RFRD
Radio Frequency Readout Device

DESIGN DOCUMENT

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1 Introduction

1.1 Project statement

The goal of this project is to develop an RF sensor system that can read a capacitance value from a passive tag from at least five meters away. In an acronym, the goal of our project is to develop a Radio Frequency Readout Device (RFRD); we will be using a capacitance sensor for the first sensor build.

1.2 Purpose

This project, in just the application for which we designed it, allows us to take a capacitance measurement from a distance. For two metal plates of constant material between them, a capacitance measurement is essentially a distance measurement - so anywhere this tag is implanted would let us gauge the distance between two metal plates - potentially useful for nondestructive evaluation of any construction. The specific application will be connecting an RF tag to each of the bolts on a street-side light post that will include eight capacitance sensors each that can be used to determine whether the bolts are tight or loose.

Going past merely measuring capacitances, this tag will let us transmit information given any transducer capable of generating a series of digital voltages to correspond to a value.

1.3 Goals

Measure capacitance from at least five meters using an IC prototype that will harvest RF energy from a reader to power a capacitance sensor and transmit said data back to the reader. The reader will subsequently transmit this data to either a smartphone or a computer, which will upload the data to the cloud when available.

2 Deliverables

The goal of the first semester is to have a functional lab-ready prototype device that serves as a proof of concept for each of the subsystems in the project as well as the overall system. By semester's end, we intend to have:

- A prototype, custom circuit capable of transmitting static data
- A prototype reader that is capable of accepting data from a tag.
- A website containing information and documents regarding our project

By the end of the project next semester, we intend to have:

- A batteryless system capable of receiving and sending a signal, consisting of:
    - A custom RFID circuit capable of transmitting capacitance data
    - A reader that is able to receive tag data and transmit received data to an external source
    - Software capable of storing captured data both locally and in the cloud

3 Design

3.1 System specifications

3.1.1 Non-functional

- IC
  - The RFRD tag must cost less than 50¢.
  - The tag size should be limited to the scale of millimeters, but is less crucial than cost considerations.
- Reader
  - The size of the reader is inconsequential.
  - The reader does not need to be battery-powered.
  - The cost of the reader is negligible compared to the cost of the tag.
- Antenna
  - Transmitting antenna should be a manageable size (should not need to be carted around, for example)
  - Receiving antenna should be appropriately durable and small enough to fit in its application.

3.1.2 Functional

- IC
  - The tag needs to be passive. It must harvest all of its power from the incoming signal from the reader.
  - Tags must include an antenna for signal reception/transmission.
  - Tags must include identification data in the form of nonvolatile memory that can be utilized to uniquely differentiate the tags for each of the bolts on a light post.
  - Capacitance sensors need to be able to determine whether the bolt is 'tight' or 'loose' (will readout a '0' for tight or a '1' for loose).
- Reader
  - The RFRD reader must be able to successfully retrieve capacitance data, from the RFRD tag at a minimum distance of 5 meters.
  - The reader should transmit and receive a signal with carrier frequency of 13.56 MHz for the purpose of testing and possibly 900 MHz for the final product in which the capacitance and identification data for each tag will be embedded.
  - The reader must be able to receive the incoming signal from each tag, capture the corresponding capacitance data, and identify which tags are linked with loose/tight bolts.
- Antenna
  - Receiving antenna must capture enough power to be able to drive every subsystem of the tag. This may require the transmitting antenna to be able to handle an especially large input power, given the 5 m target distance of the application.

3.2 PROPOSED DESIGN/METHOD

For the tag part of the project, we have designed our capacitance readout to be run into a bit string via cascaded multiplexers. The bit string is divided into four sections: start, ID, sensor data, and end. The multiplexer will step through the bit string and send the bits to the modulator, cycling through repeatedly while powered. The sensor circuit will consist of an array of capacitors, which will be charged, read into the multiplexor, and discharged before repeating the cycle.

For the reader portion of the project, we have undergone several design and method changes as the requirements of the project have been defined and as we've learned more about the limitations of the methods that we had chose. Initially, we were planning to move forward with using a 900 MHz band RF radio paired with a Raspberry Pi 3 to store and transmit the data between a smartphone or other data source. However, as we did more research into that particular radio band, we discovered that the radios that would support it, as well as the SDKs for the devices, are very costly and the documentation available is very limited, which doesn't tell us if the radios could do what we need them to.

Recently, we have decided to switch to using the 13.56MHz band for communication, which has cheaper, more readily available radios to work with and will allow us to test things easily as we can easily find testing equipment that works with the RF band. Unfortunately, most radios available for this band have very low range (<1m in general), so, instead of purchasing a radio and modifying the hardware right now, we have decided to build an Arduino-based 13.56MHz radio for our uses, which will give us more flexibility in how we transmit power and receive signals and will be cheaper to work with. We are still deciding how the reader will interface with a computer/smartphone and send data to the cloud.

3.3 DESIGN ANALYSIS

For the reader portion of the project, we are currently still working to obtain the parts to build the reader. Once we have the parts available, we will build the unit and test if the design we have come up with works properly by seeing if it is able to send out power and receive data from a known working RFID tag. If it doesn't work, we will continue to revise until the design does work. If it does work, we will begin working to see if we're able to read the custom IC that we are designing.

For the tag team, we have prototyped and tested some power harvesting circuitry to see how much power the system could harvest at various input levels. Our initial test showed that we were unable to drive the circuitry with a typical input voltage. As a result, we began looking into some lower threshold voltage diodes as an option to replace our standard ones in our discrete prototype. For our logic design, we originally thought of having a long string of D flip flops to pass the data to the antenna; however, this idea would have had a lot of dynamic power usage and taken a lot of area. We then decided to switch to a giant (64 bit) multiplexer for our logic. The advantages of this design is that we save area by eliminating the DFFs in the start and end signals by tying them to VDD and ground. We also save power because we eliminated the DFF which means less transistors transitioning between high and low states.

4 Testing/Development

4.1 INTERFACE specifications

The hardware from the IC tag will communicate via RF signals with a reader. The reader will interpret the RF signals and display something to the user to convey whether the washer is tight or loose. The layout and design of the project are pretty open ended.

The antenna communication aspect is entirely in the hardware. Any software used is just there for simulation; and the two do not interact with each other.

4.2 Hardware/software

For our project, we are using two different methods to test and design our circuit. The first method is prototyping on a breadboard using discrete components. Our primary goal for this semester is to get the breadboard or perfboard design tested and functioning as expected. This allows us to make sure that the logic and design concepts are working as expected. It also allows us to test our antennas to see how much power output can be transmitted at different distances. However, it will not be representative of the power consumption of our final IC design.

The other method that we are using is Cadence to simulate the various components. Using Cadence allows us to see a more precise value for the power consumption that the circuit will use. It also helps us to determine the area that the IC will consume.

For the antenna communication task, hardware includes electrical components and the tools for making them that interact with each other, from the soldering iron to the function generator. As stated above software exists for faster simulation, testing, and calculation - for example, to compute the input impedance of any antenna given its geometry.

4.3 Process

For the reader team, our original idea was to buy a programmable module. However, the module was $700, and we decided to work at the cheaper 13.56 MHz frequency instead of testing at the more expensive frequency range. This led us to search for modules at the new frequency range; however, most of them could only work at very small distances. Therefore, we decided to design our own module based off of a collection of various chips.

For the tag team, we started with building a standard full bridge rectifier and DC - DC boost circuit to be able to operate an IC and sensor. We also built an initial modulator circuit to send data back to the reader. The next step was to design an IC capable of measuring capacitance and sending data bits to the modulator. We are working with the antenna team to collect power from the reader via RF, and power the IC with the boost circuit. We are also working with the reader team to develop an IC which will send readable data to their reader.

On the antenna team, testing started from the absolute simplest level possible. We started with two breadboards sitting face to face, each with a (relative to lambda for 13.56 MHz) infinitesimal dipole. We connected the function generator to the first antenna and the oscilloscope probe to the second antenna. From here we experimented with further variables of the geometry involved, and with extra circuitry such as the full-wave rectifier attached to the receiver antenna. We now have enough hands-on familiarity with the problem at hand to start making the solution more complicated and workable, for example, determining antenna input impedance to test with an impedance match.

5 Results

(Mehdy, 11/3) On the task of working with the antennas, I found a ~350 mV_{pp} amplitude on the receiving end when I had a function generator connected to a small dipole. This was with the transmitting and receiving antennas ~1 cm apart from each other. I think this dismal result is the result of lack of impedance matching components plus usage of short antennas. Success in testing then, for me, depends on usage of matching networks and longer antennas. I can also use HFSS to simulate the antennas I design so that I get an accurate calculation of their impedance - using that input impedance I can design the matching network I want to transform that impedance. My first move from here is going to be breadboarding a wide variety of longer antennas, possibly in arrays, to experiment with their effectiveness.

(Mehdy, 11/6) While working with the antennas further, I found that increasing antenna length increased received voltage amplitude by about 10%. I then soldered some of my kit's long wires together and bent the geometry into a square spiral shape for both the transmitting and receiving antennas. This gave me a 2.28 V_{pp} signal at the receiver with 10 V_{pp} input into the transmitter - a very encouraging improvement, over six times the received amplitude with 10 V_{pp} into the single infinitesimal dipole antenna.

After hooking up the full-wave rectifier circuit and capacitor, however, we saw ~40% drop in voltage magnitude at the antenna port, and the signal at the capacitor was absolutely not DC. There may be some properties of the diodes that I'm working with that prevents proper AC to DC rectification of high frequency signals. Worth noting is that 125 kHz, being two orders of magnitude lower in frequency than 13.56 MHz, is significantly more amiable to rectification than 13.56 MHz with the diodes I have. This is just a question of parasitics, which may themselves be amplified because I'm testing on a breadboard. I did find that the peak to peak range of voltage at the output of the rectifier at 125 kHz input was 127.5 mV_{pp} (for 5 V_{pp} directly into rectifier) while the range for the 13.5 MHz input is 222.5 mV_{pp} (for 5 V_{pp} directly into rectifier).

One further question is impedance matching. I need to match the transmitting antenna to the function generator, and I need to match the receiving antenna to the full-wave rectifier circuit. The latter requires me to know at minimum how the presence of diodes affects input impedance. Both require me to use some abstracted method of calculating antenna input impedance. If I'm not able to use HFSS (the usage of which does present its own challenges), I haven't ruled out the option of writing my own Moment Method script using the Balanis text. Developing an abstract means of quickly calculating input impedance for my square coil is a critical next step, and that's what I'm researching right now.

6 Conclusions

On the antenna task, we have communication: A signal from the function generator can result in a signal on the tag end. The square loop antenna design looks to be one of the best for the job. However, there is not enough range, and not enough rectification to an appropriate DC signal. The next step towards optimizing the communications is going to be developing an abstracted, quick method of calculating antenna input impedance using Moment Method. This entails either using existing software or writing the algorithm from scratch - so impedance matches can be implemented on the transmitting and receiving sides of the system.

On the reader team, we are still working to get the parts for our reader ordered and the prototype reader assembled. By the end of the semester, our goal is to have the reader be able to communicate with the prototype version of the tag so that testing can be accomplished on both sides. We find it necessary to build a reader from scratch as none of the 13.56 MHz radios that we could find had external antenna connections and the built-in antennas had far too low of a range to be useful for our testing.

On the tag team, we are working with the antenna team to get power through to our IC circuit. While our main goal is building the IC circuit to test the measuring capabilities. At this point, we have some promising results from simulation testing of the sensor circuit.

7 References

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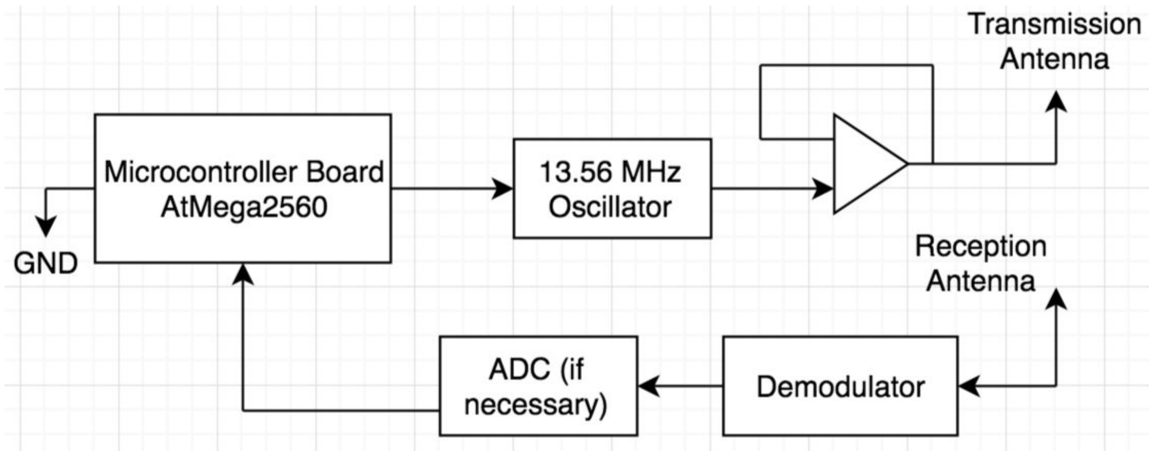
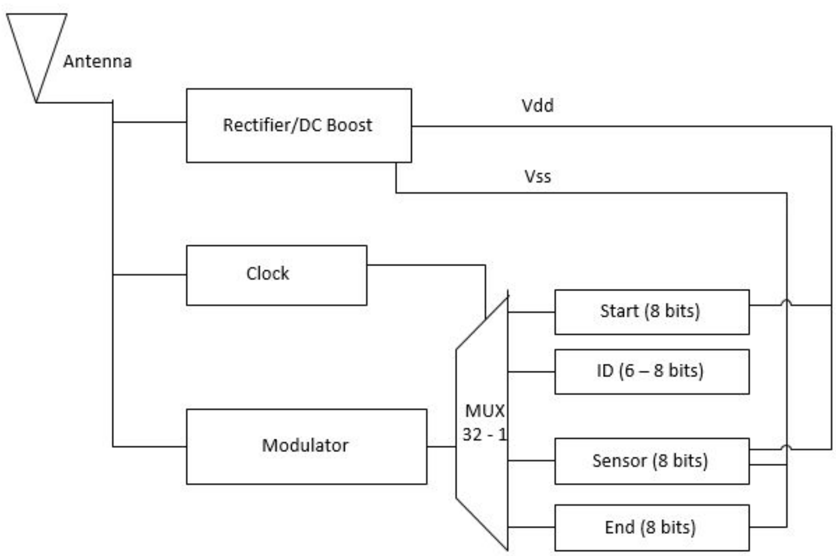
8 Appendices

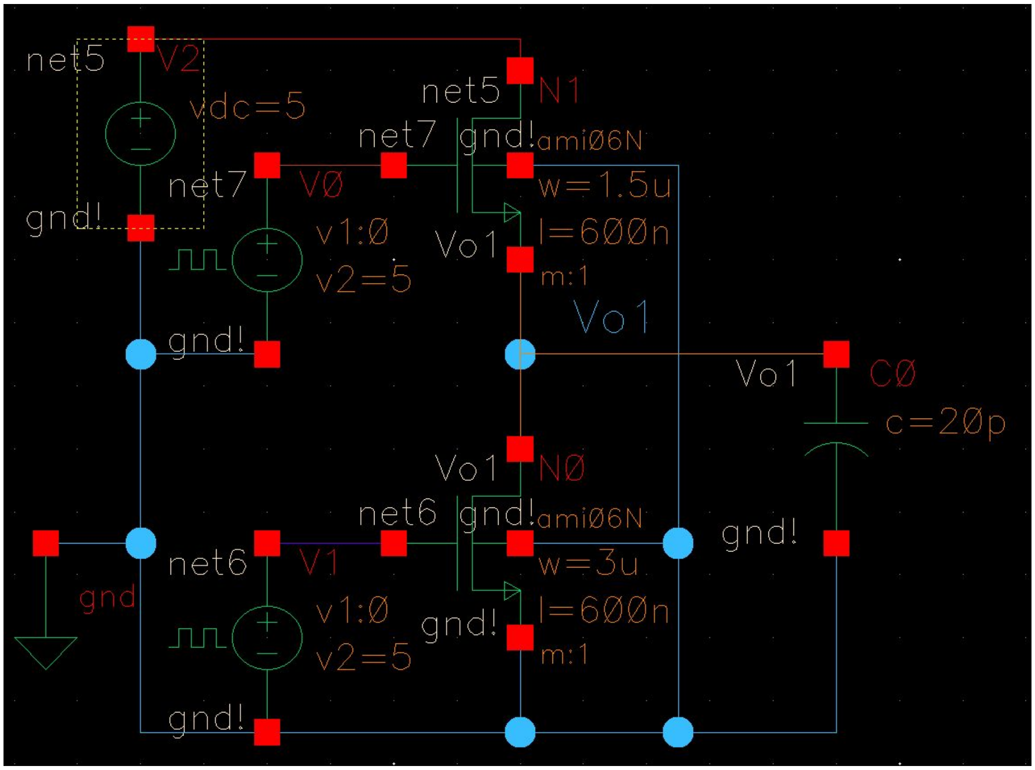
RFRD Reader Block Diagram:



The above image shows our current design concept for our reader. Right now we are planning on using an Arduino to power an oscillator to send a 13.56 MHz signal as shown above. We placed a buffer between the oscillator and the antenna to prevent any possible noise from the tag side. We are then going to read the tag signal through a separate antenna, demodulating the signal, and sending that either to a discrete ADC or the ADC built into the Arduino.



This diagram outlines the basics of our tag, with a single antenna, power harvest, sensing, and data transmission. The clock section will reduce the antenna signal at 13.56 MHz to 1.695 MHz. The start bits are tied to Vdd to help provide a baseline high level, as are the end bits, which provide a baseline low voltage level.



This image outlines the basics of our capacitance sensor, which is on the far right. The Vo pulse simulates a single bit of the start bit section, which turns on the N1 NMOS to charge the capacitor for a short amount of time. The lower No NMOS device grounds out the capacitor during the end bits to reset its value to Vss before it is recharged during the start bits.