered by any external sources other than radio waves.

2.3.1 Technology Considerations

This is a low-power device. It needs to be able to build up enough energy harvested from an antenna to operate accordingly. It also needs to be able to transmit data for when power is available: definitely run at least only once per day for a reasonable amount of time. This means that it will have to harvest energy fast enough to meet a certain demand consistently and optimally.

2.3.2 Testing Requirements Considerations

The time it takes to charge the device will slow down the testing process. When it comes to testing the power harvesting capabilities of an antenna, it will be difficult when the majority of oscilloscopes available to students don't measure frequencies higher than 200 MHz. Therefore we can use Energy Trace technology to analyze and measure the applications energy profile. While debugging and testing our energy levels Energy Trace will help us optimize the internal state of the microcontroller and power levels harvested.

2.3.3 Security Considerations

The battery-less IoT device will be transmitting unencrypted temperature readings from the ADC for brief periods of time on regular intervals over RF. Since the data being transmitted is not sensitive, data security is not a major concern; anyone with a receiver tuned correctly can receive data sent by the battery-less device. If the device was used to send more sensitive information, it would employ some form of encryption during transmission. Physical security is of no concern because this device will be tested and used in areas where people are very unlikely to attempt to tamper with or steal the device.

2.3.4 Safety Considerations

The battery-less IoT device will likely be elevated above head-height and near a Wi-Fi router. Therefore, care must be taken to ensure the device is properly mounted and secured so that it doesn't fall on anyone or anything. The device will likely be rather light, so securing the device will not require any heavy-duty or special mounts.

There will be no safety concerns regarding the antenna. The power received is assumed to be small and any reflected power that manages to radiate from the antenna will be magnitudes smaller than the signal radiated from a normal WiFi router. According to Commotion Wireless, Common indoor WiFi routers usually radiate at power levels of 100 mW, the antenna Team 21 designed will receive power at levels under 1 mW.

2.3.5 Standards

For all official antenna measurements Team 21 will be attempt to adhere to IEEE Standard 149-1979 as much as possible. This standard includes multiple ways of testing antennas, definitions of antenna measurement values, and ways to account for interference that may invalid data.

Due to the low levels of power available to the MSP430, the Embedded Systems team will need to adhere to or work around the latest IEEE 802.11 protocol or any IEEE 802 standard that may apply to wireless communications.

2.4 Previous work/ Literature Review

As recommended by Dr. Duwe, we looked into previous senior design team projects related to battery-less IoT devices and related articles. By researching these articles we got an understanding of the main components required to use Wi-Fi as a power source. We also realized how unique our design compared to what is already been done.

From all the articles listed above, we found beneficial information on similar designs. For example, one of the article was very specific on a hardware/software IOT device detailing some information on energy storage as well as energy demand of the microcontroller which is a critical part of our design. Also the literature helped us realize our challenges as we did not find many designs that have done Wifi harvesting.

Following links are some of the articles we referred

- Energy Harvesting Development Kit

https://www.powercastco.com/products/development-kits/#P1110-EVAL-01

- A Reconfigurable Energy Storage Architecture for Energy-harvesting Devices

https://brandonlucia.com/pubs/capy.pdf

- Tragedy of the Coulombs: Federating Energy Storage for Tiny, Intermittently-Powered Sensors

https://dl.acm.org/citation.cfm?id=2809707

- Design optimization and implementation for RF energy harvesting circuits

http://www.radio.walkingitaly.com/radio/RADIOSITO/biblio_energy_harv/bhv/Design%20optimization%20and%20implementation%20for%20RF%20energy%20harvesting%20c.pdf

- A tuned rectifier for RF energy harvesting from ambient radiations

https://www.sciencedirect.com/science/article/pii/S1434841112002841

- RF Energy Harvesting System and Circuits for Charging of Mobile Devices

https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5439152

- Design of an efficient ambient WiFi energy harvesting system

https://ieeexplore.ieee.org/document/6329093?denied=

- Capybara variable-capacity energy storage device

https://github.com/CMUAbstract/releases/blob/master/Capybara.md

2.5 Possible Risks and Risk Management

The battery-less IoT device is small, low-power, and designed for an indoor environment. However, the diodes used in the rectifier are vulnerable to human electrostatic discharge (ESD), and caution is advised when working with the MCU, as improper wiring may damage it. In summary, there are some financial risks, but otherwise the risks are low.

2.6 Project proposed milestones and evaluations criteria

The goal for this project is to have a battery-less device that can record temperature readings and output them at a later time. Along the way, we plan to meet the following milestones:

- MCU code working on dev board - May 2019
  - We will have functional software written to record and log temperature data in a manner appropriate for our battery-less device. Software is functional on a TI Launchpad.
- Energy harvesting circuit built - October 2019
  - We will have determined a circuit which can store energy harvested from a Wi-Fi signal into a capacitor. The optimal antenna design will be selected by this milestone.
- Rectifier circuit built - Mid September 2019
  - We will have determined a circuit capable of converting energy generated by the energy harvester and storing it into a capacitor.
- Prototype board assembled - October 2019 - early December 2019
  - The layout of the final device will be determined.
  - Software will be loaded onto the MCU. Components will be printed or soldered onto a PCB.
  - Bugs and issues will be recorded and worked out over new prototypes.
- Final product assembled - Mid December 2019
  - Device demonstrates ability to continuously harvest energy and operate.
  - Any bugs will be menial and will not significantly impact performance or functionality.

2.7 Test plan (and validations)

We are conducting a series of tests to measure all the parameters of our device. Here is the summary:

1. Wi-Fi strength tests
    a. Used to obtain general power levels from a router as a relation to distance
    b. Utilized
        i. TP-Link TL-WN722N USB adapter
        ii. Netspot Free Edition, a wifi signal strength testing program
2. MSP430 functional test
    a. measure different temperatures with the IC for fidelity and to familiarize with the IC
3. Rectifier test (upcoming)
    a. Measuring no-load voltage and 1k Ohm load voltage
    b. Measuring voltages with respect to distance from router
    c. Goal - to find how much power we can get from 1 rectifier
        i. Also find out how many rectifiers we'll need
4. MSP430 power demand test
    a. (total current used over course of operations) * (constant voltage)
    b. Using breakout board with a current-tracking program
5. Capacitor leakage test (upcoming)
    a. charge capacitor to certain voltage, leave it overnight, and check voltage the next day
    b. calculate leakage current at desired voltage and compare with datasheet
6. Full design test
    a. Put all parts together, test capability, troubleshoot, and tune

2.8 Project Tracking Procedures

We have several processes implemented to keep members on track and directed toward a common goal.

Our team will meet once a week to discuss short-term objectives as well as group and individual progress. Our Scribe will record updates from each team member to ensure progress is being made by everyone. Advancements in overall progress will be recorded in a project tracker timeline. This will increase accountability and measure the rate of accomplishment.

Additionally, there will be weekly meetings with our faculty advisor, Dr. Duwe, to keep him updated on team progress as well as to seek advice from him for any issues the team is facing. These meetings will occasionally (monthly) feature our faculty advisors, Dr. Neihart and Dr. Qiao. They will survey our progress, and offer guidance and insight into the best courses of further action.

2.9 Objective of the task

The objective of the project is to create a device that harvests RF power. converts it to DC, stores it, and uses it to power an MCU that accomplishes small tasks. These devices are meant to function as part of an IoT network. The team's end goal is to create an IoT device that works at a range of one to two meters away from the Wi-Fi router.

2.10 Task Approach

In the first meeting with Dr. Duwe, he gave us a detailed explanation about the overall idea of battery-less IoT devices and different designs aspects, the practical usage and benefits of this IoT device. After this discussion, the project was categorized into three major sections: RF, power and embedded systems. Each section has 2 members experienced in that field. The first part of the project is to build an antenna and a power circuit to harvest energy and power the MCU. This part will be the main responsibility of the RF and power groups. Once this task is completed, programming the MCU will be the responsibility of the embedded systems group. At the end, all the components from each group will be integrated to build the battery-less IoT device.

2.11 Expected Results

By mid-December 2019 our group will have a battery-less device capable of generating power through Wi-Fi via antenna. The device will store energy generated by the antenna to power an MSP430 MCU, which will take a temperature measurement and transmit the information via an RF signal. The device will have no external inputs other than the power-generating Wi-Fi signal and will be contained within the dimensions of a shoe box.

3 Estimated Resources and Project Timeline

3.1 Personnel Effort requirements

Task	Estimated Task Time (Hrs)	Notes
Write code for temperature sensing	20	Code will be written in C during early development, then in Assembly. This will be hany in coming up with estimates for required energy need for microcontroller.
Research on antennas	20	Appropriate antennas for harvesting energy through Wi-Fi
Build antenna and matching network.	40	Circuit to harvest enough energy to power the MCU for at least an hour
Build rectifier circuit.	40	Circuit to convert AC to DC and boost the voltage
Simulate Rectifier Circuit	40	Before building a physical layout of the rectifier circuit, it needs to be simulated using ADS to verify its functionality.
Flash MSP430 with temperature-sensing code.	20	Programmed MSP430 will be independently tested.
Assemble prototype boards.	40	
Assemble final product.	40	

Table 01: Task List

3.2 Other resource requirements

While developing code for the MSP430 a TI Launchpad will be rented from ETG free of charge. An MSP430 flasher will be use for programming the MCU. Additionally, soldering tools from labs in Coover Hall will be used when assembling prototypes and the final product. Other resources that will not be purchased include miscellaneous tools for building prototypes and drafting paper.

3.3 Financial Requirements

The cost for whatever specific type of MSP430 MCU will be used will be minimal. Chips from TI can be bought individually for around 70-80 cents. A few spare chips will be purchased during development so a few dollars at most will be spent on MCUs. The transmitter will be relatively simplistic and low-power. Transmitters from TI are priced similarly and will likely cost a few dollars for a few. Similarly, prototyping boards and any solder used will run a few dollars.

Sensitive Schottky diodes are needed for the rectifier. They cost about $1 per diode, or less when they're bought in bulk (groups of 25).

The expected cost of antennas will vary depending on what type of antenna is necessary to gather enough power at reasonable distances. Team 21 plans on making the antenna rather than buying it, which should reduce the cost significantly. Making the antenna and matching networks should cost roughly ten to fifty dollars for materials.

Following table shows the costs of the parts we bought so far

Part	Cost/unit($)	# of parts
Skyworks Schottky Diodes: SC-79	0.85	4
Capacitors (Mouser Electronics)	0.14	4
MSP430FR5994	20	1
TE SMA female connector	2.49	3

Table 02: Record of costs of parts

3.4 Project Timeline

	Start Date	End Date	Timeline	Status
Team 21	Jan 21, 2019	Dec 13, 2019		
Wi-Fi strength test	Jan 21, 2019	Feb 2, 2019		Active
Antenna design	Jan 21, 2019	Feb 21, 2019		Active
Antenna test	Jan 21, 2019	Feb 22, 2019		Active
Rectifier Design	Feb 2, 2019	Apr 15, 2019		Active
MSP430 functional test	Feb 3, 2019	Feb 20, 2019		Active
Rectifier test	Aug 20, 2019	Sep 20, 2019		Upcoming
MSP430 power demands	Jan 21, 2019	Aug 20, 2019		Active
Design voltage control	Aug 20, 2019	Oct 20, 2019		Upcoming
capacitor chosen	Aug 20, 2019	Aug 29, 2019		Upcoming
Capacitor leakage test	Aug 29, 2019	Sep 4, 2019		Upcoming
Capacitor + voltage control + MSP430 test	Sep 5, 2019	Sep 15, 2019		Upcoming
Test rectifiers charging antenna	Sep 20, 2019	Sep 29, 2019		Upcoming
Recharge minimum time found	Sep 29, 2019	Oct 3, 2019		Upcoming
Test full design	Oct 15, 2019	Dec 10, 2019		Upcoming

Table 03: Project Tracker

4 Closure

4.1 Closing Summary

As time goes on, society becomes more automated, batteries become more expensive as resources diminish, and more stable forms of energy need to be harvested. Our project addresses all of these concerns. Our device will harvest ambient RF energy, store energy without a battery, and perform a task to demonstrate proof-of-concept.

The main goal of this project is to have a successfully built battery-less IoT device that can be powered through Wi-Fi. This device needs to run intermittently over an extended period with only a Wi-Fi router as a power source. The MCU needs to be programmed to collect sensor data as accurately as possible. Overall, the end product should be a good alternative for a battery powered data measuring device.

Our group has overcome stagnation earlier in the semester, and is now much more organized and directed. Breaking up into distinct groups has helped increase productivity and a sense of individual responsibility. Now, the MSP430 group is working on code and power requirements. The power group is working on the rectifier and will soon focus more attention on voltage regulation to the IC. The antennas group is focused on impedance matching, antenna design, and helping the power group with simulations. For the whole group, researching similar projects and accumulating information overtime has given the team more direction and a greater understanding of the pros and cons of alternative options. Overall, we have made excellent progress and will continue to do so in the coming semester. By December, our client will have a functional proof-of-concept device to inspire his colleagues and further research into low-power, low-cost, common-material, internet-connected devices.

4.2 References

This list will include links to any research material or parts that will be used during the project.

- Energy Harvesting Development Kit

  "Development Kits," *Powercast Co.* [Online]. Available: https://www.powercastco.com/products/development-kits/#P1110-EVAL-01. [Accessed: 24-Apr-2019].

- A Reconfigurable Energy Storage Architecture for Energy-harvesting Devices

  A. Colin, E. Ruppel, and B. Lucia, "A Reconfigurable Energy Storage Architecture for Energy-harvesting Devices."Available: https://brandonlucia.com/pubs/capy.pdf. [Accessed: 24-Apr-2019].

- Tragedy of the Coulombs: Federating Energy Storage for Tiny, Intermittently-Powered Sensors

  J. Hester, L. Sitanayah, and J. Sorber, "Tragedy of the Coulombs: Federating Energy Storage for Tiny, Intermittently-Powered Sensors." Available:https://dl.acm.org/citation.cfm?id=2809707. [Accessed: 24-Apr-2019].

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- A tuned rectifier for RF energy harvesting from ambient radiations

  "A tuned rectifier for RF energy harvesting from ambient radiations," *AEU - International Journal of Electronics and Communications*, 21-Jan-2013. [Online]. Available:

https://www.sciencedirect.com/science/article/pii/S1434841112002841. [Accessed: 25-Apr-2019].

● RF Energy Harvesting System and Circuits for Charging of Mobile Devices

H. Jabbar, Y. Song, and T. Jeong, RF energy harvesting system and circuits for charging of mobile devices - IEEE Journals & Magazine. [Online]. Available: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5439152&tag=1. [Accessed: 25-Apr-2019].

● Antenna theory website, useful for researching principles behind antenna and the benefits of different types of antenna

P. Bevelacqua, "Welcome to Antenna-Theory.com!," *The Antenna Theory Website*. [Online]. Available: http://www.antenna-theory.com/. [Accessed: 25-Apr-2019].

● Commotion Wireless

Learn Wireless Basics. [Online]. Available: https://commotionwireless.net/docs/cck/networking/learn-wireless-basics/. [Accessed: 25-Apr-2019].

● Design of an efficient ambient WiFi energy harvesting system

U. Olgun, C. -. Chen and J. L. Volakis, "Design of an efficient ambient WiFi energy harvesting system," in *IET Microwaves, Antennas & Propagation*, vol. 6, no. 11, pp. 1200-1206, 21 August 2012.

● *Design of an efficient ambient Wi fi*

Design of an efficient ambient WiFi energy harvesting system - IET Journals & Magazine. [Online]. Available: https://ieeexplore.ieee.org/document/6329093?denied=. [Accessed: 25-Apr-2019].

● Capybara variable-capacity energy storage device

Abstract Research Group, "*Software+ Hardware Release"*, (2018), GitHub repository, https://github.com/CMUAbstract/releases/blob/master/Capybara.md

- CMU abstract releases

  CMUAbstract, “CMUAbstract/releases,” *GitHub*. [Online]. Available: https://github.com/CMUAbstract/releases/blob/master/Capybara.md. [Accessed: 25-Apr-2019].

4.3 Parts

- MSP430FR2100 MCU*: http://www.ti.com/lit/ds/symlink/msp430fr2100.pdf
- CC115L Transmitter*: http://www.ti.com/lit/ds/symlink/cc115l.pdf
- SMS7630-061 (high-frequency Schottky diode): https://www.mouser.com/datasheet/2/472/Surface_Mount_Schottky_Diodes_200041AD-708941.pdf
- HSMS-286x (high-frequency Schottky diode)(no longer produced): https://www.broadcom.com/products/wireless/diodes/schottky/hsms-2862
- Rectifier Capacitors: https://www.mouser.com/ProductDetail/Vishay-Vitramon/VJ0603Y104JXJAC?qs=sGAEpiMZZMsh%252B1woXyUXj9JDUs1vtt6Cvnv98b4zUL4%3D
- SMA female connector: https://www.mouser.com/ProductDetail/TE-Connectivity/5-1814832-1?qs=sGAEpiMZZMuLQf%252BEuFsOrr9TJRxzrvNvF%2Fdv53aggxs%3D
- RP-SMA female connector: https://www.mouser.com/ProductDetail/Taoglas/PCBRPSMAFRAHT?qs=%2Fha2pyFaduhagDToTLG82sBQikzJaF8K2JJr3a%2F4RyWxUxbWY%252BVKXw%3D%3D
- OshPark (PCB fab house): https://oshpark.com/

*Alternative parts may be used as we progress in development.