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Development of Wireless Power Transfer for Body Area Networks

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Development of Wireless Power Transfer for Body Area Networks

THESIS

submitted in partial satisfaction of the requirements
for the degree of

MASTER OF SCIENCE

in Electrical Engineering

by

Abel Jimenez

Thesis Committee:
Professor Peter Tseng, Chair
Professor Fadi Kurdahi
Professor Michael Green

2022

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DEDICATION

Dedicated to my parents and brother for their support over the years and encouragement in continuing my education. This would not have been possible without you my family. Thank you.

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ACKNOWLEDGMENTS

I would like to express my gratitude to Dr. Peter Tseng for accepting me into his lab and allowing me to grow as a researcher. Thanks for allowing me to make mistakes and learn. Without his support and guidance, this thesis would not have been possible.

I would also like to thank my thesis committee, Dr. Fadi Kudahi for introducing me to research, and Dr. Michael Green for being an excellent teacher.

I would like to thank my colleagues and friends Dr. Manik Dautta for guiding and driving me to pursue research, and Amirhossein Hajiaghajani for his help on this paper.

This paper contains work previously published [1] and [13] only the hardware contributions by Abel Jimenez are included in this thesis.

ABSTRACT OF THE THESIS

Low power wireless devices can be placed on human subjects to monitor changes in physiology forming a wireless body area network (WBAN). WBANs allows various sensors to communicate and provide real-time health monitoring without impairing normal activities. In this paper, we investigate the common wireless power standards, Near Field Communication (NFC), Qi, and AirFuel, and compare their specifications for wireless power transmission. These standards were designed to power mobile devices such as smartphones or RFID tags but an update to their protocols could enable their use in WBANs. Here, each standard was modified with a passive intermediate relay (PIR), which extends the range of power transmission and enables the support of multiple nodes from a single source. The designs were optimized to power a network of passive wireless sensors from a single wireless transmitter, overcoming the limitation of a single conventional receiver. Custom transmitters and receivers were developed for each wireless standard and tested for wireless data communication with sensing nodes. This paper covers the hardware and software implementations of the WBANs. All three wireless power standards were successfully adapted extending their range up to 60 cm and enabling support of up to 6 nodes. Future work and limitations of the technologies are also discussed.

INTRODUCTION

Wireless power transfer technology has started to become commonplace in consumer electronics, for good reason as wireless power is more convenient and removes the clutter caused by charging cables. The same advantages garnered in consumer electronics could also be used to advance biomedical devices used in data collection or therapy. Devices without batteries would be more compact, lighter, and more comfortable resulting in a higher quality of patient care [1]. Traditionally sensors implanted into the body had to be designed to be very power efficient to minimize the power usage, limiting the complexity and throughput of the device [2]. In a complex wireless body area network (WBAN) the total amount of devices can be limited by the complications involved with charging each device. By utilizing a wireless multi-nodal passive intermediate relay (PIR) a single source could power an entire network of passive batteryless devices over long distances allowing for greater freedom in developing new sensors.

A WBAN consists of biological sensors placed on different parts of the human body. Each sensor serves a different purpose in monitoring a different physical signal and sends the data wirelessly to a base station for data processing. The base station typical is a computer with greater processing power and will collect data from all devices to monitor human physiology. A WBAN can provide different services such as remote patient monitoring, therapy, biofeedback, or ambient assisted living [3].

Machine learning has become an important field in healthcare epidemiology allowing advancements to be made in understanding how various infectious diseases are acquired, predicting clinical outcomes of diseases, and developing targeted interventions[4]. Large amounts of accurate data are important to continuing to develop machine learning in the medical fields and developing passive wireless body sensors will enable larger amounts of sensors to be used in BANs as well as more power hungry devices and even enable new novel types of sensors not currently possible with battery-powered devices.

Modern smartphones now come equipped with two standards for wireless charging, Near-field communication (NFC) and Qi. NFC's intended use on a smartphone is for low power communication to other nearby devices, enabling technologies like contactless payment using mobile wallets [5]. Qi allows for phones to be charged without the use of a cable, and modern phones can even charge other devices using reverse Qi. A single smartphone could serve as the power source for an entire network of sensors using NFC or Qi. The cutting-edge wireless power transfer technologies utilize higher frequencies to achieve greater efficiency and have looser coupling between antennas. AirFuel is the current frontrunner in high-frequency wireless power technology and promises to replace Qi with a more efficient power transfer and allow for greater spatial freedom. These wireless charging standards could be used to power multiple sensors wirelessly, all with the phones that patients already own. The phone could also serve as the base station for receiving and collecting data from the WBAN.

In this thesis, the different wireless power standards will be covered in detail and examined for use in a WBAN. Then these standards will be implemented for testing and compared to each other. The emphasis of this paper will be on the development of the transmitter and receivers, detailing the design of each system. The paper will cover hardware development, PCB design, firmware development, and testing. To test the systems a set of simple sensor nodes was created and tested on a multinodal PIR. The goal of this thesis was to develop wireless power transmitters and receivers that function utilizing different wireless power transfer standards and to design custom sensor nodes that function over passive intermediate relays.

Chapter 1: Background on Wireless Power Transfer Standards

Near-field Communication

Of three different standards that will be covered in this paper Near-field communication (NFC) is by far the oldest with the standard being approved in December 2003 [5]. NFC was developed by extending radio frequency identification (RFID) and establishing an interface and protocol [5]. The main purpose of NFC is in use with keycards but it has found other uses such as initializing Bluetooth pairing between devices, and payment with smartphones. NFC has a range of 10 cm and typically provides 1mW of power but with stronger readers, more power can be transmitted to the tag.

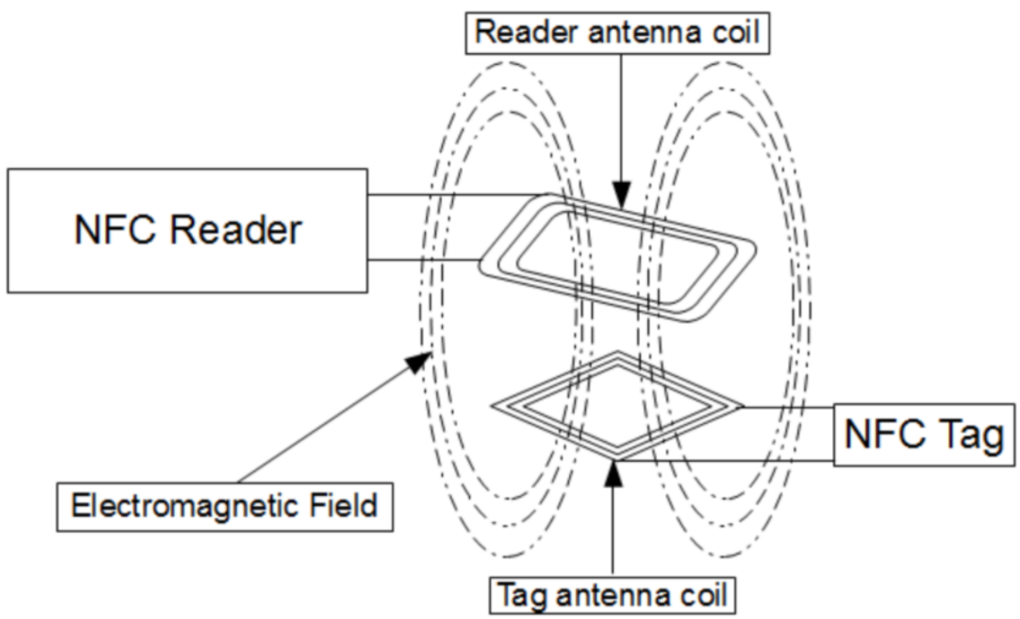

Figure 1.1: NFC Inductive Coupling [5]

NFC utilizes a center frequency of 13.56 MHz and inductively couples the reader to the tag transmitting power and data. The AC signal generated by the reader induces a magnetic field in its antenna coil coupling to a nearby tag as shown in figure 1.1. The tag receives the AC signal through its antenna and rectifies it to create DC power for the device [6]. To transmit data the reader can modulate the signal using amplitude shift key (ASK) modulation and the tag can transmit data back using load modulation [6]. The top data transfer speed of NFC is 424 Kbits as the modulation frequency is 848 kHz. Data is sent using the NFC Data Exchange Format (NDEF), which is made of 4 types of records: text, URI, smart poster, and signature [5]. Large amounts of data can be sent by an array of records called a message.

NFC is the most likely candidate for wireless batteryless sensors as by default it supports passive devices and has built-in data transmission. However, because of the low power rating and low data transfer rate, NFC is better suited for WBAN with a low polling rate and reduced energy consumption. Sensors designed for body temperature, humidity, and galvanic skin response are possible candidates.

Qi Wireless Power Consortium

Qi is the modern standard for wireless charging utilized in smartphones, with the first smartphone with Qi being released in 2011 [7]. Since then adoption has been growing with Qi now being in over 200 million devices and continuing to expand. Qi can be found in desktop chargers, power banks, and embedded charges, such as furniture, automobiles, and public locations [7]. Modern smartphones include reverse Qi enabling phones to charge AirPods and other phones using the same antenna for charging itself. The antennas need to be aligned with less than 6mm to function according to the Qi standard and a range between antennas up to 4 cm[7]. The baseline power profile for Qi sets the total power between 5 and 30 watts. The transmitter and receiver will communicate before power transfer begins and set the power transmitted to the lower end of both devices' abilities. This ensures the system will charge safely at the fastest rate possible.

Like NFC, Qi also transmits power through induction. The carrier frequency can vary from 100 kHz to 300 kHz. One of the methods Qi uses to control the transmitted power is to change the carrier frequency, and another is changing the amplitude of the signal being transmitted. In most situations, the lower end of the frequency is utilized to maximize efficiency [7]. To get optimal efficiency the antenna coils in the transmitter and the receiver should be the same, the coils should be perfectly aligned, the distance between the coils should be less than their diameter, and the antennas should be shielded by ferrite [7]. The transmitter communicates to the receiver by modulating its carrier frequency using frequency-shift keying (FSK). The receiver communicates to the transmitter by modulating its reflected impedance using ASK. Communication is mostly for establishing connections for power transfer but it can also send SSID or Bluetooth link information.

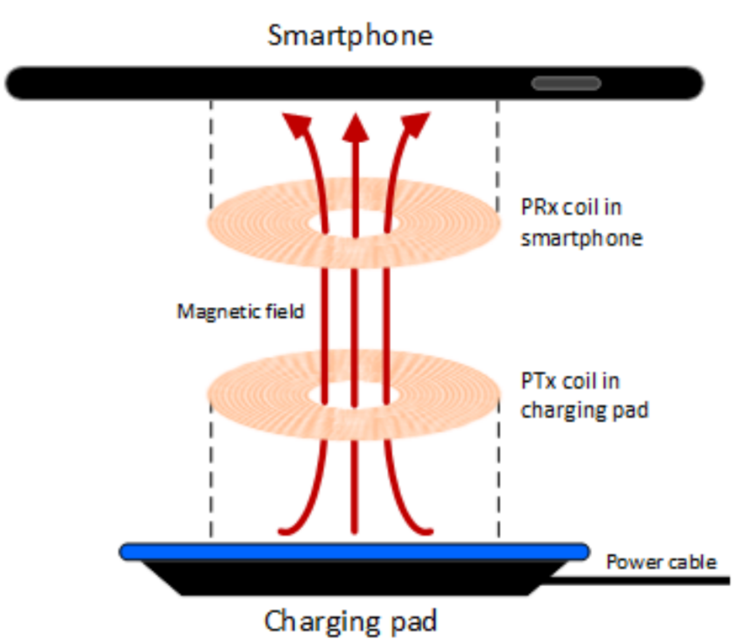

Figure 1.2: Qi Wireless Power Transfer [7]

As the most popular standard for wireless power transfer, Qi is the most tempting target to adapt for WBANs. The greater wattage rating allows for sensors that require more power, and also allows for more sensors to be connected to the batteryless network. Qi has a limited range of 4 cm but in most cases, the Qi is only usable if the antennas are touching otherwise it may not function properly or suffer from low efficiency. Qi in its latest version does not support multiple devices but with some changes to the protocol, Qi could support multinodal device charging, enabling multiple sensors to use the same transmitter to receive power.

AirFuel Alliance

The future of wireless power transfer for mobile devices is being led by standards utilizing the 6.78 MHz as the carrier frequency, such as AirFuel. The main issue with Qi was the poor coupling range and lacked support for multiple receivers. The goal of AirFuel is to solve those issues while improving efficiency and charging speed [9]. AirFuel also attempts to solve another issue with inductive charging, induction will heat metal if in the range of the charger. By increasing the frequency used for transmitting the amount of energy that can be absorbed by the foreign object decreases with the square root in the increase in frequency [10]. This allows for AirFuel chargers to be embedded into furniture, electronics, and other locations not possible before with Qi.

Creating transmitters has become possible in these frequencies thanks to advancements in gallium nitride (GaN) in switching semiconductor electronics. GaNFETs have higher electron mobility with a higher critical field strength compared to silicon. GanFETS also turn on four times faster and turn off two times due to their low input capacitance. With their lower on-resistance, GanFETS have a lower static loss and greater efficiency when in the on state compared to MOSFET [11]. Recent research has been able to develop 6.78 MHz transmitters with efficiencies of 92 percent and overall efficiency of 57 percent over 60 cm at 47W utilizing GaNFETs [12]. Efficient was a major concern in the early stages of development of the standard but thanks to the advancement with GaNFETs the efficiency of AirFuel now exceeds common commercial implementations of Qi.

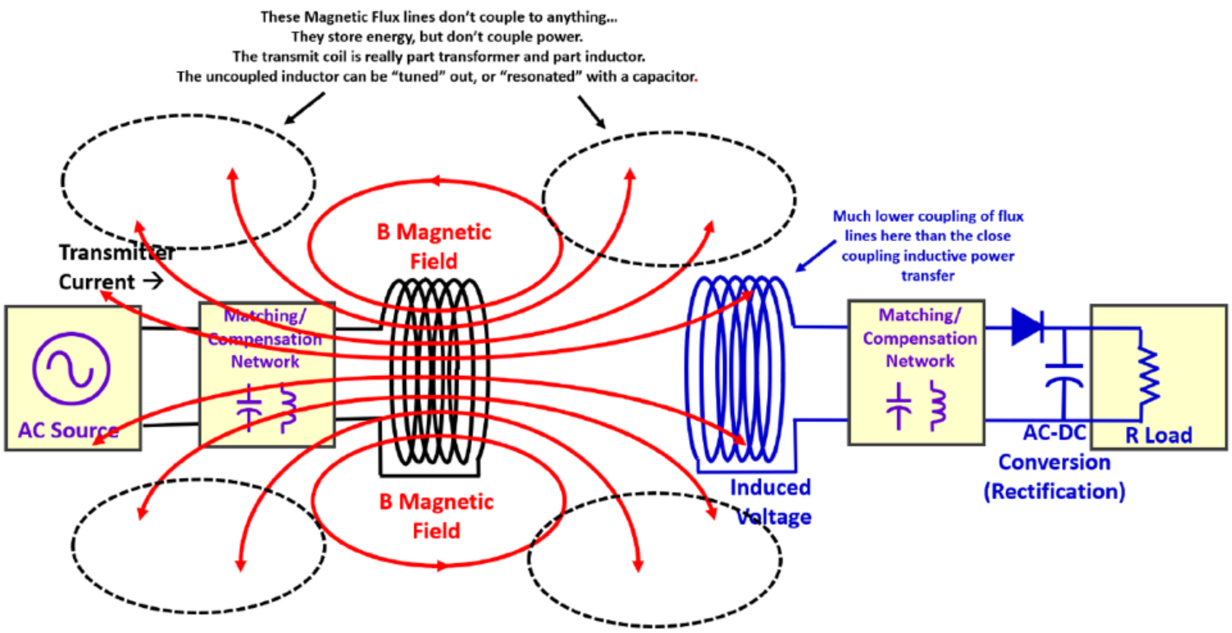

Figure 1.3: Resonant Induction [8]

Airfuel functions using resonant induction charging. As the antenna coils move farther apart magnetic field flux rapidly falls, but using resonance the energy can be "tunneled" instead of radiating omnidirectionally as shown in figure 1.3 [8]. The coupling distance can be greatly increased as well as the total amount of power being transmitted. This will result in lower efficiencies when compared to just induction charging. Resonance induction allows for the receiver and transmitter to have different sizes of the antenna as induction isn't the main source of power.

Instead of communicating through a custom protocol using load or frequency modulation, Airfuel instead adopts the use of communication over Bluetooth low energy (BLE)

[9]. One of the main design goals for AirFuel is to enable the use of multiple receivers from a single transmitter. Load modulation allows for only one device to communicate with the receiver at a time, instead, BLE can communicate with multiple receivers using a mesh or broadcast network.

While there are many advantages to utilizing a higher frequency there are also some disadvantages. GaNfets are new technology and are a magnitude more expensive than conventional silicon MOSFETs. AirFuel is still in its infancy and commercial integrated circuits are currently not available. The higher frequency dictates that Qi will always have an efficiency advantage as long as both are using the same technologies. As frequency increases the resistance of a conductor will also increase due to the skin effect, and current flow will move to the surface of the conductor [8]. Overall AirFuel shows promise to overcome Qi as the standard for wireless power transmission.

Comparison of Technologies

WPT standard	Frequency	Max Range	Average Power	Data Speed
NFC	13.56 Mhz	10 cm	1mW	424 kbits/s
Qi	100 - 300 kHz	4cm	10 W	None for Device
AirFuel	6.78 Mhz	60cm	15 or 50W	None for Device

Table 1: Comparison of WPT Standards

Each of the technologies show promise for power delivery in WBAN. NFC has all the functionality it needs data transfer, multiple device support, and passive device support. The main disadvantages NFC suffers from are its low power delivery and slow data transfer. Qi is the standard for wireless power transfer and can deliver more than enough power for most biomedical devices. It lacks multiple device support and has a power range, requiring a fixed receiver for optimal use. AirFuel has the best range and highest power transmission but lacks support and has yet to penetrate the commercial market. NFC optimal use case would be in a low power WBAN with slow periodic polling, in all other use cases Qi best meets the needs of WBANs until AirFuel reaches maturity.

Chapter 2: Project Description

The goal of this project was to explore the different technologies available for wireless power transfer and adapt them for use in WBANs. This section will cover the scope of the project as well as the process for developing the hardware and software. A sensor device will receive power wirelessly and transmit data to a computer to verify that real-time continuous signals can be sent wirelessly using a PIR.

The system shown in figure 2.1 was developed for each of the three wireless power transfer standards. The system is made up of 3 main components the transmitter module, the PIR, and the receiver module. The transmitter module consists of just the transmitter and the antenna coil. When possible the evaluation boards of transmitters were selected to save time but in some cases, custom solutions were needed to overcome the limitations of the boards or lack of availability. The antenna was designed and tuned to meet the specifications set by the WPT standard.

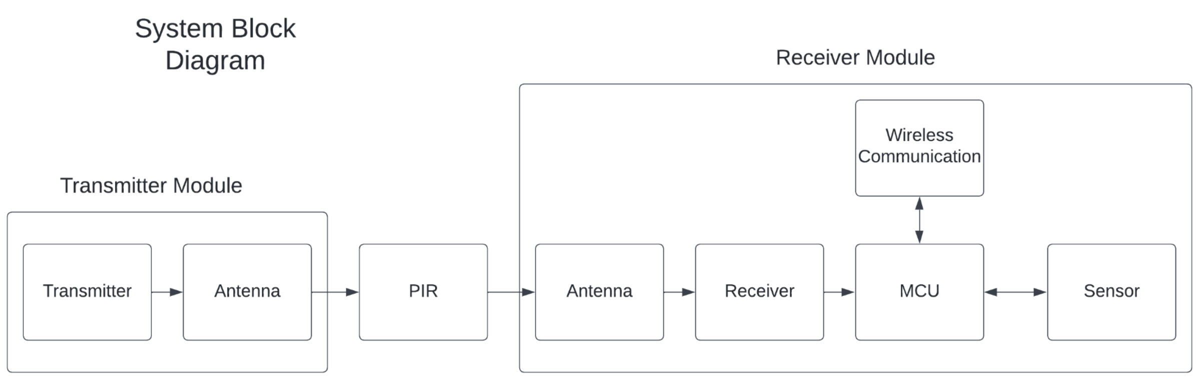

Figure 2.1: System Block Diagram

A passive intermediate relay would be used to carry the power wirelessly farther than intended. The focus of this paper is not on the implementation of the passive intermediate relay and it will only be discussed briefly. The PIR is constructed of copper wire to form an antenna coil, the PIR can be designed in many different forms and even integrated into textiles [13]. The PIR was constructed by soldering receiver antenna coils in parallel with single receiver coil functioning as the source of power. The transmitter is placed on top of the single-coil while the rest of the coils have sensing nodes placed on top. Future work is needed to optimize the design for efficiency and increase the max range of the device.

Each receiver module will have a specially designed microcontroller and sensors setup that is optimized for use with its WPT standard. NFC utilizes the built-in communication using a standard off-the-shelf NFC chip. Qi and AirFuel have no communication built-in for data transfer so instead, they will power a microcontroller that can transmit data over Bluetooth low energy (BLE). Each receiver will require an antenna tuned for the respective frequency of the transmitter module, the antenna will be tuned to the correct resonance frequency using capacitors and verified by a vector network analyzer. The sensor chosen for the receiver module is based on ease of implementation as they are just serving as a proof of concept.

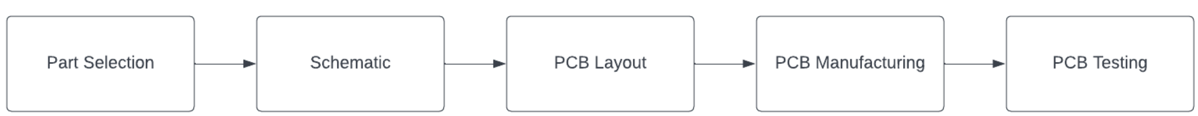

Figure 2.2: Hardware Design Process

The hardware implementation was done using the following design process (figure 2.2). First, the integrated circuits for the hardware were chosen. In normal circumstances, an IC that met most or all of the required specifications would be chosen after compared to other ICs. However, due to supply constraints, this process was flipped, and instead, the ICs were first chosen based on availability, and then the required specifications were set based on currently available selection. Parts would also sell out frequently so the parts chosen would be purchased in large enough quantities to meet the need for the entire duration of the project. Next, the schematic of the devices would be programmed into electronic design automation (EDA) software for designing the printed circuit board (PCB). KiCad was chosen over other EDA software because it is open source and is free to use. Using open-source software should be the default for academic work if possible, as it enables the project files to be shared freely and used in future research. KiCad handles the entire workflow for electronic design from schematic layout to PCB layout to device simulations. The schematic of the device is based on the reference design in the integrated circuits datasheet to speed up development time. Next, the layout for the device is done in KiCad based on the application notes for the device. Other design considerations are ease of access for testing and creating a design that can be soldered by hand for modifications or assembly without complications. When the design is complete and has passed the design rules check then the Gerber files and BOM for the PCB are sent to be fabricated. Complex designs are sent to be assembled as well but most designs are soldered and assembled by hand. After the devices are assembled they are programmed and tested for functionality before they are used to collect experimental data.

Figure 2.3: Software Design Process

The process for designing the device software is as follows. After the active components for the device have been chosen then the architecture of the software can be planned. The architecture contains the components of the software and describes how they will interact with each other. Next, a design based on the architecture describing the finer details in the software will be written. Then when the design has been finalized the software will be written in an IDE of choice. The development is done using Visual Studio Code which has integration for debugging, linting support, and syntax highlighting. After the software is written it is tested on the device for functionality, and most of the time only small changes will need to be made but testing can reveal a design flaw that requires a complete redesign of the software. The flow chart will repeat until the software is fully functional.

Chapter 3: Implementations

Body network NFC

When designing the NFC board, the transponder chip had to meet the following requirements. First, it had to be a compact design with a few extra components as required to function. It had to include a powerful enough microcontroller to compute digital signal processing on sensor data, as well as support i2c and SPI protocol for sensor communication. All of these requirements had to be met in a low power package, supporting the fully passive operation.

The RF430FRL152H meets all of these specifications. It is housed in a 4mm by 4mm VQFN package, and only requires a handful of capacitors to operate. The chip has a 2 MHz 16-bit low-power microcontroller that sips 280 uA and has a eUSCI_B module that supports SPI and i2c. It supports fully passive and battery power mode [15]. The schematic (figure 3.3) was based on the TIDM-RF430-TEMPSENSE, an evaluation board demonstrating a batteryless NFC temperature sensing patch. The design was modified to allow full access to all the IC pins and support i2c as well as analog sensors. The part count was kept as low as possible to keep the price of each board as cheap as possible. Future designs could have benefited from level shift circuitry on the i2c and SPI pins as the microcontroller operate at 1.8 but can provide 3.3V for sensors that require higher voltage using the voltage 2X output pin. A sensor using 3.3V logic would then require a level shift down to 1.8V to function with the RF430 microcontroller. In the current design, this circuitry is required externally and adds additional bulk to the device.

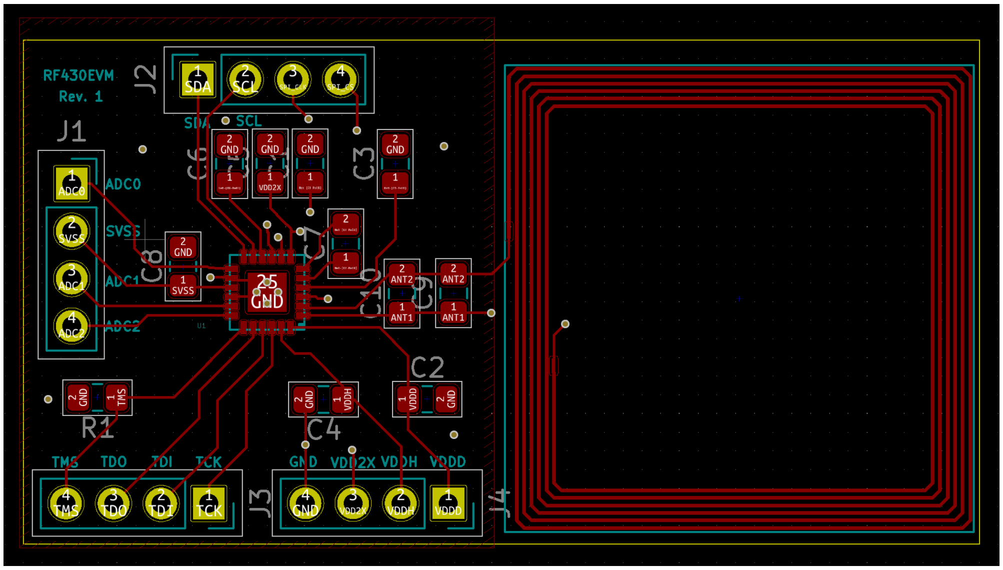

Figure 3.1: NFC Device PCB

The PCB (figure 3.1) was designed to serve as a breakout board for the device, allowing for device pins to be exposed and for sensors to be changed and swapped without soldering. Larger than normal footprints were chosen for the SMD capacitor and resistors to facilitate hand soldering of parts. The antenna was designed based on the equations for the inductance of a square antenna (figure 3.2). With an inner diameter of 25 mm and an inner diameter of 23mm with a PCB trace of 0.2mm the inductance was calculated to be 2.2uH. With a 63 pF capacitor, the resonance frequency would be set to NFC’s 13.56 MHz.

$$L = 2.34\mu_0 N^2 \frac{\frac{d_{out} + d_{in}}{2}}{1 + 2.75\frac{d_{out} - d_{in}}{d_{out} + d_{in}}}$$

Figure 3.2 Square Antenna Inductance [14]

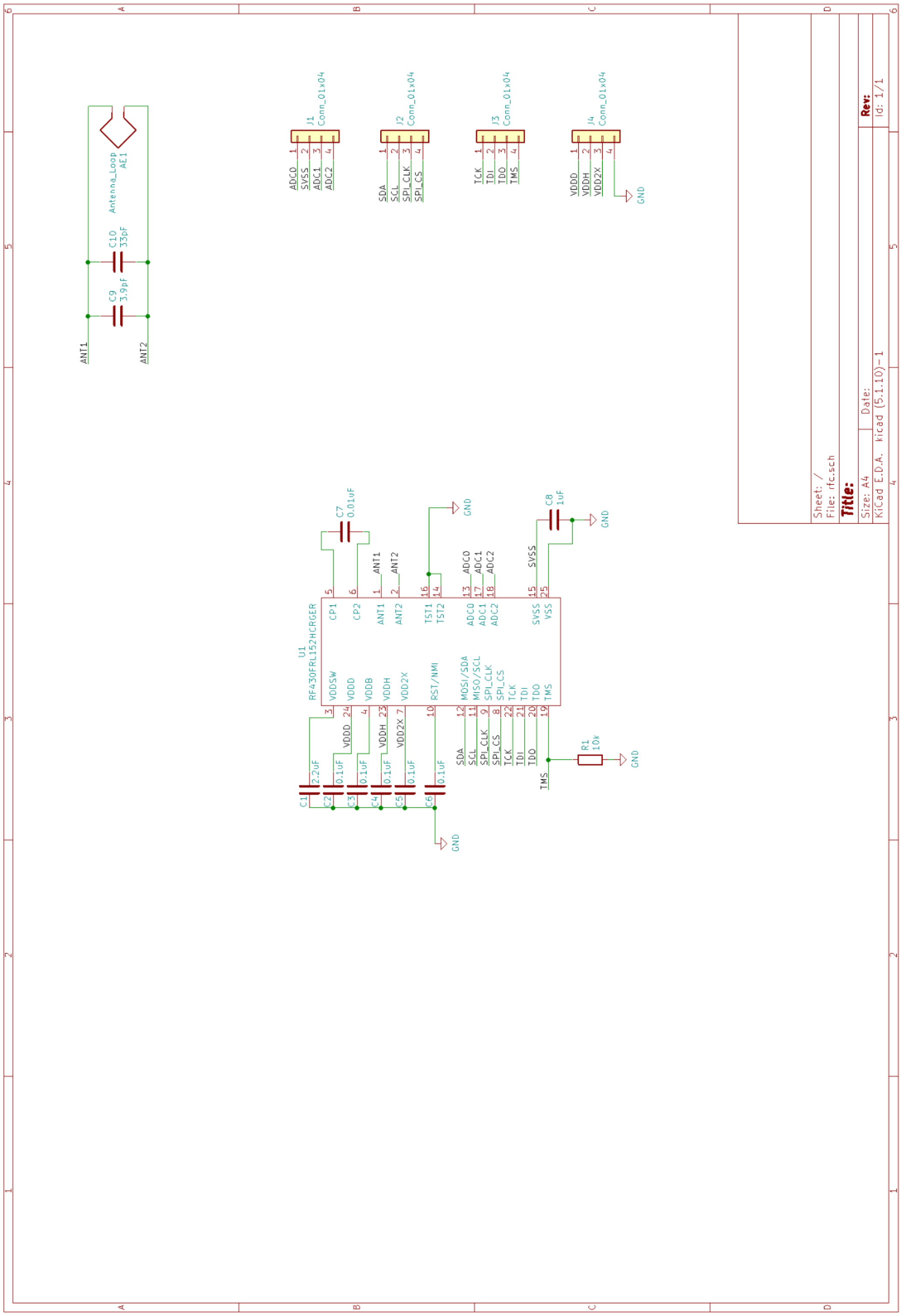

Figure 3.3: NFC Device Schematic

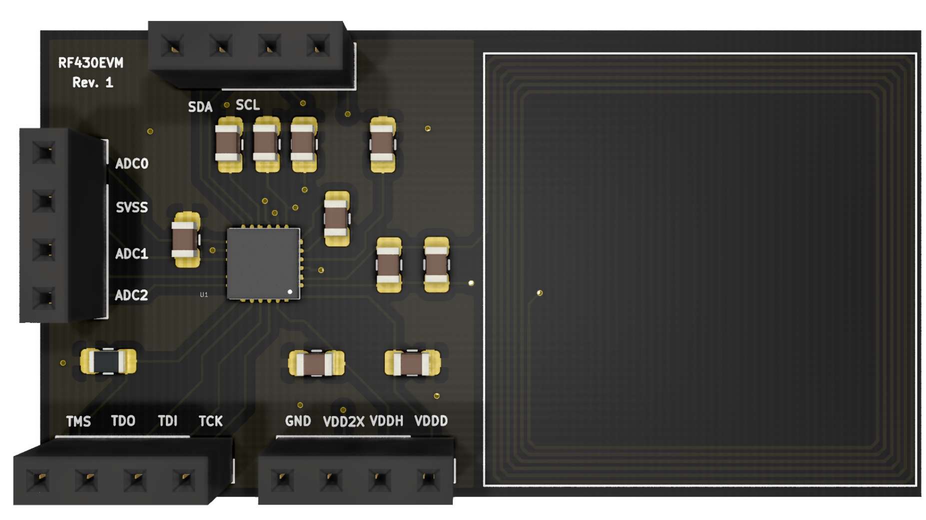

Figure 3.4: NFC Device 3D Model

A few issues in the design were found in testing. The fastest way to program the RF430 is to program its memory using over-the-air updates (OTA), however, when the device disconnects from the NFC transmitter it can result in permanent bricking of the chip. It was also found that incorrect access to system memory could also result in the device becoming unusable. Using the PIR weakened the signal integrity and resulted in an increase in device corruption. Broken devices were repaired by using a hot air rework station and replacing the RF430 ICs. In later revisions of the PCB, this issue was mitigated by changing the antenna design to more closely match the antenna of the PIR, rounded and the same size.

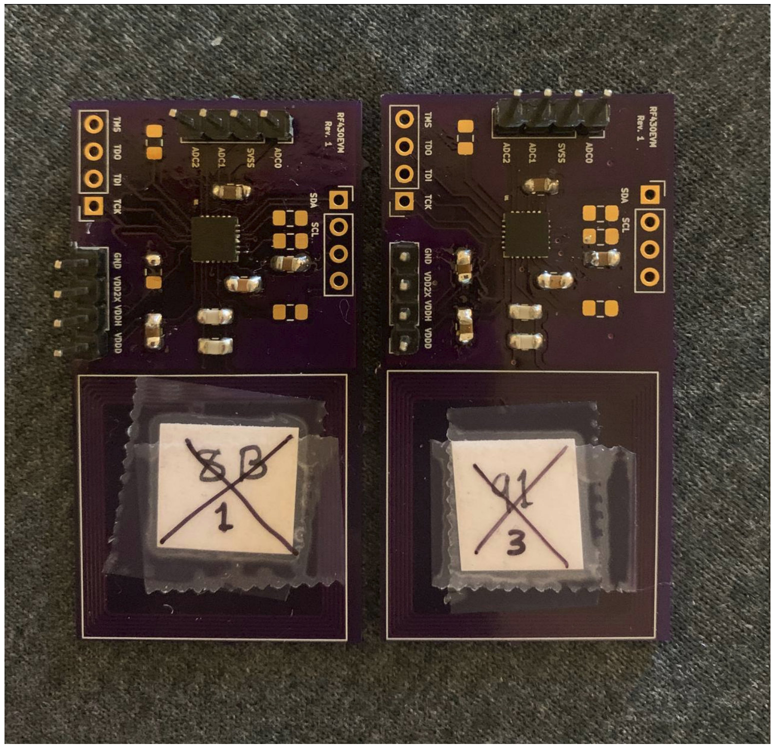

Figure 3.5: Final NFC Device

Programming the device requires a bit more steps than a traditional microcontroller. From a simplified perspective, the RF430 operates as two different devices with access to the same memory, a microcontroller, and an NFC tag as shown in figure 3.6. The microcontroller runs a simple loop and will carry out functions based on the flags selected in the CS block memory. Data collected will automatically be saved into the memory based on how the internal counter of the device. The data can be accessed by communicating with the tag through NFC. First, the internal device counter must be accessed from memory using a read command. Based on the device counter the location of the data in memory can be calculated. Another read command is used to access the data that was collected. One limitation of the RF430 is only one 16-bit integer can be collected per cycle per function. The call for I2C and analog read-only returns one integer at a time. This issue can be overcome by storing to memory directly instead of passing to a function but extra manipulation of the device's internal flags is required to ensure the data is not overwritten.

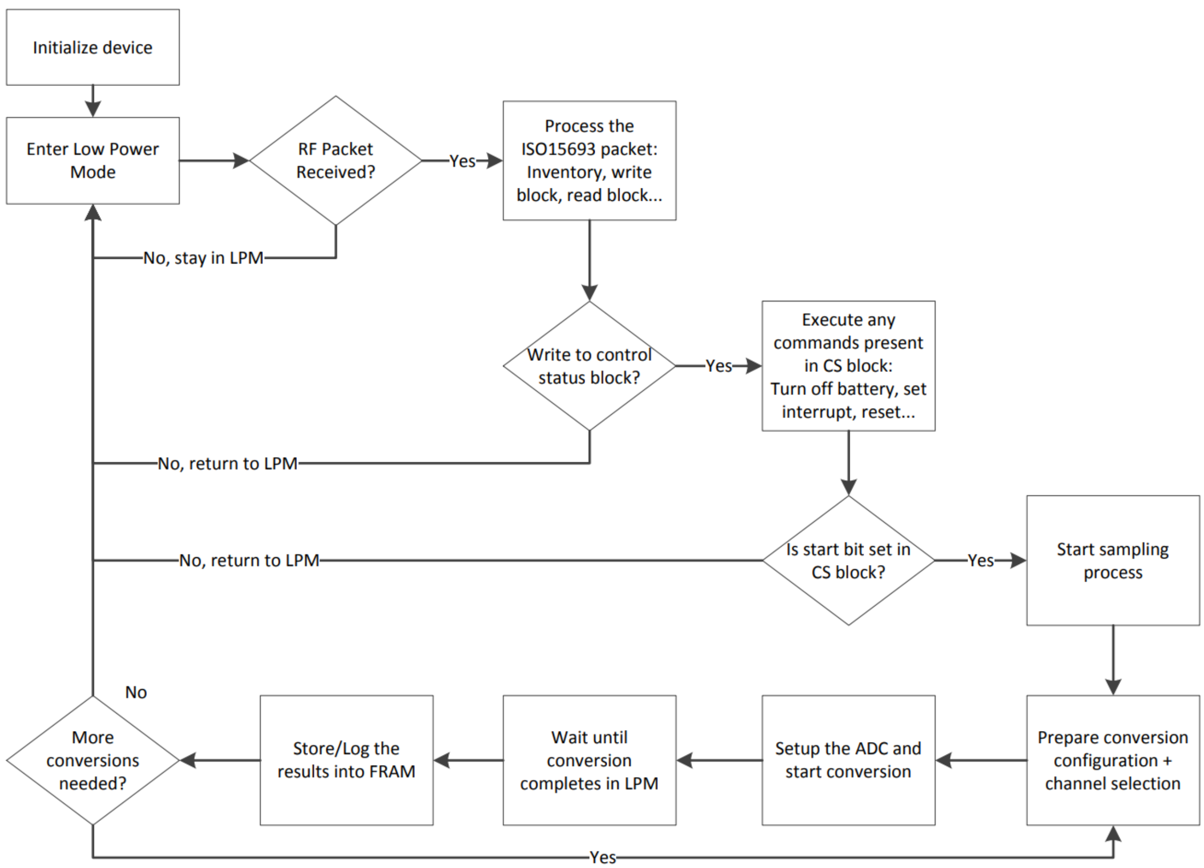

Figure 3.6: RF430 Firmware Flow

The NFC transmitter used was the TRF7970A evaluation board mounted on the MSP430G2553 for debugging purposes. The TRF7970A has a programmable output power from 100 to 200 mW and integrated protocol handling for ISO/IEC 15693, 18000-3, and 14443. The TRF7970A can eliminate read holes thanks to its dual receiver architecture that maximize communication robustness. The MSP430 was connected to a windows computer using TI's graphical user interface (GUI). The GUI allows for the program code for the RF430 to be uploaded wirelessly using the over the air (OTA) update function. Data collected by the transponder can be displayed on graphs by the software.

The main sensors used for testing were an Adafruit analog strain sensor and a CTTS-203856-S02 temperature sensor. The strain sensor was used to measure knee/ankle bending during activities. A strain sensor is ideal for use with NFC because it requires low power and will still function correctly at many different sample rates. A temperature sensor is also optimal for NFC because the sample rate can be low and requires low power. The temperature sensor measures the change in temperature of the human skin. The sensors chosen need to use less power than 100 mW and the function will poll rates less than 32 Hz.

Body Network Qi

The implementation of a Qi wireless transmitter and receiver was done in two ways. The first method was to repurpose off-the-shelf Qi transmitters and receivers (figure 3.7), allowing for quick testing and minimal development time. However, unlike NFC which lacks Foreign Object Detection (FOD), Qi will detect the presence of metal disrupting transmission. FOD in Qi is handled by two mechanisms, monitoring power loss and the change in the quality factor. The receiver reports how much power it is receiving and reports back to the transmitter. The transmitter then calculates the total loss of power and will shut off if it measures a power level below the value set in the standard. This turned out to be a major issue with the PIR as adding it to the loop would cause a decrease in efficiency triggering an automatic shut-off of the transmitter. Quality factor detection is not an issue as the PIR does not cause fluctuations and will stay constant as long as the position of the devices remains stable.

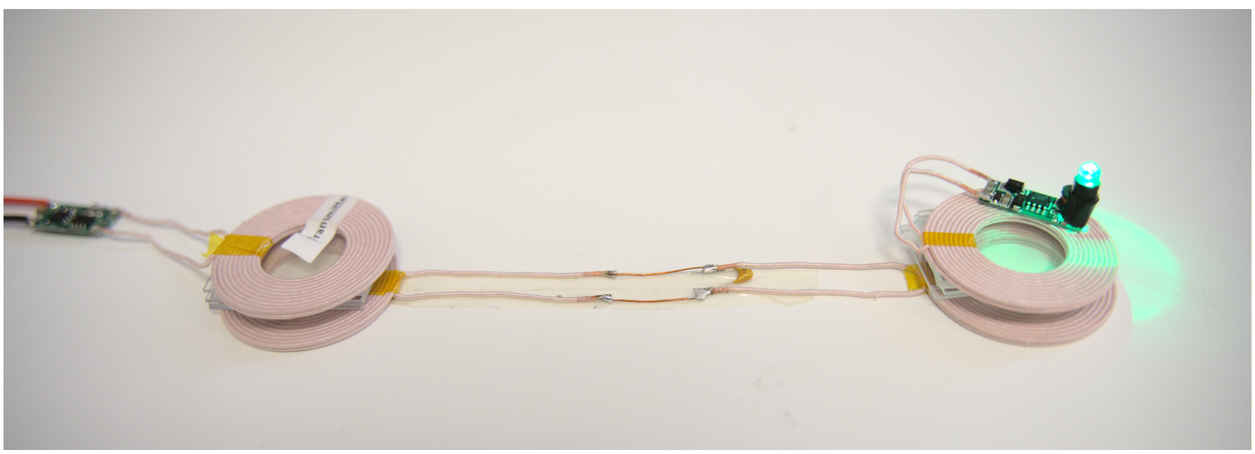

Figure 3.7: Qi PIR Test

To overcome the issues with power loss a separate non-Qi compliant transmitter and receiver were designed. The transmitter would operate in the same frequency region of 140 kHz while having non of the foreign object detection preventing the devices from working with the PIR. In a future update of the Qi standard, a new function allowing for variable loss set by the receivers would allow for the technology to be used without modifications. A class E amplifier was designed based on the equation derived from Nathans Sokal's work on radio frequency amplifiers. Class E amplifiers achieve higher efficiency compared to conventional Class B or Class C amplifiers by a factor of about 2.3 [16]. Class E amplifiers only have the MOSFET switched on when there is no voltage across the device eliminating switching loss. Using the equations seen in figure 3.9 the required values for the inductors and capacitors were calculated.

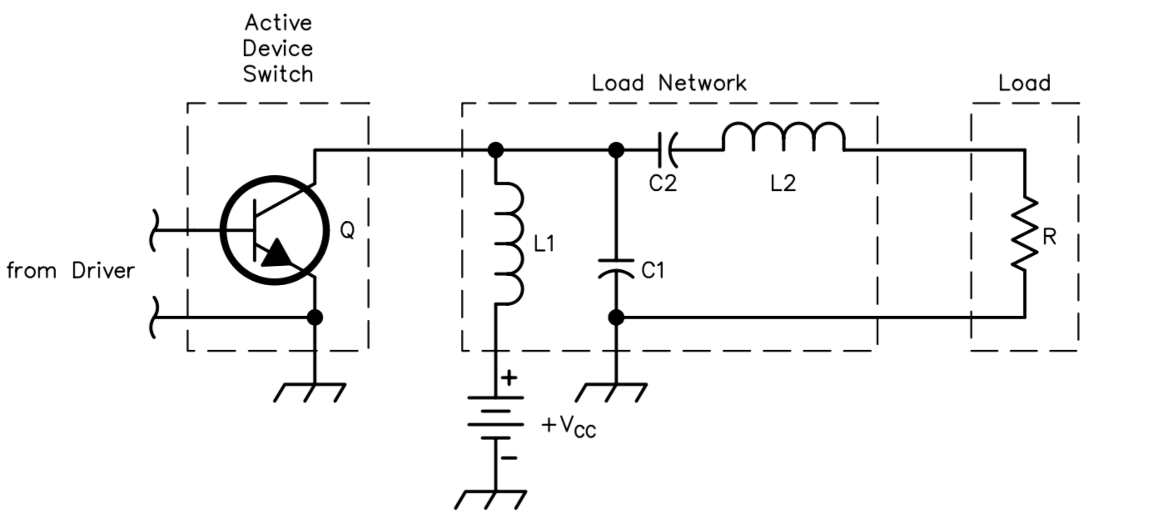

Figure 3.8: Class E Amplifier Schematic

$$R=\left(\frac{(V_{CC}-V_o)^2}{P}\right)0.576801\left(1.0000086-\frac{0.414395}{Q_L}-\frac{0.577501}{Q_L{}^2}+\frac{0.205967}{Q_L{}^3}\right)$$

$$C1=\frac{1}{34.2219\,f\,R}\left(0.99866+\frac{0.91424}{Q_L}-\frac{1.03175}{Q_L{}^2}\right)+\frac{0.6}{(2\pi\,f)^2\,L1}$$

$$C2=\frac{1}{2\pi\,f\,R}\left(\frac{1}{Q_L-0.104823}\right)\left(1.00121+\frac{1.01468}{Q_L-1.7879}\right)-\frac{0.2}{(2\pi f)^2\,L1}$$

$$L2=\frac{Q_L\,R}{2\pi\,f}$$

Figure 3.9: General Class E Equation

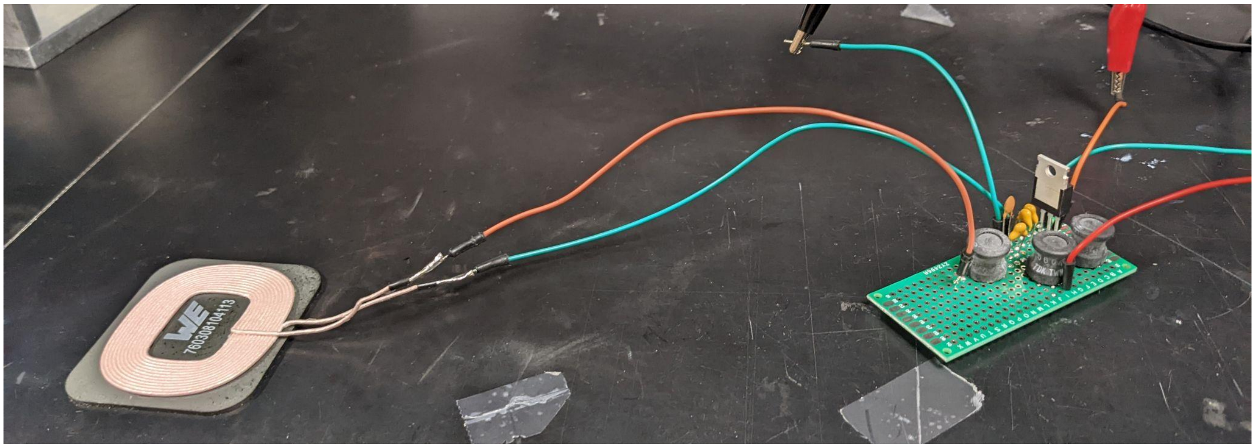

Figure 3.10: Class E Amplifier on Protoboard

The Qi receiver was implemented using as shown in figure 3.11. An antenna is connected to an array of tunning capacitors to set the resonant frequency to the desired 140 kHz. There is then a fuse for protecting the device from power spikes, a 500mA fuse was chosen to allow for many sensors to be connected to the device while still being safely under the power limitations of the circuit. Then a classic full bridge rectifier converts the signal from AC to DC. The rectifier is made up of 4 SD0805S020S1R0 diodes, this diode was chosen for its high current capability of 1A and its ability to be used in high-speed rectification. As well as its having a DC reverse voltage of 20V all in an 0805 package. Analog Devices LT117CST was chosen because the 3.3V and 5V versions of the chip are footprint compatible and it has a large input voltage of 15V. A large input voltage was needed to compensate for the power fluctuations as the antenna moves it can encounter higher voltages in an optimal transfer spot. The output of this device connects to standard Dupont cables.

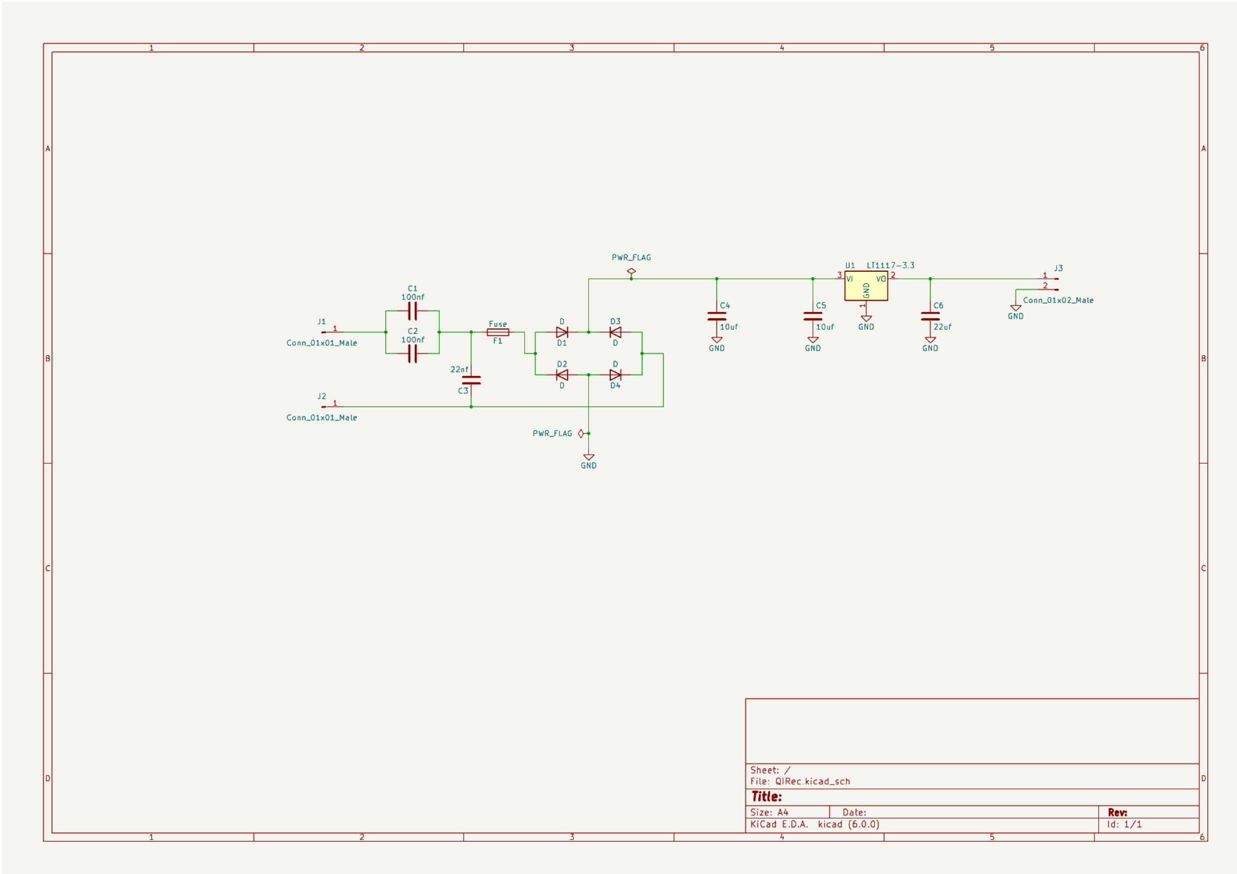

Figure 3.11: Qi Receiver Schematic

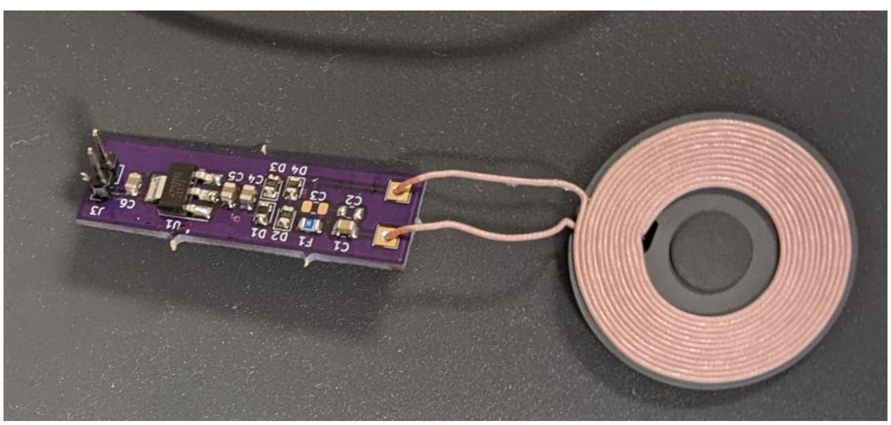

Figure 3.12: Qi Receiver

The device used for testing is the ESP32 microcontroller board running custom firmware. The ESP32 was chosen due to its large community support and built-in support of Bluetooth and

Wifi. An ADXL345 accelerometer was connected to the microcontroller using i2c. The ADXL345 was chosen because it is common availability, has high accuracy, and has low power consumption. The system is shown in figure 3.13. A smartphone Bluetooth application was developed to show the proof of concept, a network of sensors could be powered via reverse Qi on a smartphone. The sensors could then send their data to a smartphone for processing and data collection..

Fig. 3.13: PIR with Device

Body Network Airfuel

Airfuel is still in its infancy and development boards are not readily available so instead a transmitter and receiver using the same carrier frequency was used. For developing a system utilizing 6.78 MHz, an off-the-shelf transmitter from GAN Systems was utilized. The GSWP300W-EVBPA, shown in figure 3.14, was developed with wireless power transfer in mind and requires no external parts except for a bench power supply. The 300W rating is much higher than was required by the project but it was selected to have overhead so experiments with longer PIR with low efficiency would be possible.

Figure 3.14: GSWP300W-EVBPA

The same receiver (figure 3.12) developed for the Qi systems was modified to work at 6.78 Mhz. An antenna with a smaller inductance and different tuning capacitors had to be used to to increase the resonant frequency of the receiver from 140 kHz to 6.78 MHz.

The rest of the circuit remained unchanged as the diodes could still operate at higher frequencies without any issues.

Chapter 4: RESULTS AND DISCUSSION

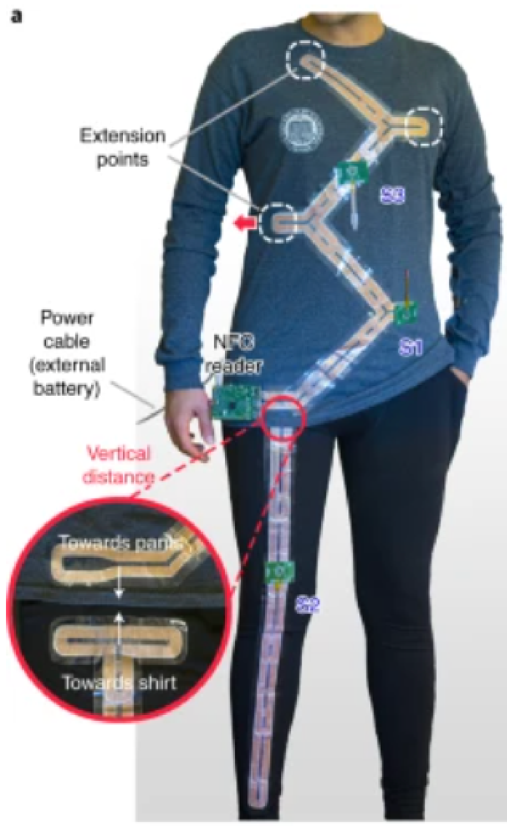

Figure 4.1: NFC WBAN [13]

Using the WBAN a sample rate of 32 Hz was able to be achieved with 6 sensors sharing the bandwidth at 5.6 Hz per sensor. The sensing nodes could be moved as far as 1m away from the NFC reader. When tested with a smartphone as the NFC reader the output power was not enough to support more than one device on the PIR. To test the network an indoor walk and run activity validation using sensors on the knee and ankles was performed [13]. Data was successfully transmitted and the test subjects' movements were correctly captured. It was demonstrated that NFC could be modified for use with a PIR potentially allowing for integration into textiles.

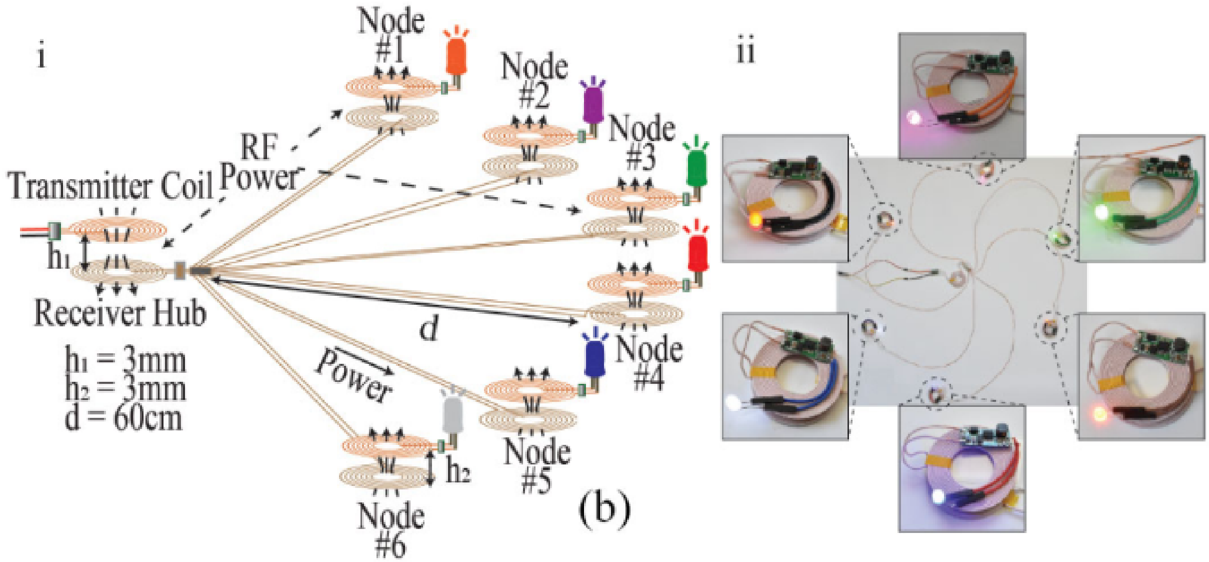

Figure 4.2 Qi WBAN [1]

Adding a PIR allowed for some of the traditional limitations imposed by conventional batteryless WBANS to be overcome. Using the single transmitter with a PIR allows for up to 12 sensors and 6 device nodes to be connected by a maximum distance of 60 cm. A sample rate of 20 Hz was achieved but this was a limitation of the sampling rate of the microcontroller use a more powerful MCU would allow the network to properly saturate the 2 Mbps of BLE. BLE allows for many more sensors to be connected when compared to the NFC implementation. Qi can deliver up to 75 times more power than NFC allowing for greater freedom of choice when it comes to sensors and microcontrollers. Both systems are induction-based and required the antennas to be placed close together.

AirFuel is resonance-based and when testing the system it was found to have 10 times the range and 3 times the spatial freedom for antenna placement. When compared to Qi the only downsides were the much greater cost to implement and the theoretical lower efficiency. In practice we found the efficiency to be comparable to each other.

Chapter 5: Future work

Testing and developing the design revealed the current limitations of the system that could be further developed. The main issue is the inability to control the nodes receiving power from the body network. The obvious solution to overcome this issue is to create active relays with the ability to disconnect and reconnect themselves from the network. Designing the PIR with an active switch would require a MOSFET or GaNFET with a low on-resistance as adding a transistor switch would greatly increase the loss contributed by the relay. The switching transistor would also need to be able to sustain enough wattage for multiple sensors and have a large enough bandwidth to account for the 6.78 MHz. The relay would require a redesign to account for the extra capacitance added by the switching mechanism. A system to communicate between the relays and the transmitter would need to be robust enough to handle disconnects from the network and have safety features built in to protect the user and the network. Bluetooth low energy can be used to communicate as it requires little power and supports data broadcast, allowing for the transmitter to communicate with many receivers at the same time.

The current design of the PIR served more as an initial design and was not optimized for efficiency. Future design simulates the design of the PIR to optimally deliver power over long distances to increase efficiency. Alignment issues should take into consideration to improve performance as well. A possible fix is including magnets so antennas can lock together in the optimal location while still providing freedom of sensor placement. The current design does not handle short misalignment gracefully due to the lack of a battery, by adding a supercapacitor to the design short disconnects would not result in device failure. Supercapacitors have a high power density, can charge up quickly, and have a longer life cycle than batteries making them ideal for use as temporary backup power.

The current design of the rectifier is a simple full bridge rectifier but to create an optimal system the design could be improved by using active rectification. The efficiency of the rectifier can be improved by using a frequency synchronous rectifier. A frequency synchronous rectifier can reduce the switching loss and therefore increase the efficiency of [18]. FET Devices also have a lower on-resistance and voltage drop than diodes which increases the efficiency of the rectifier. Increasing the efficiency of the network is important for increasing the usability of the device for longer periods of data collection.

There are other promising wireless power transfer technologies that are not induction based could also be used in WBANs. Capacitive power transfer does not use magnetic fields and instead transmits power from one electrode to another using an electric field. The main advantage would be the reduce electromagnetic radiation. Another possible technology uses ultrasound charging, power is transmitted and received by ultrasonic transducers the main advantage is the ability to transfer through liquids and metals which is ideal for medical implants. These technologies are not as efficient as induction-based charging but still show enough promise to deserve more research and development.

Chapter 6: Conclusion

Wireless Body Area Networks allow for greater mobility, smaller device, and a large number of sensors. The main focus of this paper was the development of the transmitter and receivers utilizing different wireless power transfer technologies. Three different technologies were explored NFC, Qi, and AirFuel. Each technology was explored in detail and the advantages and disadvantages of each standard were discussed. NFC lacked power and data throughput but still showed viability when paired with low power low-frequency sensor. Qi showed the most promise as it is the standard of wireless power transmission. Its 15W of maximum power when paired with BLE's 2 Mbps data transfer can meet the requirements of all WBANs. Its one flaw is its short range which AirFuel attempts to address. AirFuel improves upon Qi with greater power, greater range, and looser coupling. This thesis successfully demonstrates the use of 3 different wireless power transfer standards in a multinodal passive body area network.

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