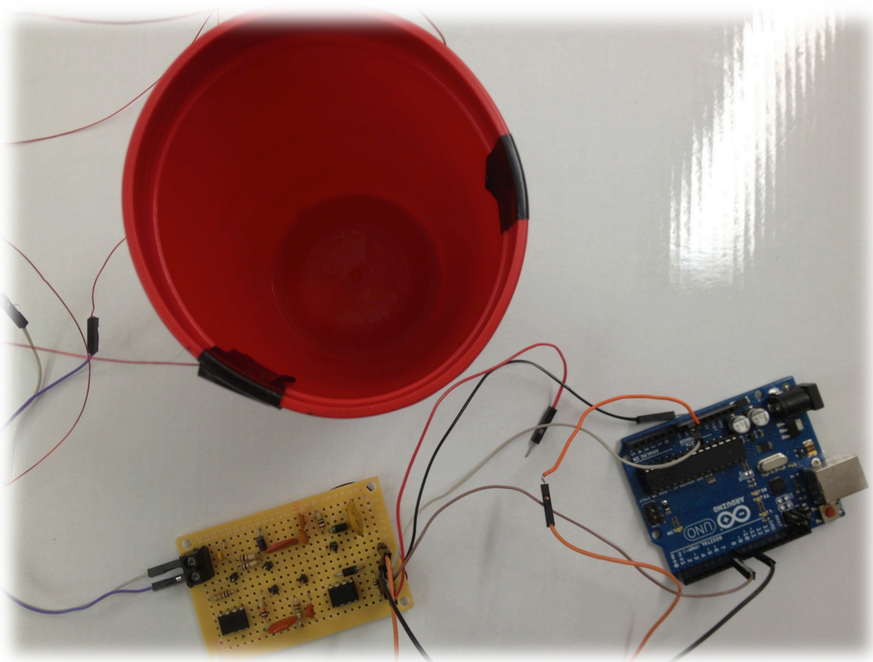
EC412 Final Project Report:
125 kHz (Low Frequency) RFID Reader



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Introduction/Motivation:

In 2008 a federal judge ordered three college students to cancel a presentation at a computer hackers' conference showing security flaws in the automated fare system used by Boston's subway. All though our project is not as mischievous (and we don't want it to be) as the MIT students' presentation, we have developed quite an interest in RFID readers because of the impact they have on near field communication systems. We have learned that the fare system used by Boston public transportation can actually be emulated using the knowledge we obtained in EC412. Our interest differs from the MIT students in that we are constructing a reader instead of manipulating the tag. We are also more interested in the variety of uses of RFID readers that can be found in every day life. BU uses RFID readers to read students' IDs, The automobile manufacturing system uses RFID readers during assembly, and RFID tags are placed inside pets in order to identify lost animals and return them to their owners.

RFID readers, also called RFID interrogators, use radiofrequency waves to interrogate a tag and receive a resonating frequency that is then interpreted as a binary code. The wireless, non-contact, use of electromagnetic fields to transfer data for the purpose of identifying tags attached to objects (EX: automobile, pet, BU) is quite useful knowledge for developing engineers. Another interesting fact is that the RFID tag does not need to be in the line of sight of the reader, which means that the tags can be inserted inside of objects. Battery power tags may operate at hundreds of meters, but the tag we are using has no battery. Tags without a source of power are called passive tags.
Our quest began with a coil a wire, a few capacitors and resisters, and a RFID tag ordered online from www.DIGI-key.com. In the end, we have developed a 125 kHz Low Frequency RFID reader that is capable of reading various passive RFID tags and the passive tags can be interpreted by a microcontroller with a clock setting of 125 kHz.

The following documentation will describe in detail our project, and also list our successes and pitfalls. After the introduction there is a block diagram. Then our simulation tools and methods will be discussed. Next, is a section containing technical information about the stages of the circuitry. Next of course we will describe how one can use our design. To wrap things up, there will be a final descriptive board layout and circuit lay out section so that it is clear that we have had great success in using the knowledge obtained in EC 412 to create an amazing device capable of near field electromagnetic communication.

Block Diagram:

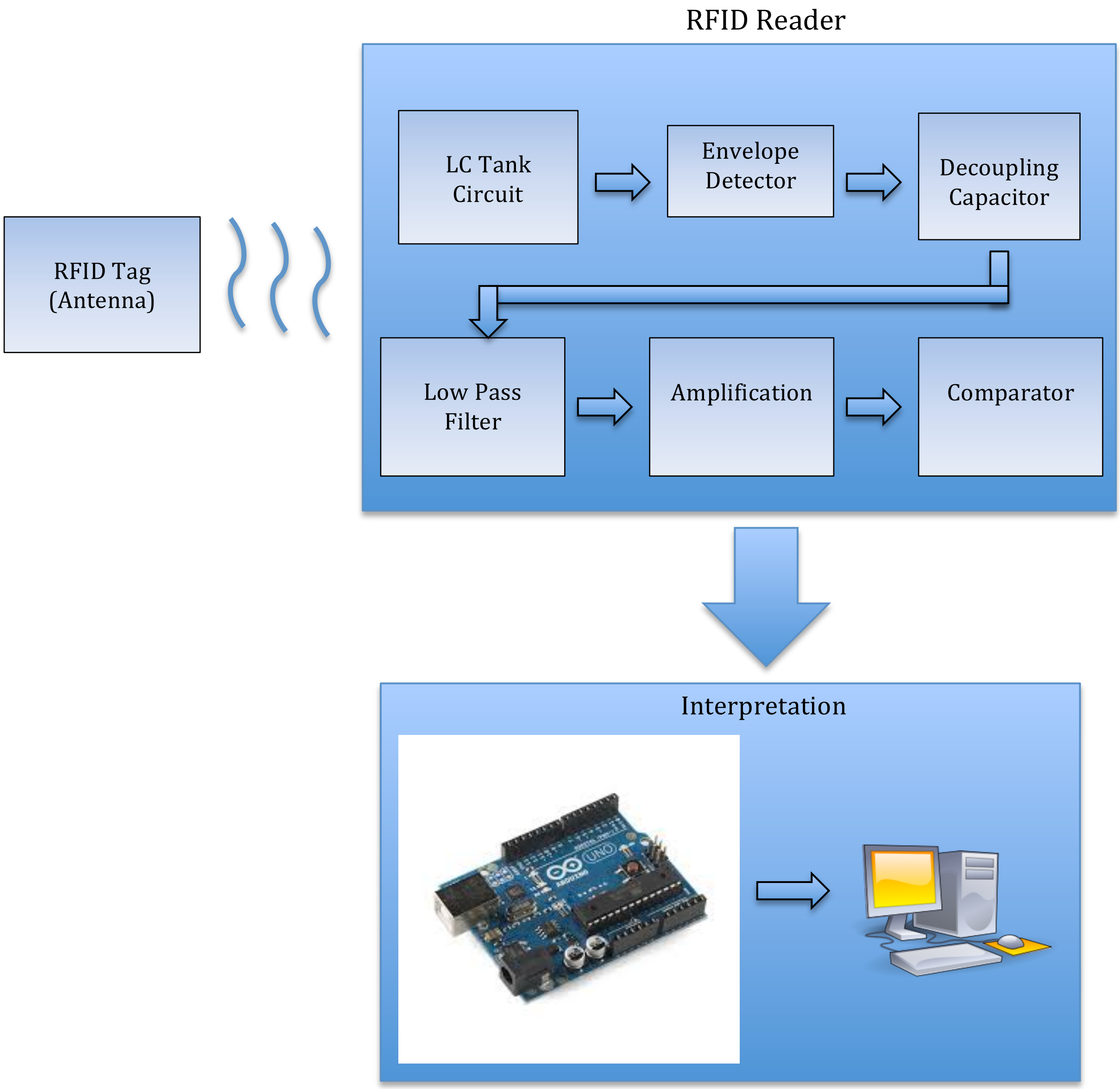


Figure 1. Block Diagram

OrCAD Simulations:

Before putting together the actual circuit on a breadboard, we designed the RFID reader in Allegro OrCAD CIS. This software enabled us to analyze the output signal of every stage of the circuit. Consequently, the process of choosing the values of the passive components was more efficient.

Figure 2 shows the circuit we simulated, including the LC tank. The LC tank circuit resembles the RFID tag's internal circuitry. We set the coupling coefficient between the coils to 0.15, which is an acceptable value for RFID tags. In the schematics, there are six colorful measuring points set at different stages of the circuit. The corresponding signals are shown in figure 2.

The first measurement was taken at the signal input of the tank circuit inside the RFID tag. The goal is to compare the input signal to the output signal from the tank circuit. This signal is assigned to the color blue. The red measurement point corresponds to resonating signal. In the yellow measurement point, we measured the output of the envelope detector. Then, the signal travels through the decoupling capacitor and a low pass filter. This waveform is represented in the light blue color both in Figure 2 and Figure 3. The second op-amp (U3) amplifies the signal by ten, and the third op-amp (U5) serves as a comparator, these signal represented in purple and green, respectively.

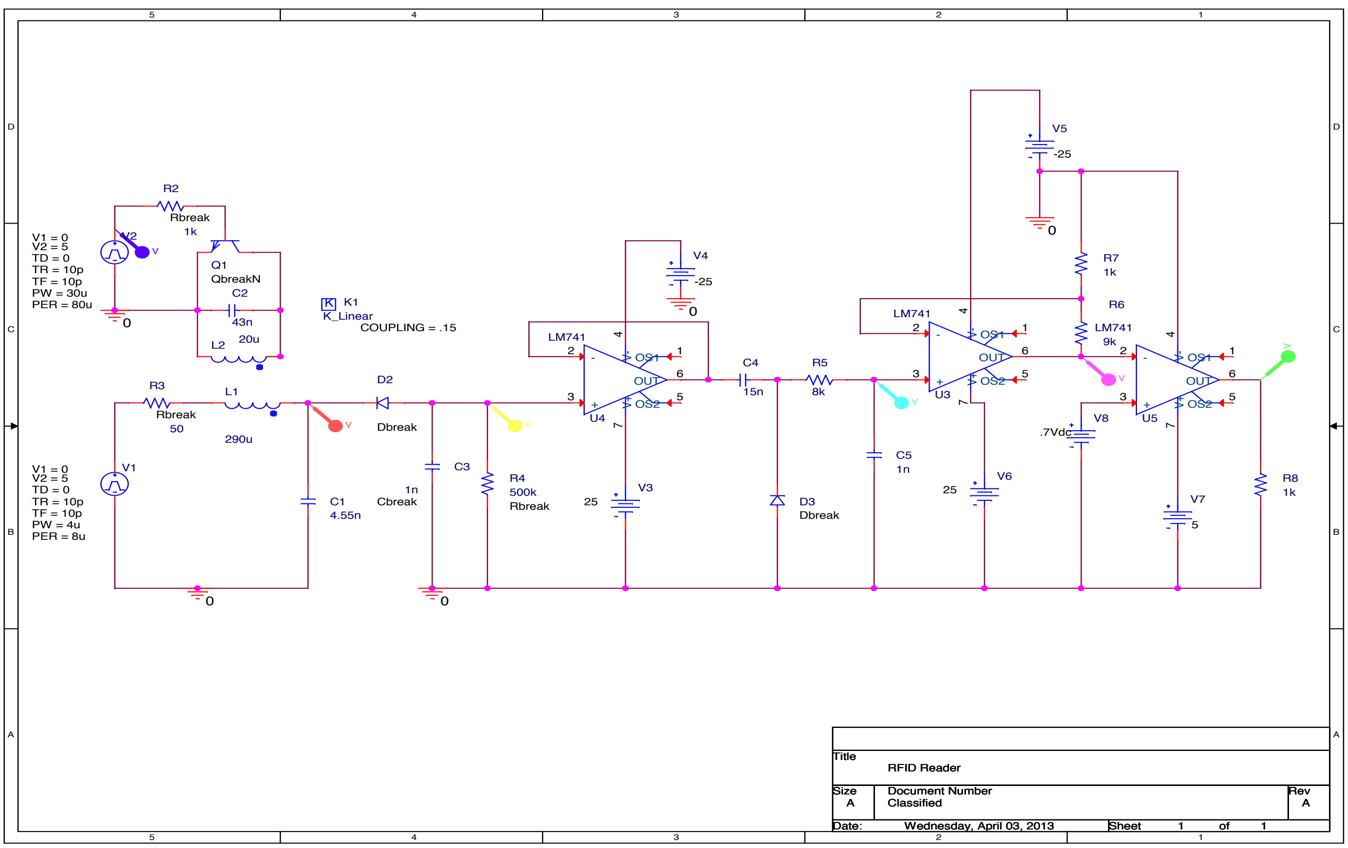


Figure 2. Simulation schematics.

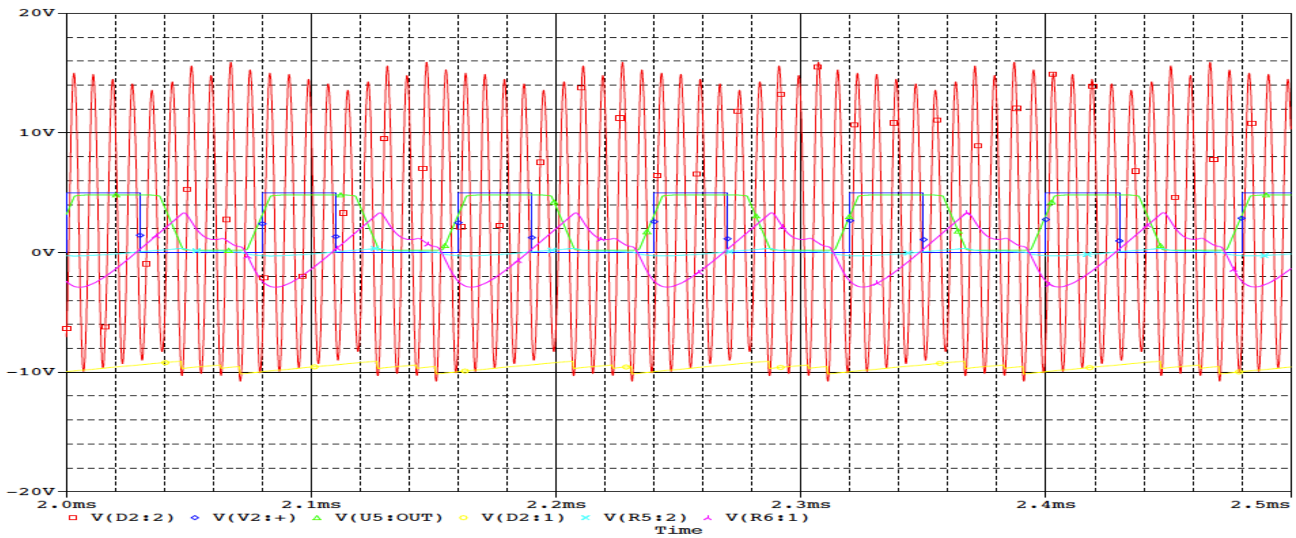


Figure 3. Simulation results.

Technical Information (Stage):

In this section, we will discuss the different stages of our radio frequency identification reader. There are 8 stages in this device, and only two active components are needed for reading memory wirelessly from an RFID tag. Please see the simulation schematics from Cadence OrCAD for circuit representations of the different stages.

(1) *Passive RFID Tag:* The RFID tag is a small circuit that can be commonly found in key chains, identification cards, telephones, and boxes being shipped across the country. There are two main components in an RFID key: the memory and the specially tuned LC tank circuit.

The memory in the key stores valuable information that can be transmitted for identification in a transceiver. The tuned LC circuit has two main purposes in the RFID key. This module is used to power the memory device, and it is also used to attenuate the signal from the coil in the RF transceiver. Please see Figure 2, for a very simple representation of a RFID key. In this simulation, a BJT opens and closes the LC tank circuit, which has a dramatic impact on the signal being produced in the larger trancieving coil.

(2) *LC Tank Circuit In Tranciever:* The series LC tank circuit is designed to resonate at 125 kHz using a 4.7nF capacitor and tuned inductive coil. Since we know that we want to have the LC circuit tuned to 125 kHz with a 4.7nF capacitor, substituting these values into the equation (Equation 1) below, we were able to solve for a rough inductance value.

$$f = \frac{1}{2\pi\sqrt{LC}}$$

Equation 1

In order to tune the inductive coil, a cup with a diameter of 3.5 inches was used to support the coil of wire that we were winding. Coils were added to the inductor, until the rough inductance value was reached. Then to fine-tune the coil, a 125 kHz 5 V amplitude square wave signal was input into the LC tank circuit. We further refined the coil until the voltage peaked, and then we taped the wire so that it remained fixed for later use.

It is also important to understand electromagnetic theory to get a full grasp of the RFID tag and LC tank circuit tranciever. When the coils of the tag and reader are close to each other, they can couple, and result in a change in effective inductance. Commonly, this coupling factor is represented by the letter M as shown in Equation 2.

$$v_1 = L_1 \frac{di_1}{dt} + M\frac{di_2}{dt}$$
$$v_2 = L_2 \frac{di_2}{dt} + M\frac{di_1}{dt}$$

Equation 2

The value of M in an RFID circuit such as ours is approximately 0.15, which is very small. The circuit has to operate in its resonant frequency so any small change in M, will result in a significant voltage drop. The LC tank circuit is powered with a 125 kHz square wave from the microcontroller.

(3) *Envelope Detector:* The next stage in the RFID reader is the envelope detector, which is designed to take out the carrier wave and keep the modulated signal from the RFID key. The carrier wave is 125 kHz, and the modulated signal is approximately 100 Hz. So an RC time constant for a low pass filter of approximately 1.6 $*10^{-3}$ seconds is needed. The formula that describes the RC time constant cutoff frequency of a low-pass filter is shown in Equation 3.

$$f_c = \frac{1}{2\pi RC}$$

Equation 3

A diode is placed in this circuit to rectify the signal so only the positive voltages can pass through.

(4) *Decoupling Capacitor:* The decoupling capacitor takes out the DC bias. This connects the envelope detector to another low pass stage. This decoupling stage is

needed, so that the signal can be input into the amplification stage while centered at 0V DC.

(5) *Low Pass Filter:* The low pass filter takes out the carrier frequency remnants, and smoothens the signal before it is input into the operational amplifier. The more that the high frequencies are attenuated, the less noise there will be in the final circuit. The cutoff frequency for this circuit is approximately 1MHz to eliminate the high peaks without attenuating the signal that we are trying to recover.

(6) *Amplification:* The amplification stage amplifies the filtered signal with a non-inverting operation amplifier configuration with a gain of 10. The operational amplifier we chose has a slew rate of 13 V/μs, which is faster than the LM741. This high slew rate is needed so that there is no distortion in our signal. After the amplification stage, we have a first order passive low-pass filter and decoupling capacitor that is used to compensate for the op-amp's non-idealities.

(7) *Comparator:* This stage takes the amplified signal and processes it into a digital signal that can be manipulated by the microcontroller to read the bit stream from the RFID tag. If the input signal into the comparator is above 0V, or the signal's ground, the signal goes high and vise versa. Again, the op-amp used for this stage was the TL081. The microcontroller will then be able to discriminate the signal into logical 1s and 0s.

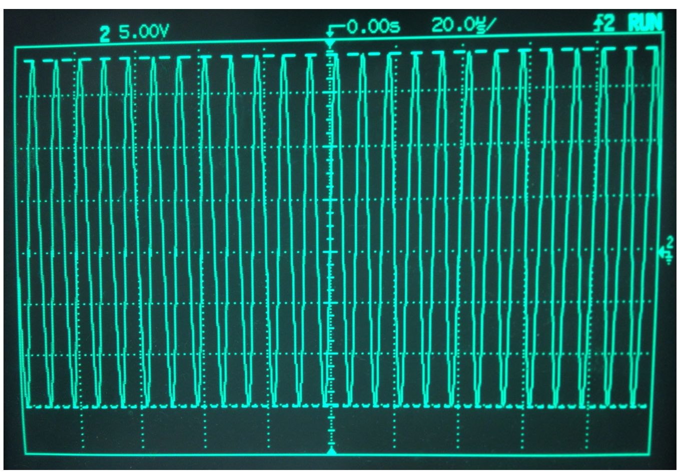
(8) Microcontroller/Digital logic: This part of the project is left for the digital designers. If time allowed, a program would be written to display the ones and zeros outputted from the RFID reader.

Measured Data:

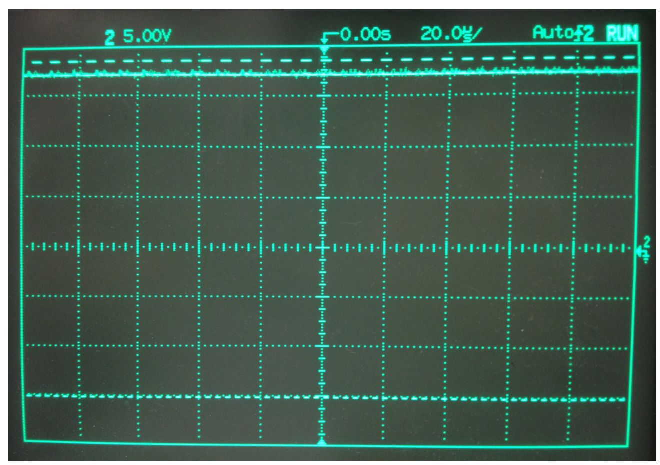
The fabricated Perf-board was developed with customized test pins. The purpose of these pins is to measure the signal output of the main stages of the board. The results of the output signal of the different stages are shown in Figure 4.

a) Coupled LC tank circuit signal with input signal (125 kHz)
b) Post envelope detection stage. It is possible to see that in this stage we are "getting rid" of the carrier wave.
c) Signal post-decoupling capacitor stage. Only noise is noticeable since the RFID tag is not in the proximity of the antenna coil. This results in random noise.
d) The measurement was taken at the same point as in image c). At this point the RFID-tag is closer to the antenna. The signal is floating around 0V.
e) The sharp peaks are being oppressed due to a low pass filter stage.
f) The signal is amplified by 10 after a stage of a closed loop op-amp.
g) The output signal of the RFID reader without an RFID tag near the antenna. The few peaks seen in the plot is due to noise.
h) Output waveform of RFID-tag #1.
i) Output waveform of RFID-tag #2.

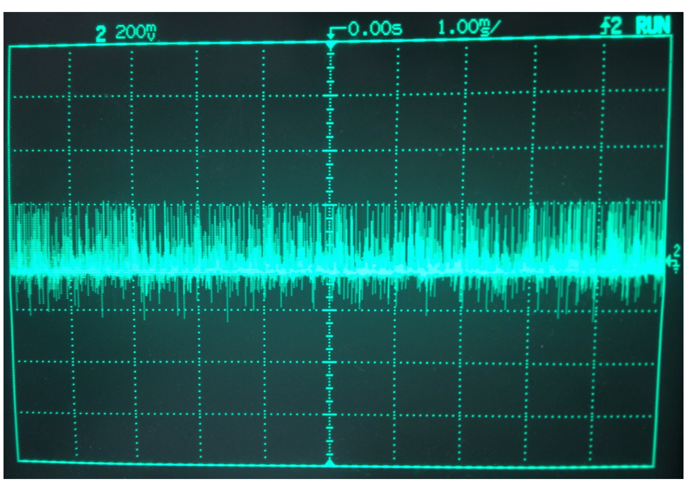
a)



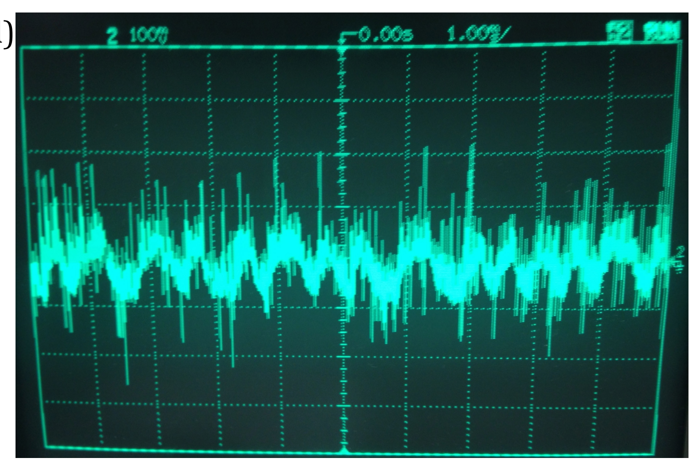
b)



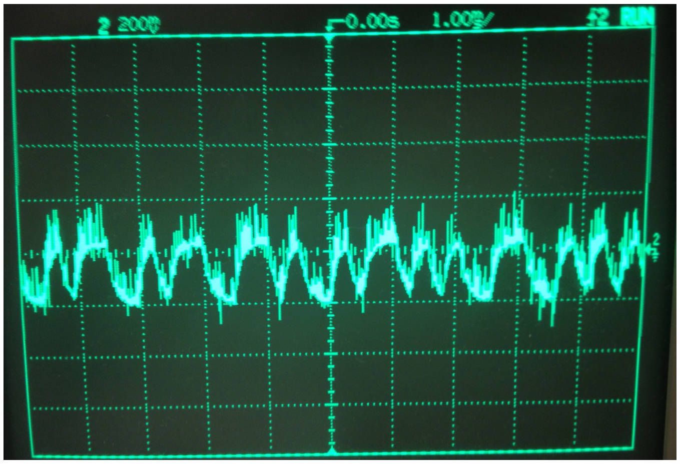
c)



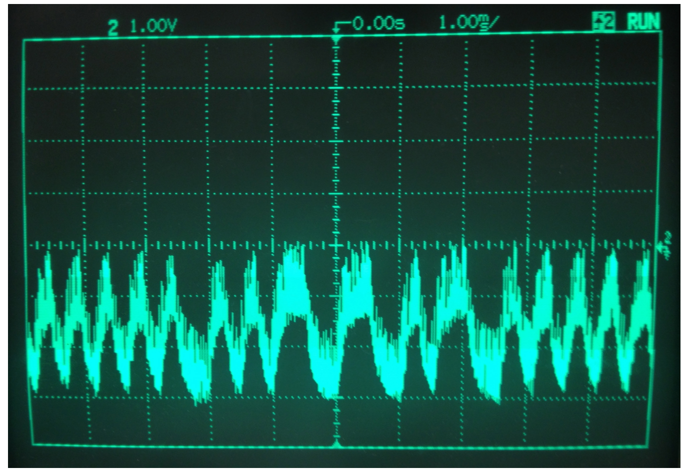
d)



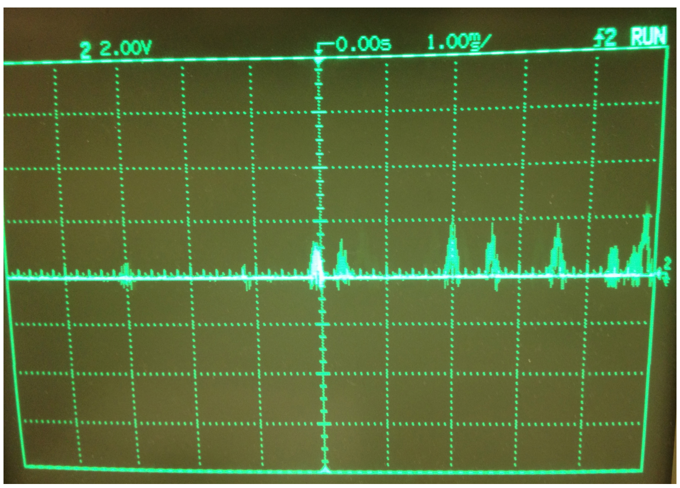
e)


2
0.00s
1.00ms/
RUN

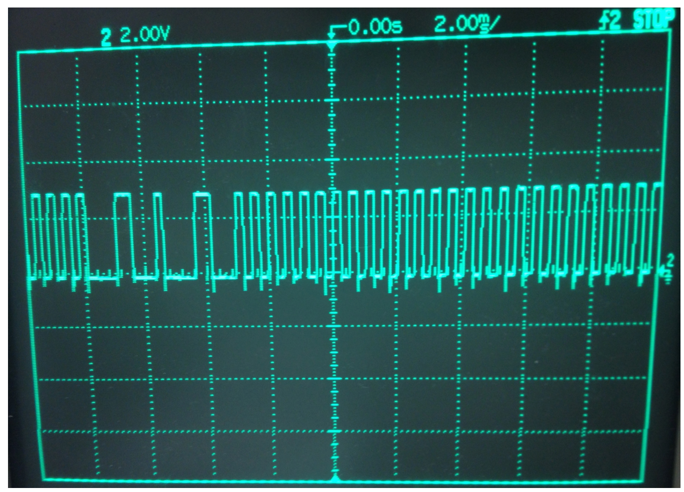
f)


2 1.00V
0.00s
1.00ms/
RUN

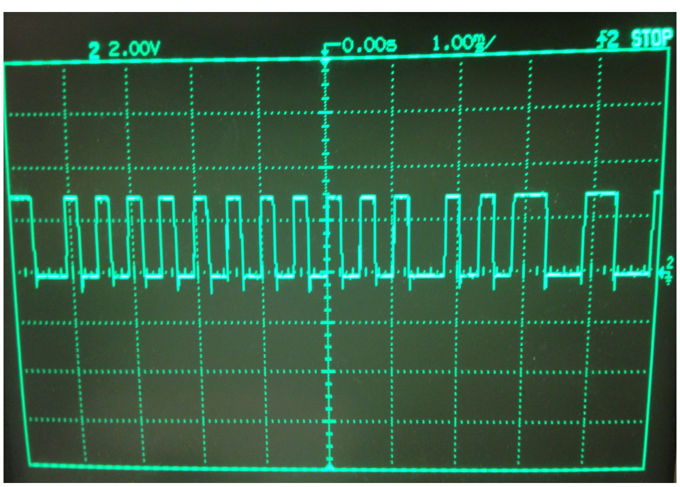
g)


2 2.00V
0.00s
1.00ms/
RUN

h)


2 2.00V
0.00s
2.00ms/
STOP

i)


2 2.00V
0.00s
1.00ms/
STOP

User Manual:

Below are brief steps that can be used to operate the RFID reader.

(1) Set device on table with transceiver coil facing the direction where you would like the user to place RFID tag.
(2) Connect the 5V power supply to red wire, the ground to the white wire, and the -5V to the black wire.
(3) Connect board to appropriate pins on the Arduino Uno (or alternatively use function generator).
    (a) Connect P7 to brown wire in the circuit.
    (b) Connect P9 to the orange wire in the circuit.
    (c) Connect Arduino GND to the GND of the circuit.
(4) Attain tag, then place tag near the transceiver coil.
(5) Turn attention to output pin to see the bit stream from the RFID tag.

Board Design:

If we were to go further with this design, we would get a printed circuit board fabricated. Shown below in Figures 5 and 6, there are schematics and a 3-D board layout, which is done in *Altium*. These would be sent to a company for fabrication, and then the board would be "ohmed" out, and the components would be populated and tested.

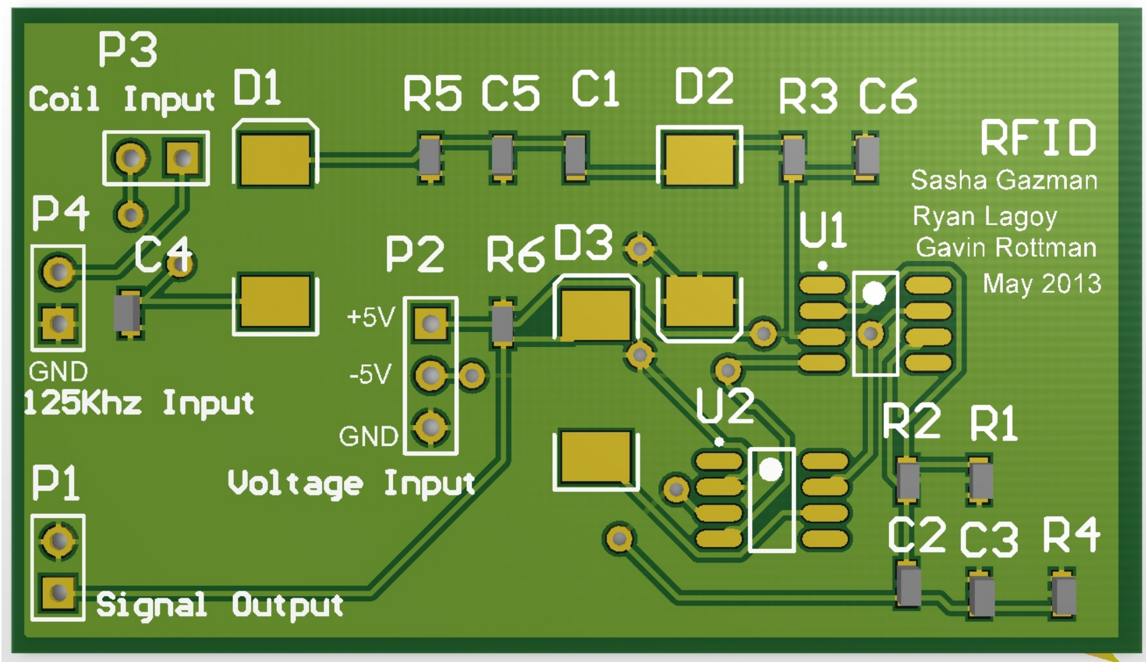


Figure 5. 3-D RFID reader board layout.

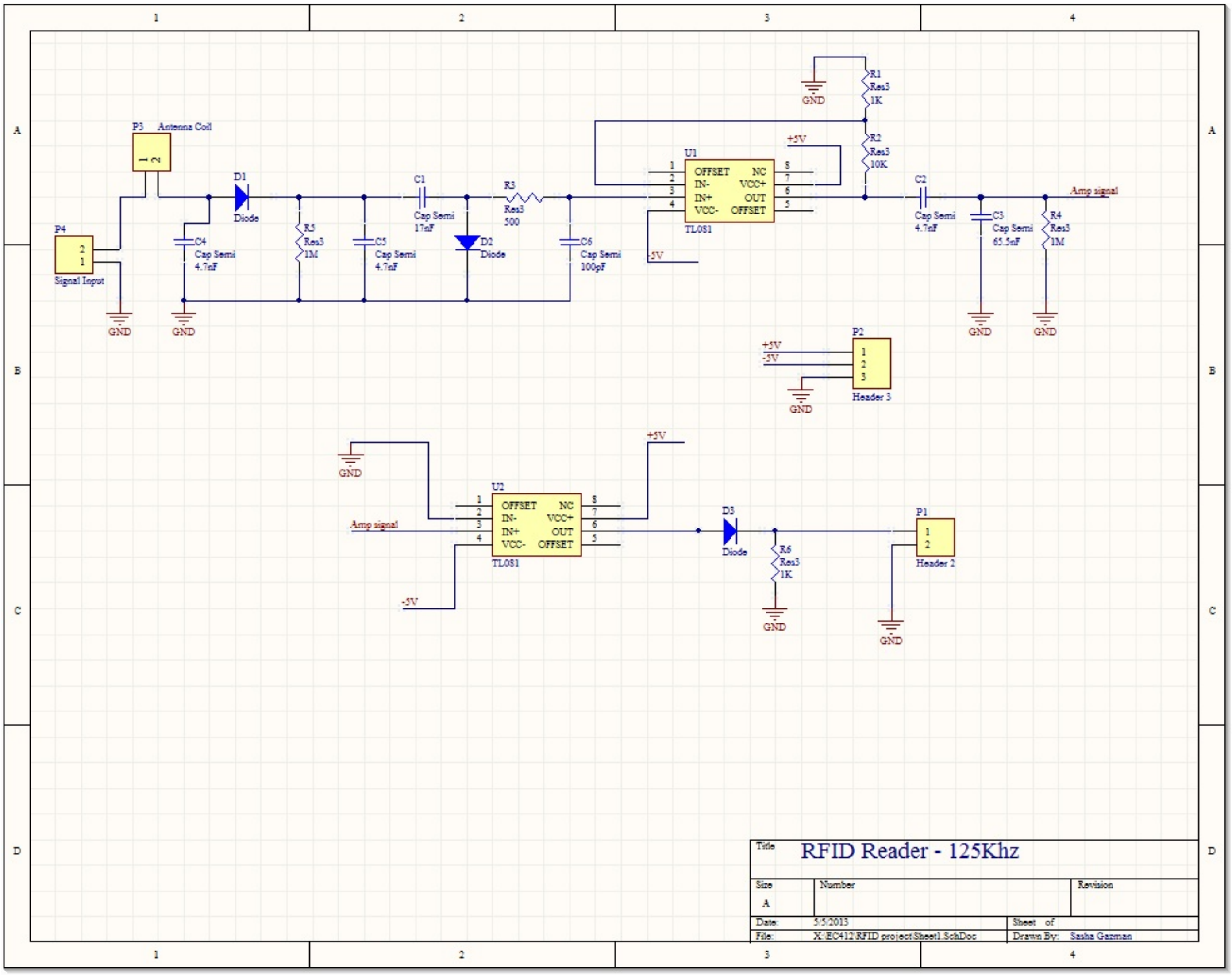


Figure 6. Simulation schematics.

Discussion of Results:

In this project, we were able to read data from an RFID chip using active and passive components. As shown in the measured data section, each stage performed as we expected for the most part. However, there were some inconstancies as can be seen between the design in Cadence and our final design. When simulating the LC tank circuit, there was a phenomenon called "squeeging" which modulated the amplitude of the carrier wave. This phenomenon is due to the instability in the circuit and is due to lack of resistance. We modified our final circuit so that "squeeging" did not occur. The envelope detector and decoupling capacitor worked as expected, and it is shown in the data. The second low-pass filter did remove some remnants of the LC tank circuit; however, in the future, a second order Sallen-Key low-pass filter could be used to reduce the noise further.

The next stage consisted of a TL081 operational amplifier, and it was chosen because it had a larger slew rate than the LM741. The op-amp did have a large output DC offset, so we needed to take out the offset with another decoupling capacitor. Also, a low pass filter was added to this stage to reduce the noise. The gain was reduced at this stage, but the signal looked very good being imputed into the last stage. The last stage was a comparator with a diode, which was used so that there was a 0V to 5V output stream of bits for the microcontroller.

To get a good output signal at each stage, the values of the passive components were adjusted accordingly.

Summary:

In conclusion, the project completed its goals. We have successfully made a circuit capable of interrogating an RFID tag, and the results can be interpreted. The circuit seemed so simple at first, when it was originally an RC circuit attached to a coil of wire rapped around a cup. Finally, once we started to use the information that we obtained from class we built something that can be incredibly useful in near-field communication. The obvious successful aspect of the project is the circuit's capability to interrogate an 125kHz RFID tag. The unfortunate pitfalls are the noise in the output, the lack of completion in the Arduino Uno's code. The Arduino Uno does not display the binary sequence in the Arduino Uno's console, however the frequency of the clock is set correctly and the circuit is capable of reading the tags. The class was extremely useful in our design because of our developed knowledge of comparators, LC tank circuits, filters, and transistors. The circuit has a passive low-pass filter, a LC tank that resonates at 125 kHz, and the RFID tag has a transistor that opens and closes to create the pulse widths that are then interpreted as a binary sequence. We are grateful for the knowledge that we obtained in EC412 and found it quite useful. Overall, the project was successful!

The following is a design based on the RFID reader information from http://playground.arduino.cc/Main/DIYRFIDReader. However, the circuit was redesigned for our use.