University of Nevada, Reno

Harnessing the Power of Radio Waves

A thesis submitted in partial fulfillment
of the requirements for the degree of

ELECTRICAL ENGINEERING, BACHELOR OF SCIENCE

by

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Abstract

Team Guide Dog was created by Taylor Gruey, Kristin Kosak, Justin Steele, and Kevin Vees to create a viable replacement to batteries. Basic batteries often need to be changed and can create a strain on the environment as well as our wallets. We intend to create a "battery pack" that can be used anywhere typical AA batteries are found. This product will essentially be a DC power supply built into a mold of two AA batteries using RF (radio frequency) harvesting to power the users desired device. Because the product is running off of RF harvesting the product will never have to be replaced, and as long as the device is within range of the transmitting antenna the device will have power.

Acknowledgment

This project was a team effort with all responsibilities shared equally between Taylor Gruey, Kristin Kosak, Justin Steele, and Kevin Vees. The team's name is *Guide Dog*: *Leading You into the Future*. The team inspiration was Kristin's dog, Karma.

Table of Content

Introduction

The main concept of this product is to dispose of using batteries for everyday devices. There will be no use for batteries, such as AA and AAA, when everything is powered off wireless energy harvesting, which will automatically work within range of the transmitter. There is also no charging required, which will provide reliability, unlike rechargeable batteries. After discovering rechargeable batteries, most of the population decided to switch from regular non-rechargeable batteries. However, rechargeable batteries take at least 8 hours for a full charge, they are an expensive buy, and over time will lose their charging ability. If there was a substitute such as the wireless RF, or radio frequency, "battery pack" that would be a one-time buy and is reliable, there is a possibility that this product would be as popular as rechargeable batteries, if not more. An average family will spend approximately $80 per year on batteries for the household (Evers). Having the RF products will save an average family that money per year plus the manufacturing costs and disposal of the batteries. Not disposing of the batteries or not manufacturing them at all will also improve environment health.

Background

Before one can harness the power of RF and begin to design, one must first understand exactly what RF is and how it works. First, RF must be looked at from a technical point of view. An RF wave is an oscillation anywhere between the ranges of 3 kHz through 300 GHz. This may sound like an extremely large range, but Figure 1 shows how RF signals fit into the entire scope of waves. To put things into perspective, all visible light is made up of a relatively small portion of the total wavelengths. Figure 2 shows the breakdown for each color and its wavelength.

Benefits of RF:

RF technology holds a plethora of benefits to the average user. When one thinks of what RF might be used for, the common answer is communication. This broad field includes anything from radio transmissions to TV broadcasts. If a person wants to send a piece of information to another device, the best way to do this will be via RF transmission. Without RF technology, TV, radio, GPS, and WiFi would not exist. Many modern advances in technology are thanks to RF technology. It is honestly easier to think about what problems would exist without RF than to think about what solutions RF has given us; simply because RF is used in so many different applications.

Business Plan of Project

The potential uses for Guide Dog's "battery pack" are gaming controllers, keyboard, mouse, TV controller, car devices (GPS), etc. With the potential customers being retail consumers wishing to replace batteries in a portable device or possibly corporate businesses interested in integration.

At this time there are currently no products out on the market using RF as a power source. Due to this void in the market, the Guide Dog's product is expected to become very popular. Due to the costs of starting a new business and producing a new product, it is expected that there will not be much of a profit in the first 5 years. After the first 5 years profit margins are expected to increase.

Over the course of creating the product a budget of $500 was given to Guide Dog. Guide Dog used a total of $481.25 of that money with $37.4 on antennas, $203.85 on Powercast ICs, $215.00 on a transmitter, and $25 on miscellaneous components. If Guide Dog was to mass produce their product the cost is estimated to be $100 for a custom made transmitter, and $43.63 for each "battery pack" of which $30.75 for IC, $10.88 for antenna, and $2.00 for miscellaneous components.

Technical Focus

Technical Background:

During research on the feasibility of a RF to DC, or direct current, "battery pack" design Guide Dog discovered a company, Powercast, which produces chips designed to convert RF power to DC. The chips are capable of outputting an operating voltage at around 2-5 volts. This was an ideal power supply simulating two AA batteries, at 3 volts. The two types of ICs produced by Powercast that were tested in the prototype were the P1110 and the P2110. The P1110 is a continuous mode IC, meaning it provides a steady voltage output, which has a high efficiency of 70%. The further away from the transmitter however, the more of a decrease in efficiency. The max distance the continuous mode can operate without sacrificing efficiency is 10 feet. This is a reasonable distance considering this product is only for use in low powered household products, which would not leave the room. The second IC that was tested was the P2110 which is a discontinuous mode IC, meaning it provides a less stable voltage as shown in Figure 3, which will provide power via a discontinuous signal. Maximum distance for this IC is about 40 feet, significantly higher, although the efficiency is lower at 55%. The efficiency compared to the distance is shown in Figure 4. The impedance designed with the chip is 50 ohms; any matching impedance, such as antennas, will have to match the impedance of 50 ohms. Figures 5-8 show the pin differences between P1110 and P2110. Figure 9 shows the specifications for the P1110 chip and Figure 10 shows the specifications for the P2110 chip. The transmitter for this device was bought from

Powercast. The transmitter from Powercast produced a vertical beam of 915MHz, which was the frequency the ICs operated on. One transmitter can provide power for up to four or five products therefore were requiring the consumer to only have to buy one transmitter. The operating frequency used for the chips is interchangeable from 850-950 MHz, with optimal performance at 915 MHz. At that frequency no interference with other household or car devices such as a cell phones or blue tooth would occur (Wireless).

Technical Methods:

The approach that Guide Dog took to solve the initial problems presented, consisted of fulfilling the desires of the public in need of an alternative battery product and the circuitry that went with it. Using wireless power instead of batteries includes having more technology integrated into the product itself. Micro technology is used within the Powercast ICs and other circuitry is included to produce an output. The method that was used to approach the problem of technical difficulty was the use of formulas and datasheets given by the manufacturer and testing the product in different stages of development.

There were other components that must be connected with the IC, or integrated circuit, in order to get the desired output. Using the formulas from the manufacturer, the values of these components were found and integrated into the design. A capacitor must be used to steady the output of the IC so the product being powered will receive a constant stream of power. The lowest value capacitor that must be used with the ICs is 10uF, which was first tested. An additional resistor for the P1110 IC and an additional capacitor for the P2110 IC must also be included for the product to function properly. The 10uF capacitor was suggested on the datasheets and did not need to be calculated. For the additional resistor the following equation was used: R = $\frac{12.35M}{V_{out}-1.235}$, Vout was set to 3.3 volts and R was found to be about 6 Mohms. For the additional capacitor the following equation was used: $C = 15V_{out}I_{out}t_{on}$ (Wireless). These components were then used with the first test along with a wire for receiving the signal from the transmitter. The overall expected efficiency of the product was 27.5—56%, with the Powercast ICs being 55—70% and the antennas being anywhere from 50—80%. Upon testing there was very little power that was being produced from the product. The first step of solving the problem of lack of power would be to address the antenna problem.

The method used to solve the antenna problem was an act of trial and error. Several antennas were purchased at a specific frequency and gain, and were tested with the circuit. However, the antennas that were purchased didn't produce any more input than what was being produced with just a wire. Therefore the method of using the manufacturer formulas was again used to check and possibly change the values that were being used. After many testing sessions, the antennas were found to not have a ground plane and that gain could possibly increase with a ground plane with the purchase of a patch or dipole antenna. It was also found that the breadboard caused an unwanted internal antenna and that by decreasing the wire lead from the receiving antenna to the Powercast IC the power obtained would improve.

The main method used for testing the physical product was trial and error. The antennas were ordered three at a time and same with the other components. Every antenna ordered was tested along with the changed components to see which one would match the circuitry. The use of the trial and error method is also beneficial because the data that was collected with all the antennas is recorded and can be compared to other results obtained. This allows the user to see exactly what component of the circuit is affecting the overall performance. By starting with the method of using formulas, this is the reference point of where to start with the trial and error session for the testing. Once the area of values is known, parts can be ordered according to those calculations. After a desired antenna and components have been selected, the small adjustments of the circuit are started. The initial results from the purchase of parts have shown improvements from previous testing, though the results still did not yet meet expectations.

Upon final testing of the antenna, Guide Dog was able to achieve any desired voltage from the chip from up to 10 feet away from the transmitter. This was achieved by soldering everything on a single PCB, so that there was as little loss as possible. This voltage was stored in an array of capacitors and additional circuitry, which caused the voltage drop to decrease at a much slower rate as the user moved away from the transmitter. This drop in voltage is small enough to still operate the consumer device, but as distance increases, the user's device will lose power and eventually cease to function. This distance varies depending on what consumer product is being used at that time.

Prototypes and System Configuration:

The prototype design has been the primary hindrance behind Guide Dog's functional and efficient product. Due to the Powercast IC's unique package style, it proved difficult to prototype. Guide Dog originally set out to breadboard the design in order to provide a proof of concept. This would show that the product is functional, and then further steps could be taken to improve the overall design of the product. Figure 11 shows the block diagram which the prototype must follow. The most important part of this diagram is the 50 ohm antenna which is connected to the Powercast IC. Guide Dog's method for approaching this design will be discussed below.

The breadboard design was Guide Dog's first prototype design. This design consisted of soldering wire leads off each IC copper pad and running them into the breadboard. The theory behind this was that it would allow the user to easily breadboard the design, and insert various components into the circuitry in order to observe which worked best. Figure 12 shows the final prototype design for the RF to DC circuit. One can see that though not aesthetically pleasing, it successfully allowed Guide Dog to breadboard the IC and test the circuit with various components.

The breadboard prototype did not work. The Powercast P1110 and P2110 ICs were found to be extremely fragile. When soldering wire leads onto the pads, any movement in the wire created a force on the copper pad, and the small trace connecting the copper pad to the rest of the IC was disconnected and impossible to fix. This resulted in two of four ICs becoming unusable. Once this lesson was learned, Guide Dog successfully installed two Powercast ICs into the breadboard without any broken leads. This resulted in a successful circuit, but with an unusually small efficiency coming from the antenna. After some research, the problem was identified as a result of the antenna not having a ground plane and the breadboard itself. Figure 13 shows the internal circuitry of a breadboard. One can see that the breadboard has numerous copper traces leading along the board. These traces acted as an unwanted antenna, and the antenna was not able to perform as expected. Additionally, the long leads coming from the ICs and antenna resulted in losses. This is because the RF circuitry is very sensitive (especially at a high frequency of 915 MHz), and the leads needed to be as short as possible.

Guide Dog then began working on RF to DC Prototype 2.0. The primary idea behind this new prototype design was that the leads needed to be as short as possible. In order to accomplish this, the ICs and all components would need to be soldered directly onto a PCB (printed circuit board). Guide Dog began researching and developing a PCB which would fit the needs of the new prototype; however, it was quickly found that unless an individual orders PCBs in bulk, it can be very expensive. Designing and ordering a PCB from a manufacturer was simply out of the budget.

Shortly after this issue arose, Guide Dog members researched a board called "Carrier PCB" or "Breakout Board". This can be seen in Figure 14. These boards costs next to nothing, and solved all PCB and budget problems. After obtaining the PCB Carrier, some slight modifications had to be made due to the Powercast IC's unique package. Next, all passive components were soldered directly onto the PCB, which resulted in a complete, functional PCB.

The next step was to design a universal "battery pack", which the prototype PCB could securely be placed into. Figure 15 shows the final design for the universal "battery pack". Using styrofoam to secure the PCB into the plastic molding, two small jumper wires were ran through the rear of the molding and connected to the external antenna. This design allows for convenient antenna placement, and also allows the Powercast IC to receive maximum efficiency from the 915 MHz RF signal. The current prototype 2.0 model can be seen in Figure 16.

Guide Dog tested prototype 2.0 and received moderate results. The next step for Guide Dog was to manufacture more universal "battery packs" (created via a 3D printer), and assemble additional prototype units. These additional units used different internal circuitry and antennas. Guide Dog planned to have two to three prototype units which could all be powered on at the same time using a single RF transmitter. Depending on which antenna was to be used in the final design, either the plastic molding would be modified in order to secure the antenna, or Guide Dog would research various methods for attaching the antenna. Those methods must both be aesthetically pleasing as well as practical for the end user. The final design for the antenna was a simple one: replace the ugly duct tape with discrete gorilla glue. Gorilla glue allowed Guide Dog to stay within budget, as well as provide a cheap and reliable method to secure the antenna to the plastic molding. A small amount of glue was used as to demonstrate an aesthetically pleasing product.

In the end, Guide Dog printed two additional 3D “battery packs”. This allowed the team to show two working prototype units, as well as have an empty “battery pack” that can be passed around to the audience. Since there was virtually no additional budget to use, Guide dog believes that this cheap method will be extremely successful in showing the audience just how universal a wireless “battery pack” can be.

Results and Evaluation:

The results from the initial breadboard testing were undesired with the final output being 0.5 volts (V) with an unreadable amplitude (A) regardless of minor changes in component values. The desired results were ~3V and ~25—50mA, which was not obtained. It was found this was due to having the wrong type of receiving antenna and interference from the breadboard. The breadboard was then tested again with an improvised antenna that was configured correctly, and the output result was ~2.5V with no testing of the amplitude being done at that time.

After the issues with the antenna and breadboard had been resolved, testing of prototype 2.0 began. The new results showed a desired improvement. The “battery pack” then output ~3.3V and ~1—2mA; though the amplitude was still less than the desired results. Improvements in the currents results and design were discussed among the group and changes were made accordingly.

Guide Dog finally constructed the final prototype, which was demonstrated at UNR’s Innovation Day. In order to show the versatility of a wireless “battery pack”, two different prototypes were designed. The first was a dipole antenna which was programmed to output 2.5V, and the second was the patch antenna, which was programmed to output 3.3V, and both “battery packs” were capable of producing a discontinuous 100mA output. The two prototypes are shown in Figures 17-18. This amount of power was enough to power a remote control. These two very different antenna designs along with the variable voltage output shows that Guide Dog’s product can truly be used anywhere. The two prototypes operated as expected, and were able to produce consistent voltage outputs from a distance of up to 10 ft. This shows that the product is both successful and practical.

Future Work (Development and Improvement):

After much testing Guide Dog found that the transmitter that had been purchased was not capable of producing as high of an output to the “battery pack” as had originally been expected. The final “battery packs” would still function, but with a more powerful custom made transmitter the output power from the “battery packs” could be increased to power more powerful device, such as a gaming controller. For future development a custom made transmitter would be produced to run Guide Dog’s “battery packs”.

Facilities, Equipment, and Other Resources

Facilities used in the development of the prototype were the UNR Senior CAP Stone Lab, IGT RF Lab, and UNR Microwave Lab. Equipment used in the development of the prototype was soldering iron, oscilloscope, and multimeter.

Summary/Conclusion

The project being developed at Guide Dog was intended to be a replacement for household batteries. The product used “RF harvesting” to convert radio waves directly to DC power. The intention of the design was to replace batteries with a more convenient, earth friendly solution. All design circuitry fits into a 3D printed mold of AA batteries. This allows the product to be used anywhere that AA batteries are used. The potential applications are limitless. As the product becomes more developed and advances made in RF harvesting it could potentially replace all household batteries. This is the dream of Guide Dog and we hope to make this a reality.

Guide Dog was successful in constructing two final prototypes which showed the ability to convert a 915 MHz radio wave into a DC output. These devices were tested at various distances, and proved to be an effective DC power supply which could be implemented into any standard consumer product. The device was also capable of producing a discontinuous current of 100 mA at 3 V. This shows that the prototypes were successful, and opens up many opportunities for future development.

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Appendix:

Appendix A: Figures

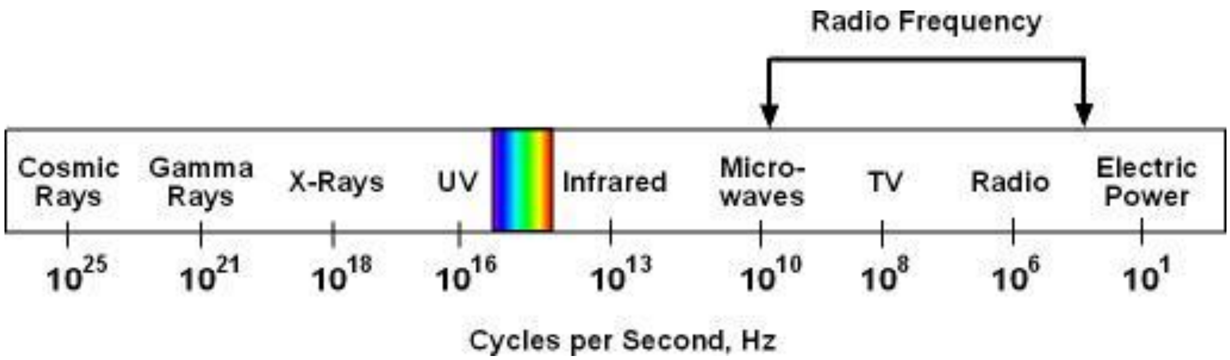

Figure 1: RF Frequency Spectrum (Wanna)

Color	Frequency	Wavelength
violet	668–789 THz	380–450 nm
blue	606–668 THz	450–495 nm
green	526–606 THz	495–570 nm
yellow	508–526 THz	570–590 nm
orange	484–508 THz	590–620 nm
red	400–484 THz	620–750 nm

Figure 2: Visible Light Spectrum

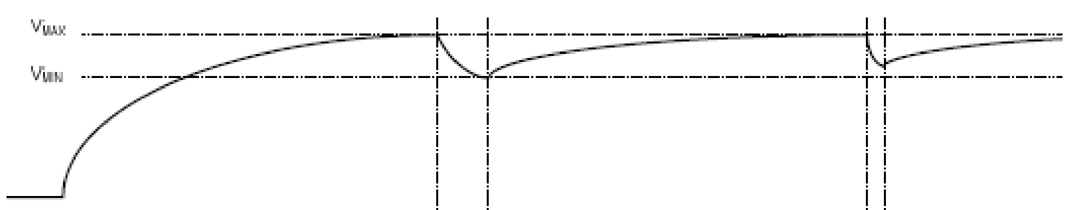

Figure 3: Discontinues Mode Output (Wireless)

Figure 4: Efficiency of Powercast chips (Wireless)

Figure 5: P1110 Pin Configuration (Wireless)

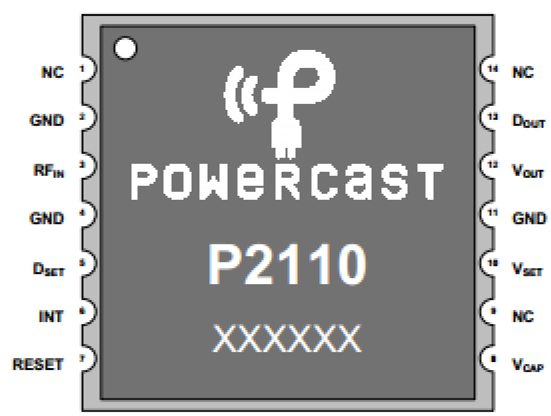

Figure 6: P2110 Pin Configuration (Wireless)

Pin	Label	Function
1	LI	Li-ion/LiPo recharging pin. Connect directly to the analog ground plane for 4.2V maximum recharging. NC when using ALK or V_{SET} pin.
2	GND	RF Ground. Connect to analog ground plane.
3	RF_{IN}	RF Input. Connect to 50Ω antenna through a 50Ω transmission line. Add a DC block if antenna is a DC short.
4	GND	RF Ground. Connect to analog ground plane.
5	D_{SET}	Digital Input. Set to enable measurement of harvested power. If this function is not desired leave NC.
6	V_{SET}	Maximum Output Voltage Adjustment. Sets the maximum output voltage on the V_{OUT} pin. Connect to an external resistor. NC when using LI or ALK pin.
7	GND	DC Ground. Connect to analog ground plane.
8	V_{OUT}	DC Output. Connect to external storage device. Maximum output voltage set by V_{SET}, LI, or ALK pin.
9	D_{OUT}	Analog Output. Provides an analog voltage level corresponding to the harvested power.
10	ALK	Alkaline recharging pin. Connect directly to the analog ground plane for 3.3V maximum recharging. NC when using LI or V_{SET} pin.

Figure 7: P1110 Pin Functional Description (Wireless)

Pin	Label	Function
1	NC	No Connection.
2	GND	RF Ground. Connect to analog ground plane.
3	RF_{IN}	RF Input. Connect to 50Ω antenna through a 50Ω transmission line. Add a DC block if antenna is a DC short.
4	GND	RF Ground. Connect to analog ground plane.
5	D_{SET}	Digital Input. Set to enable measurement of harvested power. If this function is not desired leave NC.
6	INT	Digital Output. Indicates that voltage is present at V_{OUT}.
7	RESET	Digital Input. Set to disable V_{OUT}. If this function is not desired leave NC.
8	V_{CAP}	Connect to an external capacitor for energy storage.
9	NC	No Connection.
10	V_{SET}	Output Voltage Adjustment. Sets the output voltage by connecting a resistor to V_{OUT} or GND. Leave NC for 3.3V.
11	GND	DC Ground. Connect to analog ground plane.
12	V_{OUT}	DC Output. Connect to external device. The output is preset to 3.3V but can be adjusted with an external resistor.
13	D_{OUT}	Analog Output. Provides an analog voltage level corresponding to the harvested power.
14	NC	No Connection.

Figure 8: P2110 Pin Functional Description (Wireless)

T_A = 25°C, V_{OUT} = 3.0V, unless otherwise noted.

Parameter	Symbol	Condition	Min	Typ	Max	Unit
RF Characteristics						
Input Power	RF_{IN}		0		20	dBm
Frequency			902		928	MHz
DC Characteristics						
Output Voltage	V_{OUT}		0		4.2	V
Output Current	I_{OUT}				50	mA
Output Current	I_{OUT}	No RF_{IN}		-1.5		µA
V_{SET} Range	V_{SET}		1.8		4.2	V
Signal Strength	D_{OUT}	RF_{IN} = 0dBm		61		mV
Digital Characteristics						
D_{SET} Input High				1		V
Timing Characteristics						
D_{SET} Delay				20		µs

Figure 9: P1110 Specifications (Wireless)

T_A = 25°C, V_{OUT} = 3.3V unless otherwise noted.

Parameter	Symbol	Condition	Min	Typ	Max	Unit
RF Characteristics[1]						
Input Power	RF_{IN}		-10		10	dBm
Frequency			902		928	MHz
DC Characteristics						
Output Voltage	V_{OUT}		1.8	3.3	5.25	V
Output Current	I_{OUT}				50	mA
V_{CAP} Maximum	V_{MAX}			1.25		V
V_{CAP} Minimum	V_{MIN}			1.02		V
Signal Strength	D_{OUT}	RF_{IN} = 0dBm		275		mV
Boost Efficiency		I_{OUT} = 20mA		85		%
Maximum INT Current				0.1		mA
Digital Characteristics						
RESET Input High				1		V
D_{SET} Input High			1.8			V
INT Output High			V_{MIN}		V_{MIN}	V
Timing Characteristics						
D_{SET} Delay				50		µs
RESET Delay				6.6		µs
RESET Pulse Width			20			ns

[1] See typical performance graphs for operation at other frequencies or power levels.

Figure 10: P2110 Specifications (Wireless)

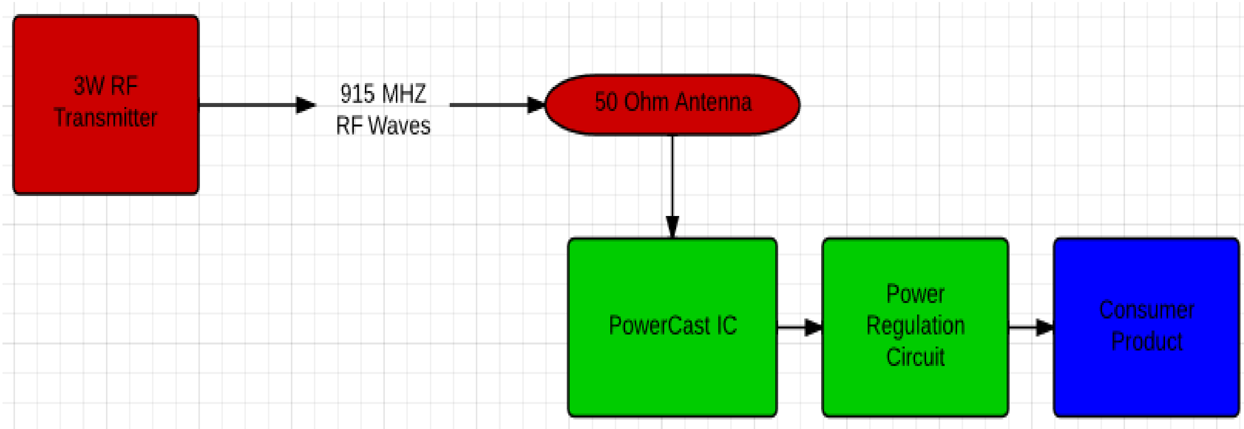

Figure 11: RF to DC Flowchart

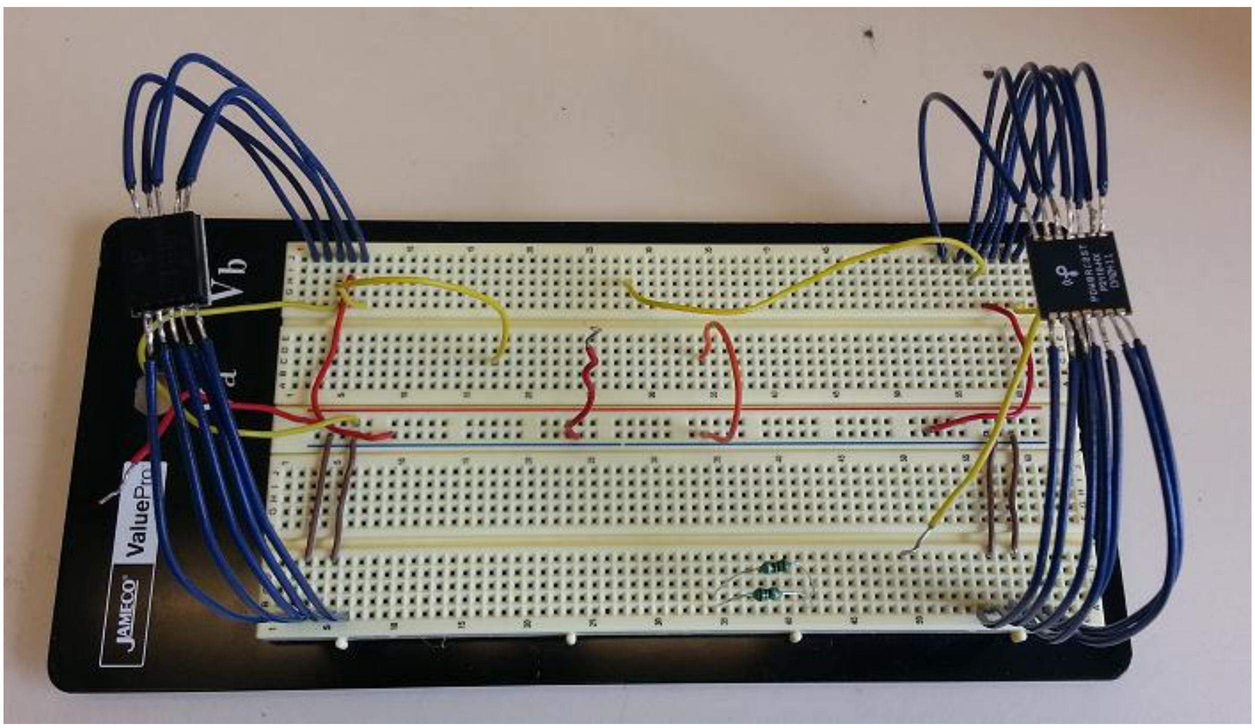

Figure 12: Original Breadboarded Prototype

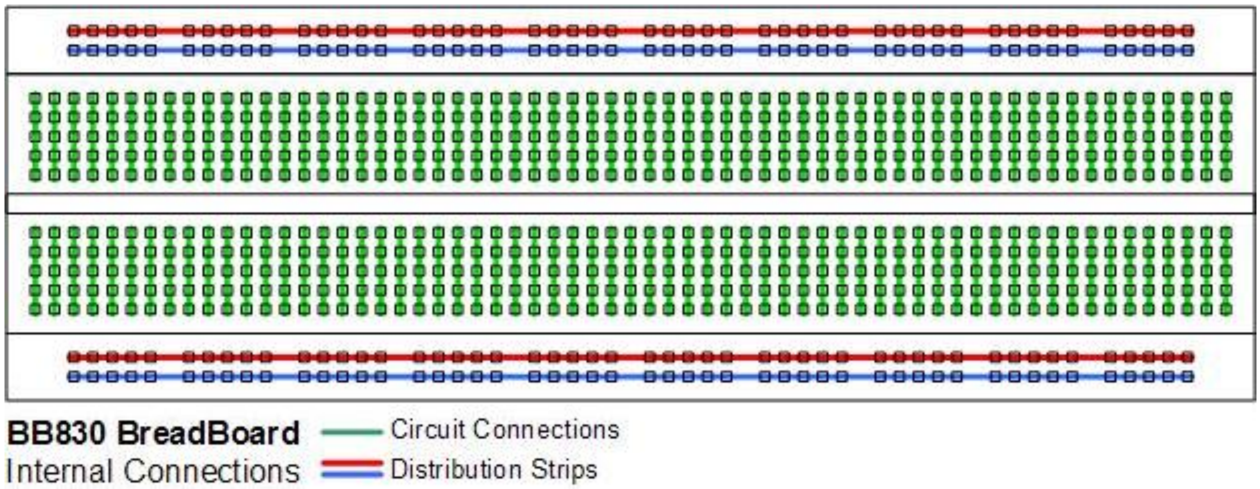

Figure 13: Internal Breadboard Schematic (BusBoard)

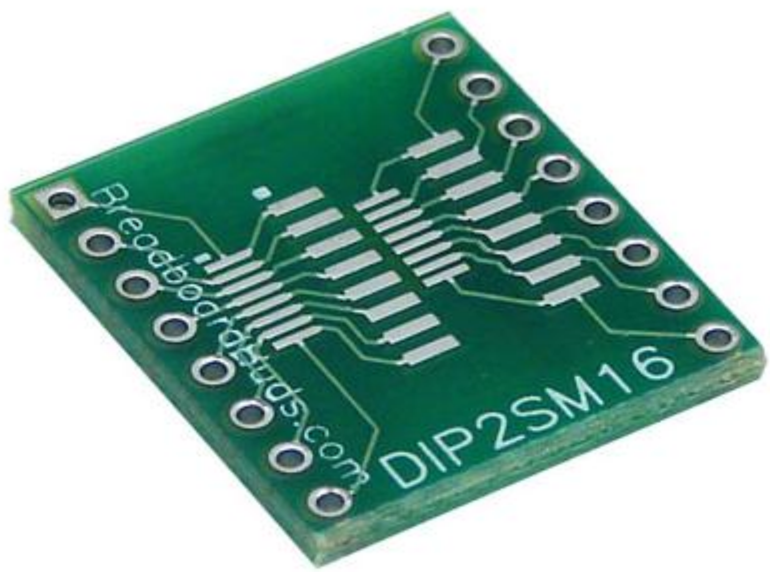

Figure 14: PCB Carrier (Technologicalarts)

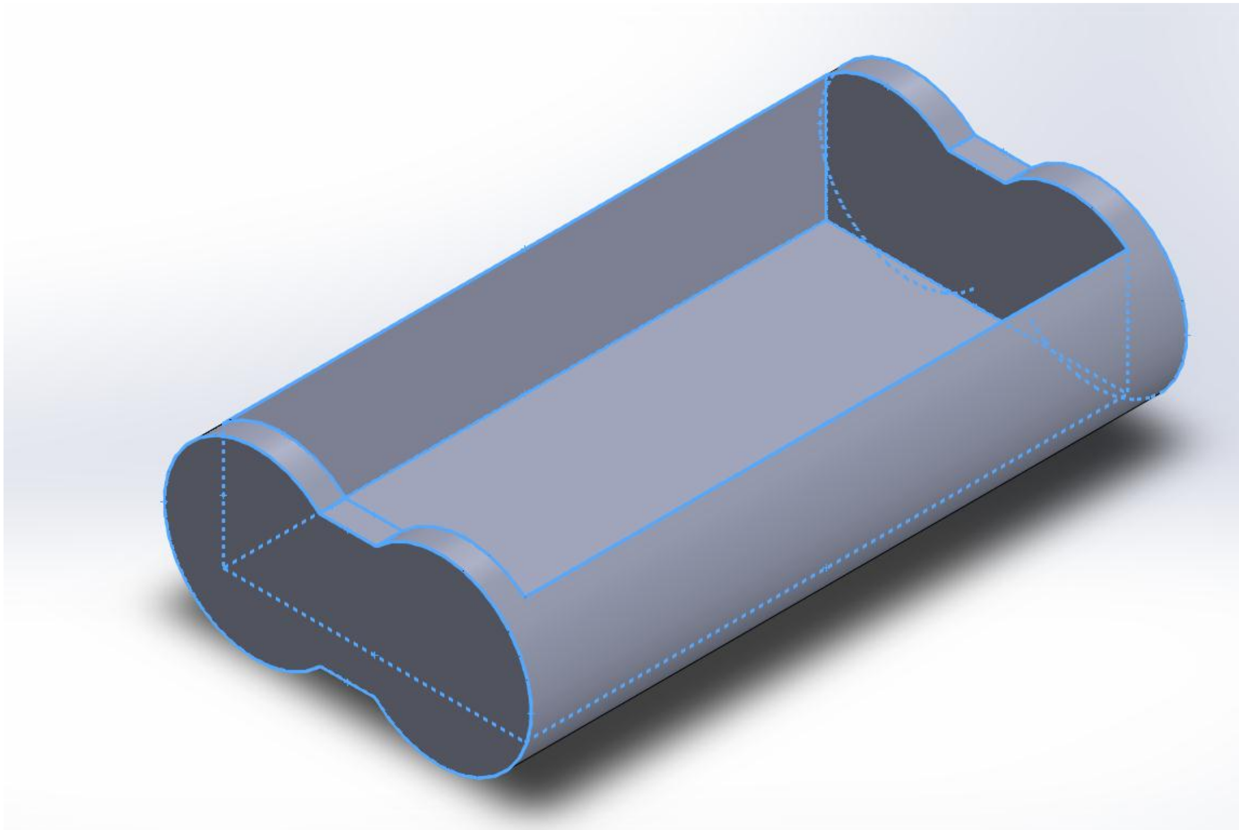

Figure 15: Prototype 2.0 Concept

Figure 16: Prototype 2.0

Figure 17: Final Prototype 2.0 Dipole Antenna

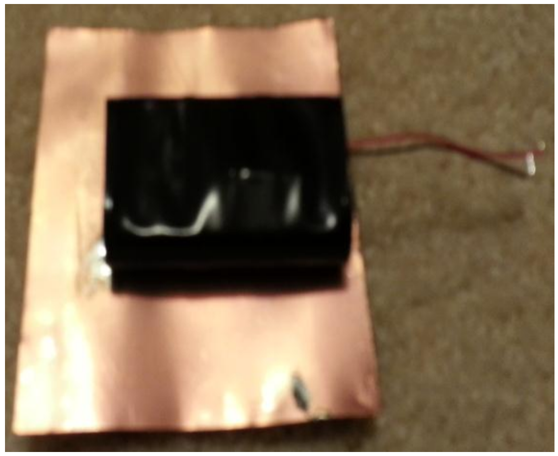

Figure 18: Final Prototype 2.0 Patch Antenna