RF Energy Harvesting for Medical Applications

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***Abstract* — The aim of this project is to demonstrate the ability to harvest radio signals propagating in free space to power low power electronics or sensors. Though the concept of energy harvesting is not new, the approach of this project is a new variation of past attempts by integrating the device into a user's belt near where 900MHz cellular signals are generated and collected. We were able to achieve ~3mW of power harvested with this approach using a Powercast integrated circuit (IC). The power harvested is then used to power a heart rate sensor and body temperature sensor.**

***Index Terms* — Energy Harvesting, Sensors, Medical, Wearables, IoT, Low Power, Powercast, Antenna**

I. INTRODUCTION

Every year the number of electronic devices, sensors, and systems increase. This is especially true with the onset of wearable technology for health monitoring. Tracking your heart rate on your smartwatch is plenty cool, but they are only useful if they remain charged (powered). We identified that these devices, like all consumer electronics, have an alarming dependence on batteries. This project aims to reduce that dependence with a specific focus on biomedical sensors.

A. Motivations

There are both personal and industrial motivations for this project. One the personal level, one of this project's group members wears not only an insulin pump, but also a set of cochlear implants. He depends on these devices to go about his normal day and these devices depend on the batteries that operate them. This member has experienced on several occasions just how scary it is to run out of, or low on, batteries without a way to recharge/ replace them.

On an industrial level, there is a tidal wave of activity related to the internet of things (IoT) which many experts say energy storage (a power source for the IoT system) is the sole bottleneck to major adoption. IoT applications range from smart electronics/appliances in your homes to remote sensors that monitor stresses in oil rigs or a bridge. This project will demonstrate that our design can help bring power to these remote sensors. The utility of this is the saved expense of changing the batteries. To get an idea of the potential of industrial impact of this design, we found that the market for IoT applications is expected to pass a trillion dollars. This doesn't suggest the market for our proposed system is over a trillion dollars in worth, but that there are a trillion dollars' worth of applications our system can be applied to in future developments [1].

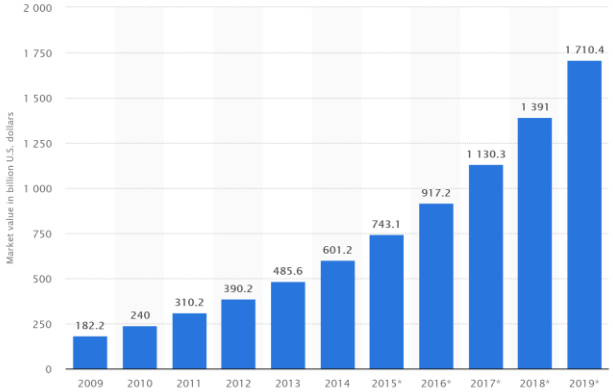

Fig. 1

Fig. 1 makes it easy to understand why the RF energy harvesting market is focused on the IoT market and why companies, like Freevolt, are flocking to the market. Freevolt is focused on RF energy harvesting in the IoT market. They quote:

> *"…the benefit of the Freevolt technology means the sensor is easily deployed, and once set up - you may never need to recharge it with a cable or… to change its batteries."*
> *-Free Volt*

The system we propose will have a very similar result thus providing validation to our approach and the utility of our design.

B. Early Problems & Design Changes

This project was initially intended to directly charge batteries that are powering a system or to directly power a system. Our design would then measure the amount of energy being harvested and communicate the results with the end user so they would know. This approach is problematic for a few reasons. First, the end user does not often care about the power that is being harvested. They care if their system is operational and doing its job properly. Next, the amount of power that can be harvested is between 1-5mW in practicality. This is very little and needs to be used wisely. The power draw by a power monitoring circuit is so large that there would be such little power left over to charge a battery or power a circuit. Therefore, it would be functionally useless to the user. Finally, because of the design problems just described, it would take a long time to collect enough power to run the system. This means the system would not update very often being of little use to the users that do care about the amount of power harvested. We mitigated these problems by following the final design described in the next section. The major pillars of the design remained the same while changing the load and software to be more functional and offer more utility to the end user.

C. Final Design Overview

To decrease the dependence of electronic devices and sensors on batteries, we have developed a system that can harvest energy from cellular signals. In this project, the harvested power will be used to power a heart rate sensor and temperature sensor. Other sensors can also be used, but these fit the medical intention. In the past, energy harvesting was viewed as a lost cause in practice as it could only harvest micro-watt (uW) levels of power which has little utility for most applications. Yet, several case studies in the lab environment could achieve milli-watt (mW) and watt (W) levels of power. This is because they would use a nearby and dedicated source for their design where in practice you cannot enjoy the same luxury. We addressed this problem by viewing the cell phone in a user's pocket as a small mobile source providing 1-3W that would follow the user wherever they go. To utilize this energy, we designed our project as a wearable on a user's belt or shirt to maintain proximity to this cellular 900MHz source.

Outside of energy harvesting, this project also required an energy efficient method to take data from these sensors as well as transmit that data off the board. We found microcontrollers equipped to do this, however the question becomes how to transmit the data off the board when working with such little power? Adding a battery to power this part of the circuit is counter intuitive as battery dependence is again established. Near-Field-Communication (NFC) can transmit and receive data like Bluetooth would, however a smartphone is what provides the power for the data exchange.

D. Marketing Specifications & Design Goals

The design goals for this project is to keep the system small and simple. Our goal is not to add stress to our user's life by using this system. Furthermore, future applications in remote sensing for IoT or more intense medical applications would require the system to be self-sufficient in its function again requiring little to no user interaction. Other goals include building the system into a wearable in such a way that is largely unnoticeable. Being unnoticed includes being lightweight and comfortable. The system should also include a communication system to convey the system performance (sensor data) to the user upon request via mobile application or another user-friendly platform.

The marketing specifications are described in the following table below:

Topic	**Specification**
Size	<4in^2 surface area
Energy Harvested	>1mW
Sensor Accuracy	+/- 20%

E. Conclusion

In utilizing an integrated circuit designed specifically to harvest 900MHz cellular signals for energy harvesting called Powercast and a microcontroller from Texas Instrument that is equipped to work with our medical sensors and NFC, we designed a circuit that is 2.7" by 1.2" that harvests ~3mW to power two sensors.

II. HIGH LEVEL DESIGN CONCEPTS & BLOCK DIAGRAM

This project is focused on designing a system that can harvest RF signals to power sensors. The design must be simple and highly efficient due to the low power that is available. The design should not require extensive user interaction with the system and must be small enough in size to fit into a wearable such as a belt or shirt.

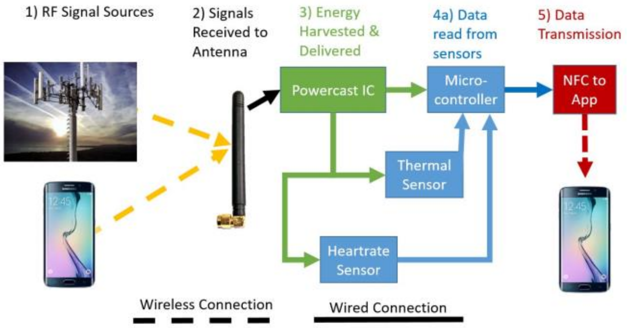

Fig. 2

III. RELEVANT TECHNOLOGIES, COMPONENT SELECTION, & TRADEOFFS

Aside from more basic components an antenna, energy harvesting IC, two sensors, a microcontroller, and NFC are utilized in this design. Each of the following paragraphs will individually introduce these technologies.

A. Antenna

Antennas come in a variety of different form factors (PCB trace, chip, whip/wire), parameters (gain, efficiency, frequency, gain, etc…) and styles (monopole, dipole, half-wave, quarter-wave, etc...). There are advantages and disadvantages for the different form factors mentioned above, but it largely depends on application parameters. The style of antenna and specifications are much more important to consider. For applications where the source location is unknown or, in this case, not guaranteed, then an overly specific antenna (one with high gain) would not perform well. The Fig. 3 below describes gain and its relation to directionality. The higher the gain the narrower and directed the lobe becomes. The lobe is essentially what carries the information (and energy). If you increase the gain too high, there is less of a chance for our antenna's lobe to come in contact with cell signals in the environment. For this reason, we selected a lower gain antenna.

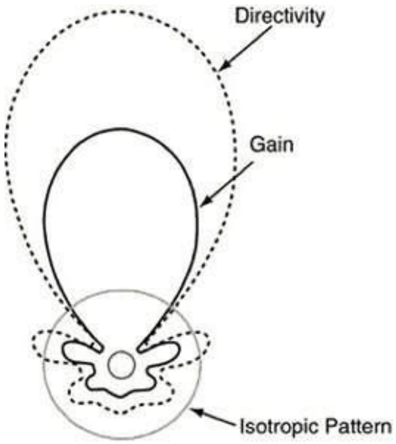

Fig. 3

The antenna should be tuned to the cellular band of 900MHz, not require a dedicated power source (passive), be small in packaging, and most importantly feature a high efficiency. These specifications lead to the selection of a chip antenna capped the Pulse Electronics ISM 900 MHz Ceramic Antenna featuring a small surface mount package (0.393" by 0.124"), a gain of 2 dBi, and 70% efficiency.

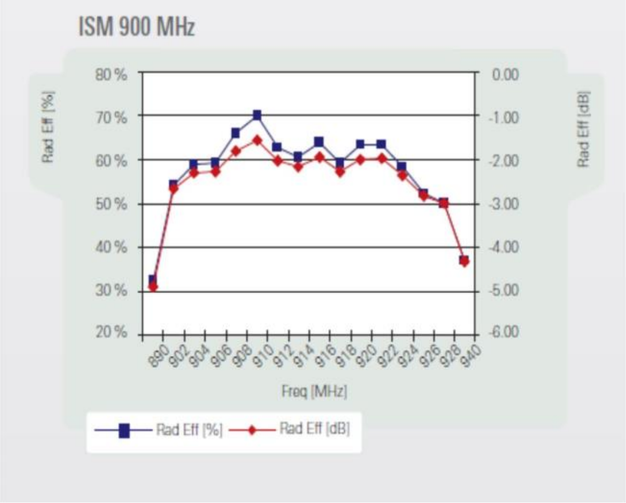

Fig. 4

B. Energy Harvesting

Energy harvesting is a result of a research topic known as the *rectenna* which is described by Fig. 5 below:

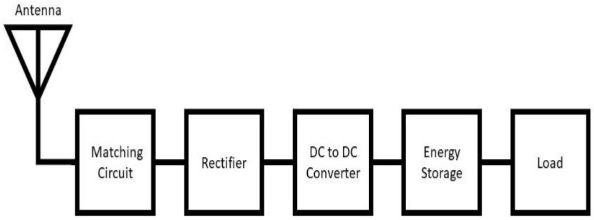

Fig. 5

The rectenna is exactly as it sounds, an antenna and rectifier combination. This will lose any information carried by a signal while turning it into a DC voltage source [2] which is okay considering its purpose is to harvest energy and not read information. From this concept, energy harvesting ICs were designed to be connected to a variety of different antennas helping the technology's business case. A typical module, such as the Powercast IC this project uses, has a few key stages the signal goes through to harvest the signal for power. These stages are demonstrated in Fig. 6 below:

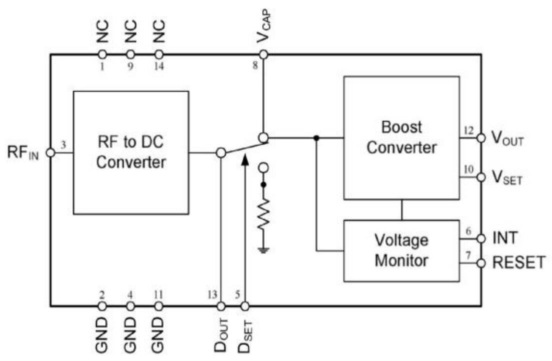

Fig. 6

As shown in Fig. 6 the signal, coming through pin 3, is rectified before being converted to a higher voltage via boost converter. Other electronics are involved to provide digital functionality too however, these pins are largely unused in this project. One of the greatest utilities in using the Powercast IC is the ability to control its timing cycle with a capacitor in pin 8. A larger capacitor will take longer to charge, but provides an output voltage longer too.

There are two different Powercast IC that can be selected. The Powercast 1110B is made for close by and strong sources (requires -6 dBm to operate). The Powercast 2110B, which we selected, is specialized to harvest lower power signals (requires -11 dBm). This is one of the most critical components in this design. Its small package (0.55” by 0.53”), relatively good performance (50%-60% depending on frequency), and ease of implementation (few support passive components required) made it the best option for our design over other alternatives such as those made by Texas Instrument which are larger, required additional passives to support operations, or relied on batteries to ensure proper operation.

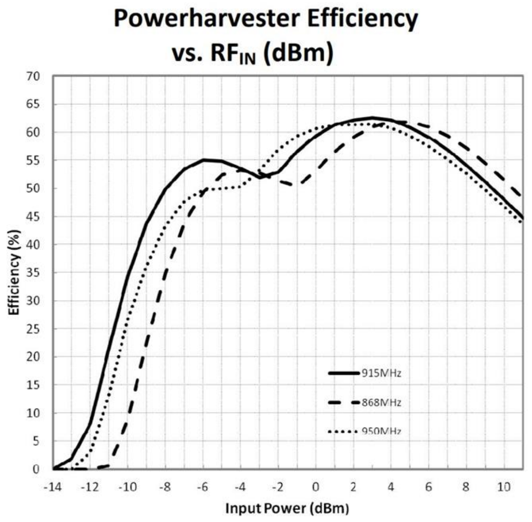

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Fig. 7

C. *Sensors*

The utility in our design is achieved by sensors. Simply harvesting energy and communicating information to the end user about the magnitude of power being harvested has little real-world utility. In this project the sensors are medically focused (bio-sensors), however other sensors can be utilized as well. These bio-sensors are built to measure heartrate and body temperature. The bio-sensors used were selected based on group member’s comfort, efficiency, size, and most importantly compatibility with the remaining design.

D. *Microcontroller & NFC*

Bringing us to the final major stage of the design is the microcontroller which is NFC enabled to act as an option for data transmission. We selected NFC as our form of communication due to its low power intensity, allowing readings to be taken without consuming any of our system’s power, as opposed to alternatives like Bluetooth LE which could consume up to 15 mA. The microcontroller we selected, the RF430FRL152H Microcontroller, comes with firmware to allow for simple sensor data value storage ready for NFC reading.

NFC is a form of contactless communication between devices which requires a reader, and a transponder, or tag as it is otherwise referred [3]. The other important principle is that the power for the communication is provided by the host device and as such no internal power is needed for the tag. NFC systems work by having the reader create a radio frequency current which communicates with the transponder that holds the information that the reader wants. This communication gives enough power to power, read and ultimately resend a transmission to the host. The transponder does not need any power to broadcast because of this. An NFC tag can be embedded into a PCB and hardwired directly into the board, and is passive, requiring no power. The reader does require power, but can be in the form of a cell phone. As of now, iPhones do not have NFC capabilities, so an Android phone would be required for this functionality. An NFC tag can be embedded into a PCB and hardwired directly into the board, and is passive, requiring no power. The reader does require power, but can be in the form of a cell phone. Most modern Android phones come with NFC capabilities, and as of now iPhones do not, so an Android phone would be required for this functionality should we decide on NFC.

The RF430FRL15xH device is a 13.56 MHz NFC transponder chip. It is equipped with a 14-Bit Sigma-Delta analog-to-digital converter, an internal temperature sensor, a resistive sensor bias interface, and an MSP430 microcontroller. The microcontroller has 2KB FRAM, 4KB SRAM, and 8KB ROM with a supply voltage range of 1.45V to 1.65V, and very low power consumption, with only .14mA in active mode, and .016mA in standby mode. A block diagram for the device is represented in Fig. 48 below. In the diagram, RST/NMI represents the device's reset/interrupt input, and P1.0-1.7 represent general purpose digital I/O pins. The power supply system is interfaced with the following pins: VDDB represents battery supply voltage, VSS is the ground reference, VDDH is the rectified voltage from RF-AFE, VDDSW is the switched supply voltage, VDD2X is the voltage doubler output, VDDD is the digital supply voltage, while CP1 and CP2 are terminals to the charge pump flying cap. ANT1 and ANT2 are antenna inputs. ADC0 – 2 are analog-digital converter input pins, while TEMP1 and TEMP2 are resistive bias pins. TMS, TCK, TDI, and TDO all interface with the JTAG as mode select, test clock, data input, and data output respectively. CLKIN represents the external clock output pin.

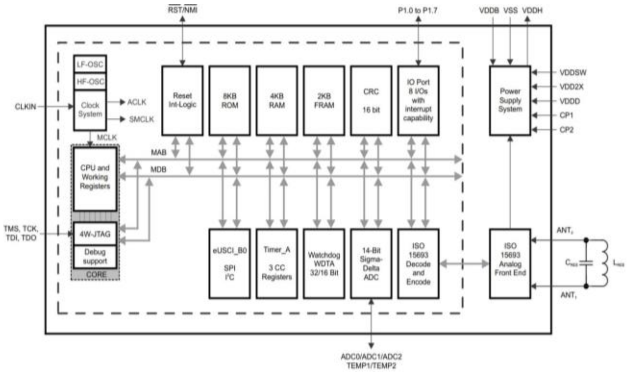


Fig. 8

IV. SOFTWARE REQUIREMENTS

The software used in our project should be able to read sensor data values, and transmit them to an external source for a user to be able to view it in a way that makes sense to a person.

A. Microcontroller

The NFC communication is done using ISO 15693 Protocol, which we chose due to its simplicity for reading individual data values from blocks of memory. An NFC-enabled Android phone uses a specially designed mobile application in order to read the data in byte format, and subsequently convert it to visual data that a user could understand. An alternative to ISO 15693 is the more widely known protocol NDEF, which is commonly used due to its ease of implementation in Android development. Its implementation on the end of the Microcontroller, however, would be more difficult using the firmware of the board itself.

TI supplies a TRF7970 GUI which allows for a simple way to configure. and write to the flag block of the microcontroller's FRAM which configures the firmware of the microcontroller to collect data. The firmware will sample the value at the sensor's input at a predefined rate, and store this value at the next consecutive memory slot available. When memory is filled it continues again from the beginning, overwriting older values.

B. Connecting Android to NFC

In order for an Android app to connect to NFC tags it must be configured in its AndroidManifest.xml document to respond to the intent filter for NFC action tech. Once this is done, a foreground dispatch is set up on the NFC adapter in order to monitor for new intent. When the tag is near the phone, intent is discovered, and the phone connects to the microcontroller using Android's built in NfcV class. Because the connect() function cannot be called in the main thread of the application, NFC communication is done in a separate Runnable thread. Once connected, the application on loop calls the transceive() function to send the 'read block' command, referencing each block in order, reading each data segment as a byte array.

C. Processing Data in Android

The app then converts the byte array returned from the transceive() function into a string of the hexadecimal value originally stored in memory using a StringBuilder. Because each block contains two 4 byte values, this hexadecimal string is then converted into a pair of long integer values, representing the actual values stored in the block. The application then implements a graphing library, GraphView, to display the data as a line graph. The loop will continue until either an IOException error is reached meaning the phone has lost connection with the board, or the end of the board's readable memory has been reached.

D. Viewing Data on Mobile Application

GraphView is the graphing library used, as opposed to alternatives like MPAndroidChart and AndroidPlot due to its simplicity of implementation. Because the dataset we are using is fairly small at 512 values, maximum performance isn't entirely necessary, simplicity of implementation is important. The data will be visible in the form of a line graph to properly visualize the heartrate data which we are monitoring. An alternative way to view the data would be viewing raw data in a table directly from the ADC. We did not make this the standard way to view data because it is difficult to visualize a heartrate by looking at numbers. For other applications of this product such as body temperature monitors might find this way of viewing data to be more appealing.

V. PROTOTYPE & TESTING RESULTS

We built a prototype circuit of the energy harvesting stage of our design. This stage is mission critical to the design. The prototype circuit is described in Fig. 9 and Fig. 10 below:

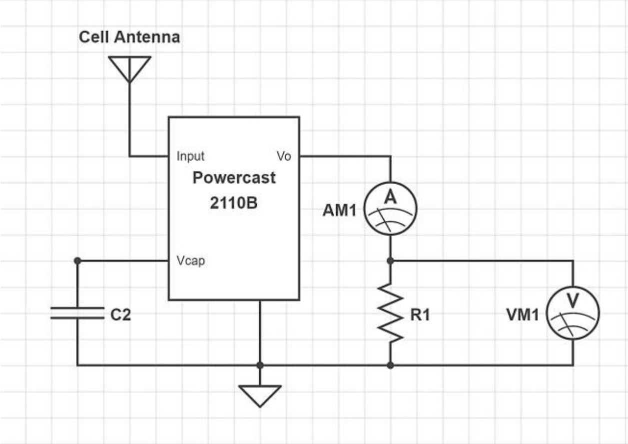
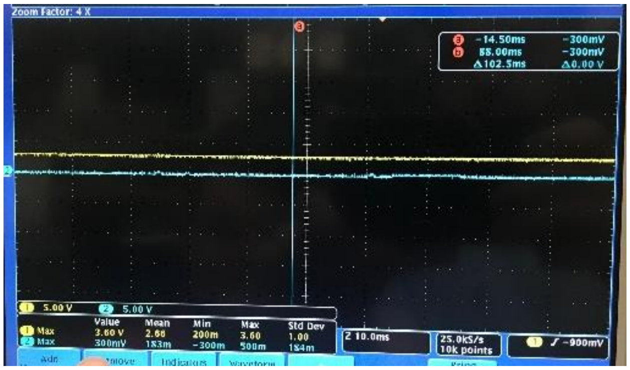


Fig. 9



```
a  -14.50ms   -300mV
b   88.00ms   -300mV
   Δ102.5ms   Δ0.00 V
1 5.00 V   2 5.00 V
        Value   Mean   Min     Max    Std Dev
1 Max   3.60 V  2.66   200m    3.60   1.00
2 Max   300mV   183m   -300m   500m   184m
Z 10.0ms   25.0kS/s 10k points   1 ∫ -900mV
```

Fig. 10

Ideal Source Results

Power Transmission	1W continuous
Frequency	900MHz
Powercast Output	50mW @ 3.80V

Practical Source (iPhone 7plus) Results

Power Transmission	≥1W interrupted
Frequency	900MHz
Powercast Output	3mW @ 3.8V

This prototype circuit performed well all things considered. Given the antenna's efficiency of 70% and the Powercast's efficiency of ~55%, the maximum power to be harvested from the ideal source (a consistent 1W signal) would be 250mW. Our circuit was only able to harvest 50mW largely because the 1W signal's strength weakens exponentially with increased distance as shown in equation 1 below.

$$Precieved = \frac{Ptransmit * G^2 * lamda^2}{(4\pi)^3 * R^4} \tag{1}$$

The reason only ~3mW is harvested from the practical source, an iPhone 7 plus, is because the practical source is not continuous. Instead, phones send many segmented 1W pings carrying data to cell towers. We found in testing that unless sound is detected by the phone, these pings will carry little to no power. This was a problem as the Powercast requires -11dBm to function.

We used an evaluation board to prototype with the RF430 microcontroller which enables us to test the sensors and NFC data transmission.

VI. DESIGN & IMPLEMENTATION

Though the energy harvesting stage of the design is the most critical stage of the system, the RF430 microchip and heartrate sensor were the most complex and difficult to implement. See the design's finalized schematic in Fig. 11 below:

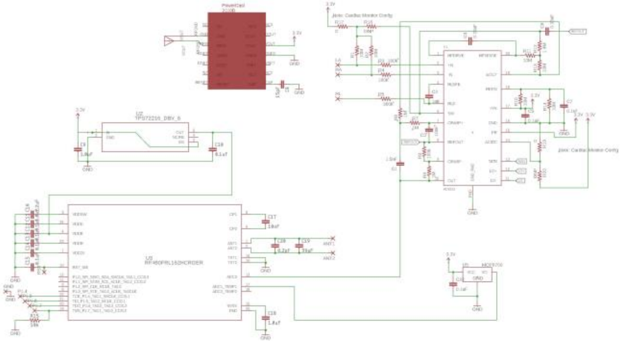
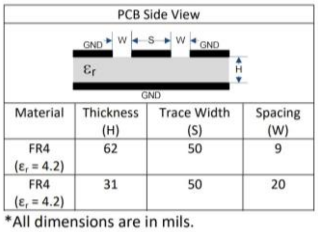


Fig. 11

A. *Energy Harvesting*

The Powercast component has a few minor design requirements on the PCB level. First off, the antenna must be 50Ω matched with trace requirements for the PCB. The material should be FR4 with a height of 0.062" and the trace should be 0.050" wide and at least 0.009" away from any other traces [4].



Material	Thickness (H)	Trace Width (S)	Spacing (W)
FR4 ($\varepsilon_r = 4.2$)	62	50	9
FR4 ($\varepsilon_r = 4.2$)	31	50	20

*All dimensions are in mils.

Fig. 12

Also required by the Powercast is a timing capacitor on pin 8. Essentially the capacitor is charged to 1.25V at which point it discharges to 1V. A larger capacitor will take longer to discharge between these voltages. The following equation can be used to determine the appropriate size capacitor.

$$C = 15V_{out}*I_{out}*T_{on} \quad (1)$$

The timing diagram for the Powercast is described below in Fig.:

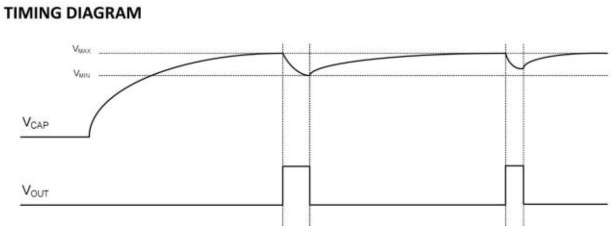


Fig. 13

B. *Temperature & Heartrate Sensor*

The sensors used in this system are powered by the output of the Powercast and their outputs are fed into the ADC pins of RF430 microcontroller. The sensors use a variety of resistors and capacitors are used as support components. Mostly, these components act to help tune the signal or provide a reference voltage.

C. *Microcontroller & NFC*

The output of the Powercast is 3.80-4.00V. The RF430's input voltage threshold is 1.65V. The output of the Powercast could be modified by adding a resistor to drop the voltage, however this would result in too little voltage to operate the sensors involved. For this reason, the Powercast output goes through a buck converter to drop the output voltage between 3-4V to 1.5V into the RF430.

The RF430 requires a variety of passives as support components and takes the temperature sensor and heartrate as inputs to its ADC in pin 13 and pin 17 respectively. The most complex passive components to select are between pin 1 and pin 2 used for impedance matching in the NFC antenna. The NFC antenna selected has an inductance of 5.2uH. Based on the RF430 development board drawings we selected 8.2pF capacitor in parallel to 39pF capacitor creating a total impedance of about 10mΩ, the same impedance used on the RF430 development board. Other passive components used to support the RF430 includes a series of headers which can be used to program the microchip. This helps achieve the desired small product size and flexible software design should different requirements be needed later.

D. *Layout*

The final board layout implementing the design is shown below in Fig. 14. In designing this layout a few overall design concepts were kept in mind. First, additional pads were left un-used on traces to provide easy access for testing if there are issues with performance. Also, all components are of reasonable size to be hand soldered if needed. Two layers are used for traces (top and bottom) along with a ground plane to the board. This ground plane helped manage the layout of the board and also provides EMF/EMI protection to the data trace lines. This is important considering the circuit is harvesting EMF signals in the first place.

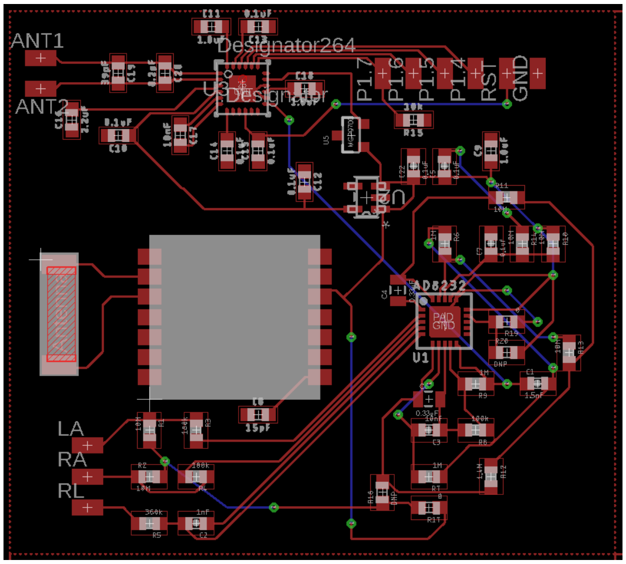


Fig. 14

VII. CONSTRAINTS

The system that we proposed exists in a rather gray area. This is because it begs a question of who owns the signals that we plan to harvest. Each stakeholder involved believes they have ownership over these signals. Both Wi-Fi Networks and Cellular Networks provide signals that hold valuable data. These signals and its data is what the end user pays for. So the question is, are you paying for data or the power? Network providers such as Brighthouse, Verizon, etc… argue that they are selling the service to provide the data and that the power used to send the signal carrying the data is a part of their overhead. Therefore the service provider owns the power which means they own the power our system is harvesting.

Consumers argue that they pay for the operations of the company that provides the service. This argument is particularly strong with Wi-Fi networks in homes. The homeowner pays their own power bill which is what provides the energy that would be harvested from the Wi-Fi network. Network providers do not have a strong argument for the homeowner case, but what about somewhere like café, hotel, university, or (now days) any other building. In that case, the user of our system would be harvesting energy from signals they are not paying the power bill for. This argument is not as practical for cellular network providers. The provider actually is selling the data to the user and the user is not exactly paying for the power. We have found that the general consensus for cellular networks is that once the signal leaves the tower, it is for the user/customer to use as they wish. Again, this topic has a gray area and we did not find any laws, standards, rulings, etc…

Our system is designed with off the shelf and heavily vetted components that satisfy standard regulations such as RoHS and UL. Most of the components are surface mount and our PCB will be very low profile. This low profile (thin) PCB allows the components to avoid unnecessary stress and strain. The PCB will be embedded inside a belt which is where it will operate. Each module of our system will be its own PCB. The manufacturing of this PCB is more than feasible and will utilize surface mount technology to install each component on the board. The constraint comes from the assembly of the system. An electronics manufacturing group will not want to work with embedding the technology into a belt. This would be out of their scope and domain expertise. This becomes the constraint because the electronics OEM (original equipment manufacturer) might produce the PCB, but they will not combine the PCB with the belt which is like an OEM not installing the PCB into an enclosure. Meanwhile, the copper wires (which also need to be embedded inside belts) end up hanging off the side of the PCB. These wires need to be protected and thus is an implementation challenge for the proposed system.

VIII. FUTURE DEVELOPMENTS

This project is a proof-of-concept that proves cellular signals can be used as a power source for external biosensors. We see this technology being miniaturized into a chip which would be embedded into a variety of devices. This system has a bright future in the world of consumer electronics, personal communication devices, and sensors too as it facilitates the reduced dependence on batteries. In the medical device space specifically, this project could enable many devices to be internal to the user which is currently not possible as batteries need to be changed.

One example of a future medical application is the artificial pancreas which is essentially a closed loop system where an insulin pump and a glucose meter share information back and forth while both system are completely embedded internal to the user. This artificial pancreas would likely be comprised of sensors. Each sensor would be outfitted with our energy harvesting system. Fig. 15 below shows an example of an embedded insulin pump.

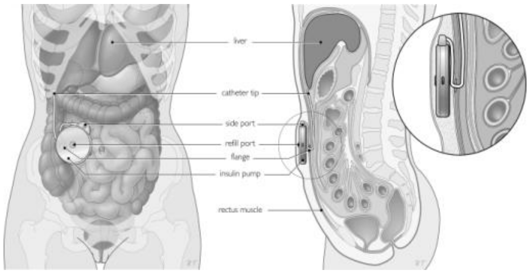


Fig. 15

The mass market applications of RF energy harvesting also allows us to apply this system to a variety of other applications outside medical applications. For example, sensors have been added to many bridges, oil rigs, and buildings. These sensors are being used to measure the strain on these structures to potentially deter a catastrophic event like the one that happened in the Gulf of Mexico in 2010. Each of these sensors are outfitted in remote locations and require either frequent battery changes or very expensive long-lasting batteries. Our system could help power these sensors on buildings and bridges.

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