RFID Refrigerator Organizer

Wireless Senior Capstone Design
Advisor: Christopher Rose

By

Eric Wasserman
Nishit Raval
Hiran Patel

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1. Abstract

The purpose of the RFID Refrigerator Organizer is to design a system that can keep track of food products in a refrigerator. The food products will be tracked using a RFID reader/tag system and will allow the user to access this information from a Java application. Our procedure includes the following goals:

1. Build an RFID reader using open source software available through GNU Radio and the Universal Software Radio Peripheral (USRP).

2. Implement the RFID reader to communicate with RFID tags attached to each food product.

3. Design an application that allows the user to see which food products are currently available, when the reader last polled the tags, when the user first placed the item in the refrigerator, and view a list of products which the user should purchase.

2. Theory

2.1 RFID Tag

A UHF (900 MHz) passive RFID tag consists of an antenna and an Integrated Circuit (IC) chip. The antenna is approximately 16 cm or half the wavelength of the 900 MHz carrier signal sent by the reader. Each RFID tag has a slightly different IC, but most follow a similar architecture to the one shown in figure 1. There are two main components of the IC chip, the RF front end and the signal processing unit.

The RF front end performs the following three operations:

- Convert the incoming RF signal to DC current voltage which will be used to power the clock generator, the digital end, the bias circuit, and the power on reset.
- Demodulate the incoming RF signal and pass the data to the digital end.
- Take the data from the digital end, modulate it with the continuous wave from the reader, and effectively backscatter the data back to the reader.

The second component of the tag, the digital part or signal processing unit of the IC, responds to certain pre-programmed commands including query, select, read, and write. When the signal processing unit detects one of these commands from the demodulator, it responds with either a random 16 bit number (RN16), its EPC identification number, or it writes the data to its nonvolatile memory.

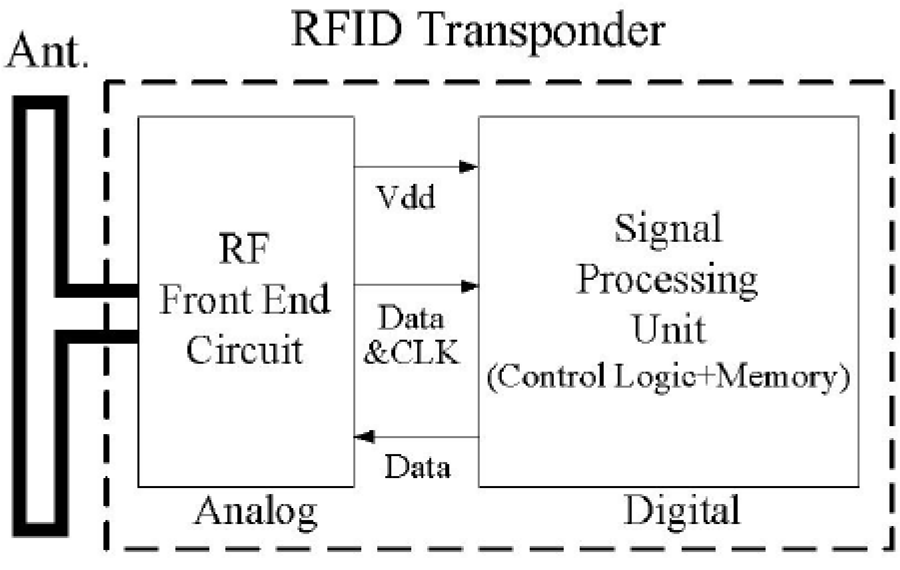


Fig. 1: RFID Tag architecture

Figure 2 shows the architecture of the RF front end. Each block will be explained in detail below.

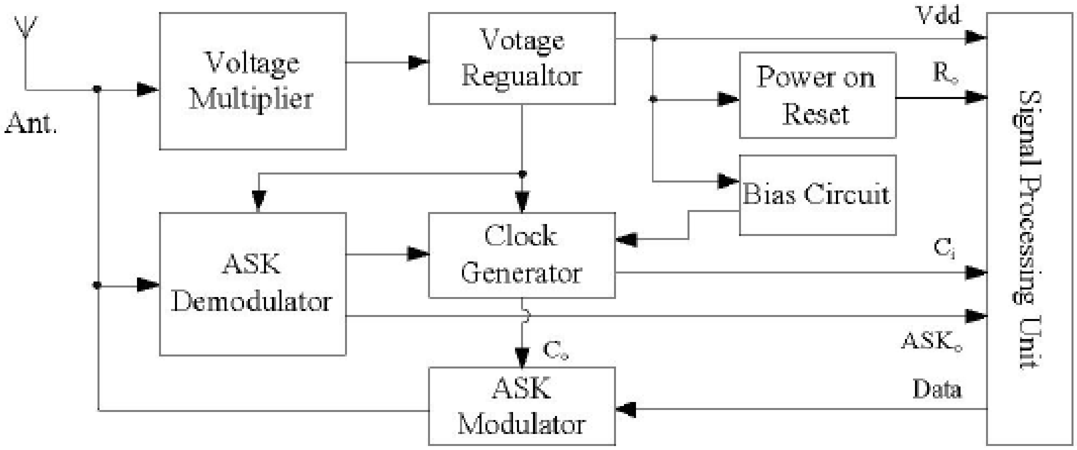


Fig 2: RF Front end architecture

2.1.1 Voltage Multiplier

The voltage multiplier is an extremely important part of the RFID tag IC design. The voltage multiplier takes the RF signal from the tag antenna and converts it from AC to DC and then multiplies the voltage by a certain amount to enable the entire chip to operate. To explain the voltage multiplier we will demonstrate the voltage doubler, as shown in figure 3 below. The DC output of a voltage doubler is a little less than twice that of the peak input voltage. The capacitor connected to the antenna is used to prevent DC current from flowing between the antenna and the diodes. The second capacitor stores the resulting charge. The voltage doubler has two different states of operation that are explained below.

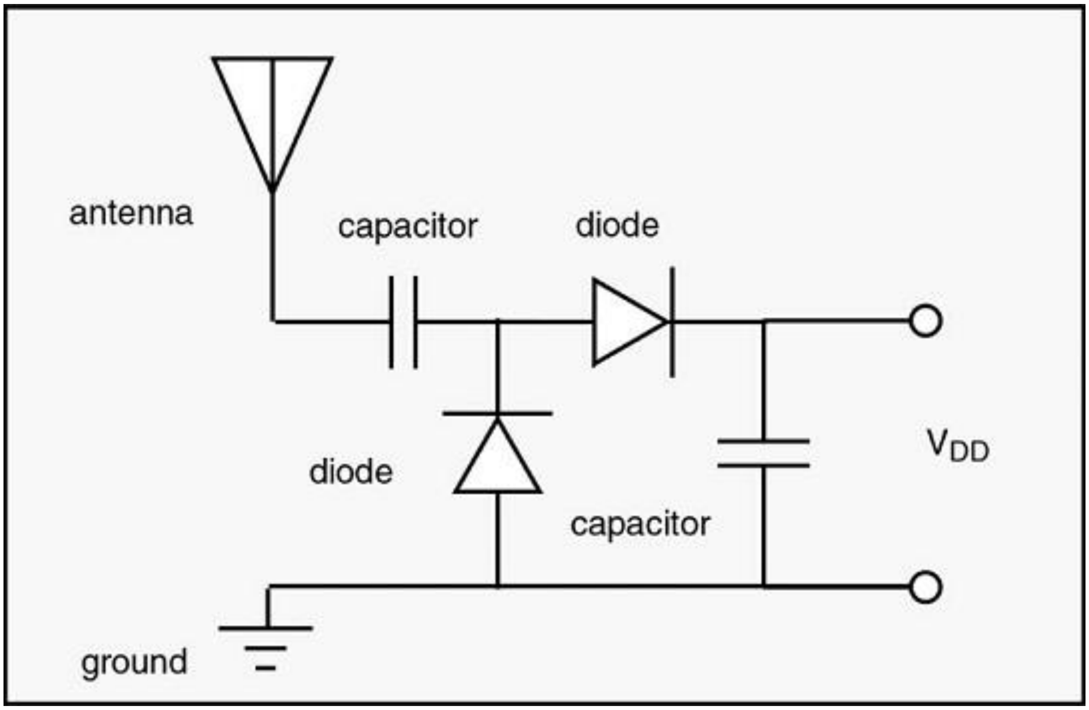


Fig. 3: Voltage Doubler

When the RF input signal is negative and greater than the turn-on voltage,V_{ON}, of the diodes (0.15 - 0.46 V for a Schottky diode, and 0.7 for junction diode), the leftmost diode turns on and the rightmost diode turns off. This is depicted in figure 4. Current will then flow from the ground through the leftmost diode and charge the 1st capacitor (seen on left). As the input signal reaches a negative peak,$-V_{PK}$, the voltage difference across the capacitor increases to $V_{PK} - V_{ON}$.

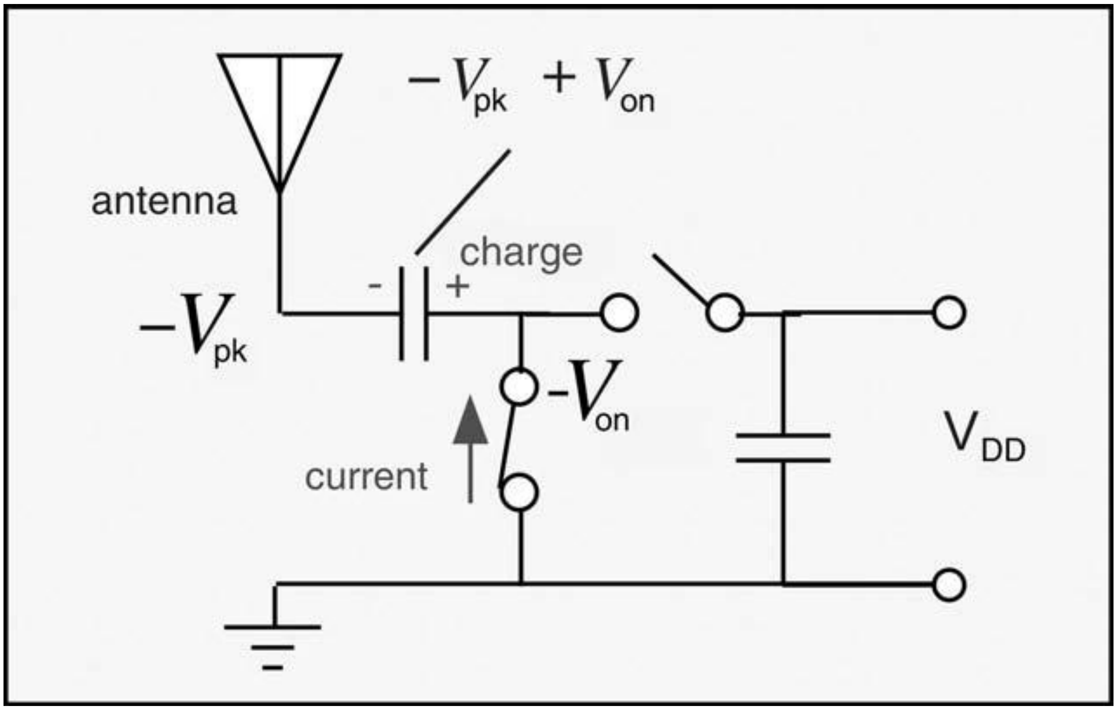


Fig. 4: Voltage Doubler when RF input signal is negative

When the RF signal changes polarity (becomes positive) and V_{PK} is greater than V_{ON}, the leftmost diode turns off and the rightmost diode turns on. The 1st capacitor will begin discharging and flow through the rightmost diode. The total output voltage presented to the rest of the IC (load), V_{DD}, is described in equations 1 and 2. V_{PK} is the incoming signal from the antenna, V_{PK} - V_{ON} is the voltage across the leftmost diode as it discharges, and - V_{ON} is the potential drop across the rightmost diode.

$$V_{DD} = V_{pk} + (V_{pk} - V_{on} \qquad \text{Eq. 1}$$

$$V_{DD} = 2(V_{pk} - V_{on} \qquad \text{Eq. 2}$$

In figure 5 below, it can be seen in that the output voltage is twice that of the input voltage. In a typical tag IC, the voltage multiplier consists of many voltage doublers cascaded together so as to provide a much higher voltage than the amplitude of the received RF signal. The output voltage can further increase by a constant factor N relative to the number of voltage doublers provided in the circuit: $V_{DD} = 2N(V_{PK} – V_{ON})$. As the number of stages increases however, the efficiency of the circuit dramatically falls.

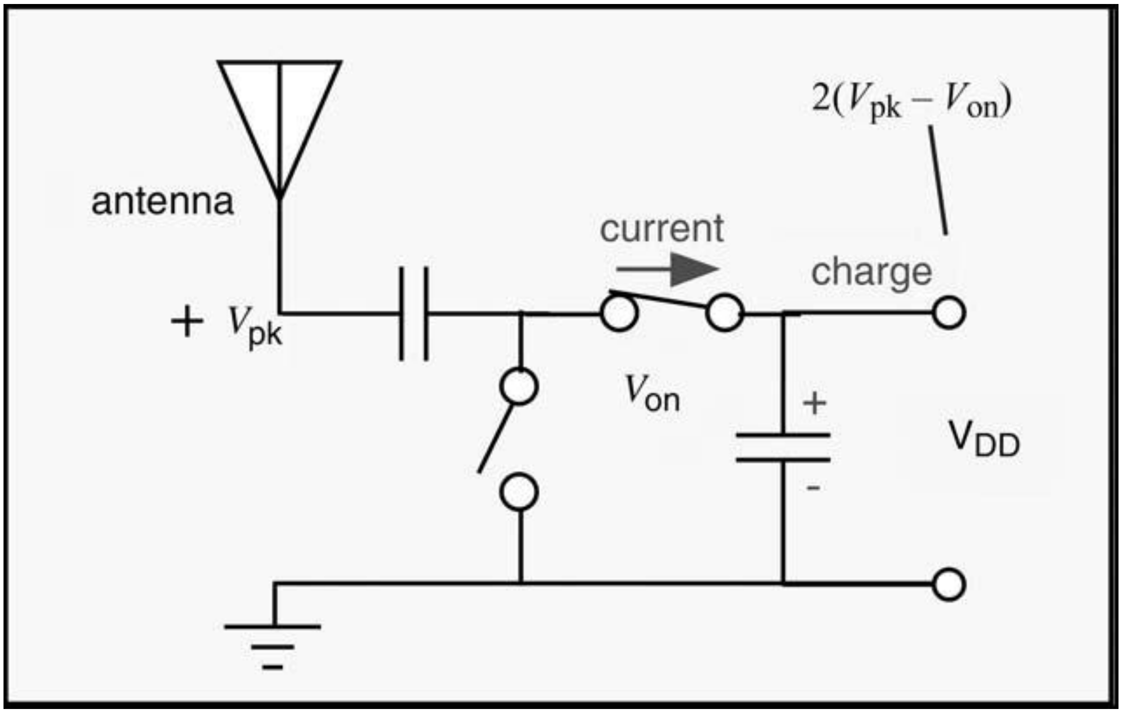


Fig. 5: Voltage Doubler when RF input signal is positive

2.1.2 Voltage Regulator

The voltage regulator is used to keep the voltage from the voltage multiplier stable. Since the RF signal coming from the reader varies in strength, the converted DC current will also vary. This will adversely affect the performance of the IC. Typical voltage regulators are made using a resistor and a Zener diode. Although not all voltage regulators in tag ICs use this type of schematic, for explanation purposes we will elaborate on this design. A simple diagram for the voltage regulator is depicted in figure 6. The resistor is in series with the Zener diode and the diode's breakdown voltage can vary, but for a low power tag IC, we will assume that the breakdown voltage is 2.4 V. The important thing to note about Zener diodes is that when they are reverse biased, as long as the input voltage is greater than the breakdown voltage, the voltage across the Zener diode will always be equal to the breakdown voltage. The current may increase when the input voltage increases, but the voltage remains the same. Let us assume that the input voltage varies around 3 V. An RFID IC will not operate unless it gets a current of at least 10 µA. With this information we can calculate the value of the resistor in equation 3. We will initially use a current of 60 µA to determine the resistance.

$$R = \frac{V_{in} - V_D}{i} = \frac{3 - 2.4}{60\mu A} = 10k\Omega \qquad \text{Eq. 3}$$

Now let's see what happens when the voltage varies between 2.5 and 3.5 V. Keep in mind that the voltage across the Zener diode will always be 2.4 V but the current will change.

$$i = \frac{V_{in} - V_D}{R} = \frac{2.5 - 2.4}{10k} = 10\mu A$$ Eq. 4

Eq. 5

$$i = \frac{V_{in} - V_D}{R} = \frac{3.5 - 2.4}{10k} = 110\mu A$$

Despite the change in the input voltage, the output voltage stays at 2.4 V and the current is still enough to power the IC.

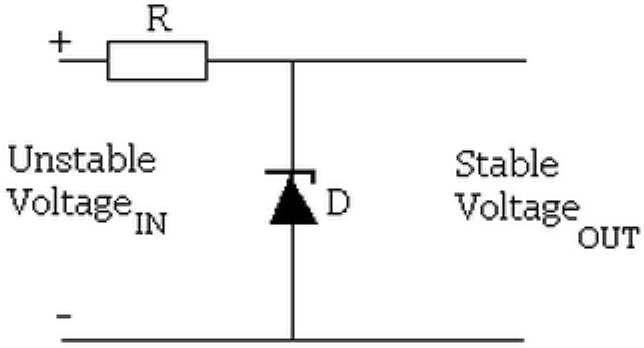


Fig. 6: Voltage Regulator

2.1.3 Demodulator

The type of demodulation our tag uses is ASK demodulation. In general, RFID tags can use ASK or PSK demodulation depending on the reader. Figure 7 shows the CMOS schematic of the ASK demodulator. The demodulator consists of an envelope detector, a low pass filter, an average detector, and a comparator. In figure 8 you can see an example of an ASK modulated RF input signal along with its demodulated waveform.

Figure 8 shows an example of a typical envelope detector. The envelope detector takes the RF signal sent by the reader and provides an output which tracks the envelope of the message signal. The diode turns on and the capacitor stores up the charge on the positive cycle of the input signal. When the input signal falls below its peak value, the diode will turn off (open) because the voltage stored at the capacitor will be greater than the input signal voltage. As a result, the capacitor will begin to slowly discharge through the resistor. This process repeats when the input signal is on the positive half of the cycle. The rate at which the capacitor charges and discharges, given the input signal contains a 915 MHz carrier, is known as the time constant, and is described in equation 6 below.

$$\frac{1}{915x10^6} \ll RC \ll t_1 \qquad \text{Eq. 6}$$

The time constant, RC, must be far less than t_1, the signal period of the incoming signal, in order to maintain its integrity and to also filter out the high-frequency carrier. The average detector is used to track the average of the incoming signal. The, the comparator outputs the message signal by comparing the output of the envelope detector with the average value of the message signal.

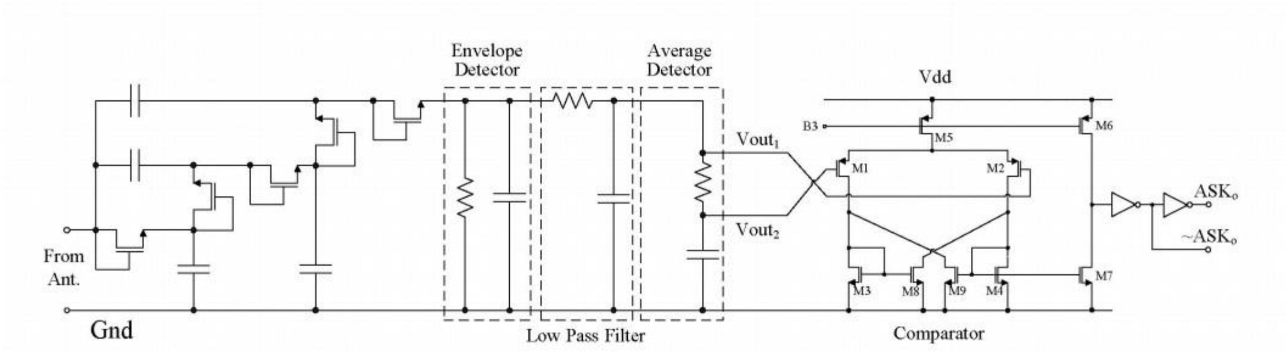


Fig. 7: ASK Demodulator

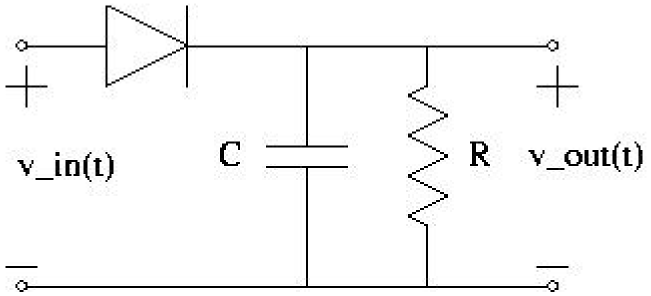


Fig. 8: Envelope Detector

2.1.4 Clock Generator

The purpose of the clock generator is to provide a stable clock signal for the signal processing block and modulator. It takes the demodulated signal as its input and outputs the clocked signal to the digital logic. The clock generator consists of two parts, an oscillator and a 3-bit counter (figure 9). The oscillator produces a signal at the data bit rate ranging from 40 - 640 kHz depending on what the reader requests. The 3-bit counter takes the two inputs from the oscillator and the demodulated ASK signal and determines where to output the clock signal.

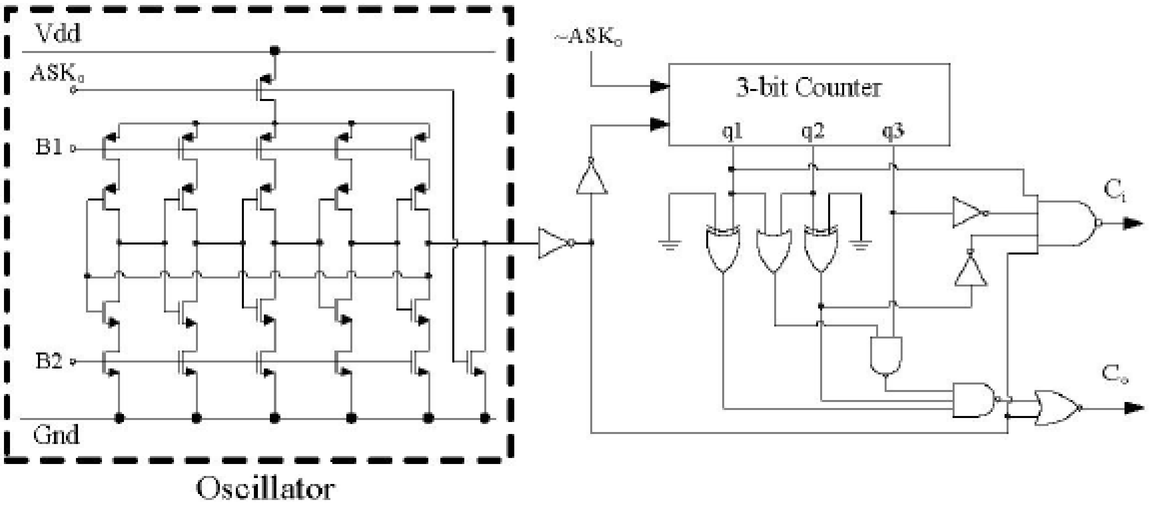


Fig. 9: Clock Generator

2.1.5 Power on Reset

The Power on Reset (POR) circuit handles two important functions vital to the stability of the IC. The first function is to output a reset signal to reset the logic circuitry within the digital section. The reset signal is sent once the POR circuit receives the output from the voltage regulator. The second function is that it prevents the chip from malfunctioning when the voltage levels across the IC chip drop.

2.1.6 Bias Circuit

RFID tags use a self-biasing circuit in an effort to provide the correct operating voltage (bias point) needed for the clock generator, power on reset, and ASK demodulator circuit. This will in turn enable the IC to consume less power.

2.1.7 Modulator

The modulation and backscattering of a signal from the RFID tag to the reader relies entirely on the principle of maximum power transfer. Maximum power transfer states that when the impedance of the load (IC) is equal to the complex conjugate of the impedance of the signal source (tag antenna), then the amount of power absorbed by the IC is equal to the amount of power reflected by the IC. When the tag is receiving data from the reader, the impedance of the load as seen from the output terminals is equal to the complex conjugate of the impedance of the antenna. The tag absorbs 50% of the maximum power from the RF signal and reflects the other 50%. When the tag needs to respond to a reader’s signal, it changes its load impedance to reflect (scatter) more than 50% of the RF signal based on the bits being transmitted. Two types of circuits can be used to backscatter the RF signal.

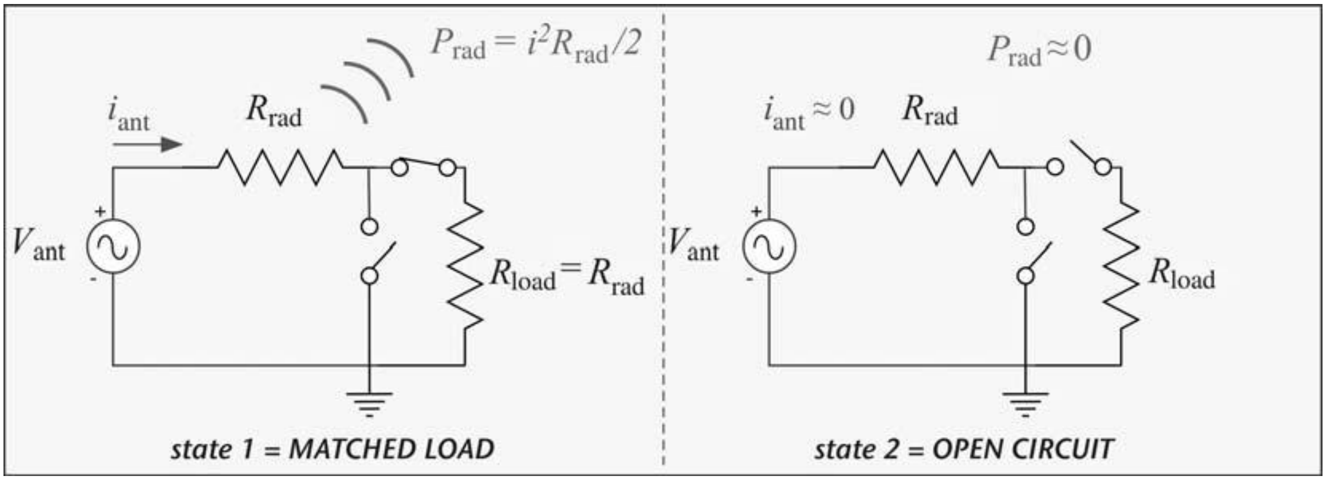


Fig.10: Backscatter using Open Circuit

The first circuit is shown in figure 10. It utilizes an open circuit in parallel with the load resistance. This circuit is a simplified representation and only includes the real part of the impedance whereas in a true IC, there would be a real and a complex part. In the circuit diagram, R_{rad} represents the resistance produced in the antenna when current flows through it. R_{load} represents the resistance of the IC as seen from the antenna. State 1 represents the default state for the RFID tag. When the tag is in state 1, the power scattered by the antenna is equal to the product of the current squared and the resistance. The current flowing through the load resistor can be calculated from Ohm's law.

$$i_{ant} = \frac{V_{ant}}{R_{rad}+R_{load}} \qquad \text{Eq. 7}$$

We can then determine the power delivered to load in the default state. In the default state, the load resistance is equal to the resistance from the antenna to achieve maximum power transfer. The power then delivered to the load and scattered back through the antenna is given in equation 8. This corresponds to the power delivered to the unmodulated antenna.

$$P_{load} = P_{rad} = \frac{{i_{ant}}^2 R_{rad}}{2} = {V_{ant}}^2/(8R_{rad}) \qquad \text{Eq. 8}$$

When the tag is in state 2 there is no current flowing through the IC so zero power is delivered to the load and therefore no power is backscattered. The change in backscattered signal power corresponds to an ASK modulated signal where the amplitude of the signal changes relative to what bits are being sent.

During the process of modulation, the tag switches between states 1 and 2 in order to backscatter a signal of changing amplitude. In MMS encoding, the number of tag state transitions that occur within a cycle time determine what bit was sent. If a logical "0" is sent, then there will not be any state changes in the signal regardless of whether the state is 1 or 2. If a logical "1" is sent, there will be 1 state change regardless of whether it changes from state 1 to

2 or 2 to 1. In MMS encoding, the tag switches symmetrically between states 1 and 2. This means that the tag will spend half of the modulation time in state 1 and the other half in state 2. The power that is backscattered from the tag is due to the change in current between the modulated and unmodulated states. The average backscattered power is then equal to half the peak power found in equation 8. The power delivered to the IC during modulation is then equal to the backscattered power.

Another circuit for backscattering is shown in figure 11 and utilizes a short circuit in parallel with the load resistance. Once again this circuit is an oversimplification and does not include the complex impedances of both the antenna and IC load. This circuit works in a very similar way as the previous circuit except that when the IC is in state 2, no current flows through the load. Instead all of the power is backscattered by the antenna which is twice the power dissipated in the matched load (state 1).

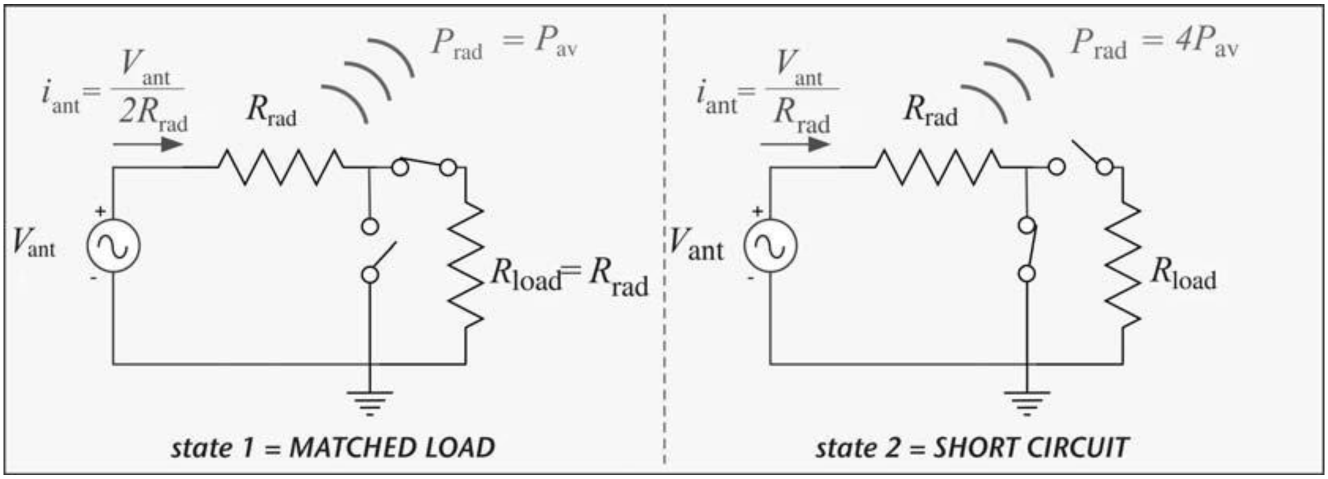


Fig.11: Backscatter using Short Circuit

2.1.8 Impedance Matching Proof

This proof is derived from the Maximum Power Transfer Theorem (also mentioned above) which states that in order to deliver the maximum power to a load (in this case the IC chip), the impedance of the load must be matched to the impedance of the source (antenna). In reactive circuits, this means the impedances of the source and load are equal in magnitude and opposite in phase. In effect, the source and load are complex conjugates of each other. We will show this in the derivation below.

$$|V_S| = |Z_S + Z_L||I_S| \qquad \text{Eq. 9}$$

where Z_S and Z_L are the impedance of the source antenna and load respectively. I_S is the current received at the antenna passing through the IC chip.

$$|I_S| = \frac{|V_S|}{|Z_S + Z_L|} \qquad \text{Eq. 10}$$

Equation 11 describes the power delivered to the load. We want to find the real and imaginary parts of Z_L so as to maximize this power delivered.

$$P_L = I_{RMS}{}^2 R_L = \frac{1}{2}\left(\frac{|V_S|}{|Z_S + Z_L|}\right)^2 R_L = \frac{1}{2}\left(\frac{|V_S|^2 R_L}{(R_S + R_L)^2 + (X_S + X_L)^2}\right) \qquad \text{Eq. 11}$$

where R_S and X_S are the real and imaginary parts, respectively, of the impedance Z_S, and R_L and X_L are the real and imaginary parts, respectively, of impedance Z_L.

Since we want the power delivered to the load to be a maximum, we want the denominator of the equation above to be as small as possible. We can do this by setting $X_L = -X_S$. This leaves us with:

$$P_L = \frac{1}{2}\left(\frac{|V_S|^2 R}{(R_S + R_L)^2}\right) \qquad \text{Eq. 12}$$

Now, we can find the value for R_L that will maximize equation 12 by differentiating the denominator with respect to R_L and setting it equal to zero.

$$\frac{d}{dR_C}\left(\frac{R_S{}^2}{R_L} + 2R_S + R_L\right) = -\frac{R_S{}^2}{R_L{}^2} + 1 = 0 \qquad \text{Eq. 13}$$

Now solving for R_L, we find that $R_L = R_S$. We have therefore shown that the real part of the impedance is equal in magnitude and opposite in phase when the power transferred to the IC chip is a maximum.

2.1.9 Backscattered Subcarrier Modulation

As stated in section 2.1.7, the RFID tag changes its impedance in order to reflect a different amount of power corresponding to the message signal. An important thing to note that was not mentioned in the previous section is that the RFID tag does not backscatter the binary message signal. It backscatters an ASK modulated message signal. This means that the final backscattered signal will have been amplitude modulated twice from its original baseband message signal. The first carrier signal is a sequence of alternating 1's and 0's set at the RFID reader uplink frequency. The uplink frequency of the RFID reader used in our project is 40 kHz. This ASK modulated signal at carrier frequency 40 kHz is then ASK modulated a second time at the carrier frequency of the continuous wave being transmitted from the RFID reader. The CW frequency in our project is 915 MHz. This is the result of Miller Modulated Subcarrier (MMS) encoding.

MMS encoding takes the baseband signal and multiples it by a series of alternating 1's and 0's with a frequency of 40 kHz. The baseband signal is itself encoded by varying the number of state changes of the transmitted bit corresponding to a "1" or a "0". The tag state has a change in the beginning and end of every clock cycle. For every binary "1" there is an additional state change in the middle of the cycle whereas for a "0" there is no additional state change. There are three different ways to use MMS encoding. Each way involves changing the data rate of the ASK modulated signal. The different types of MMS encoding are depicted in Figure 12.

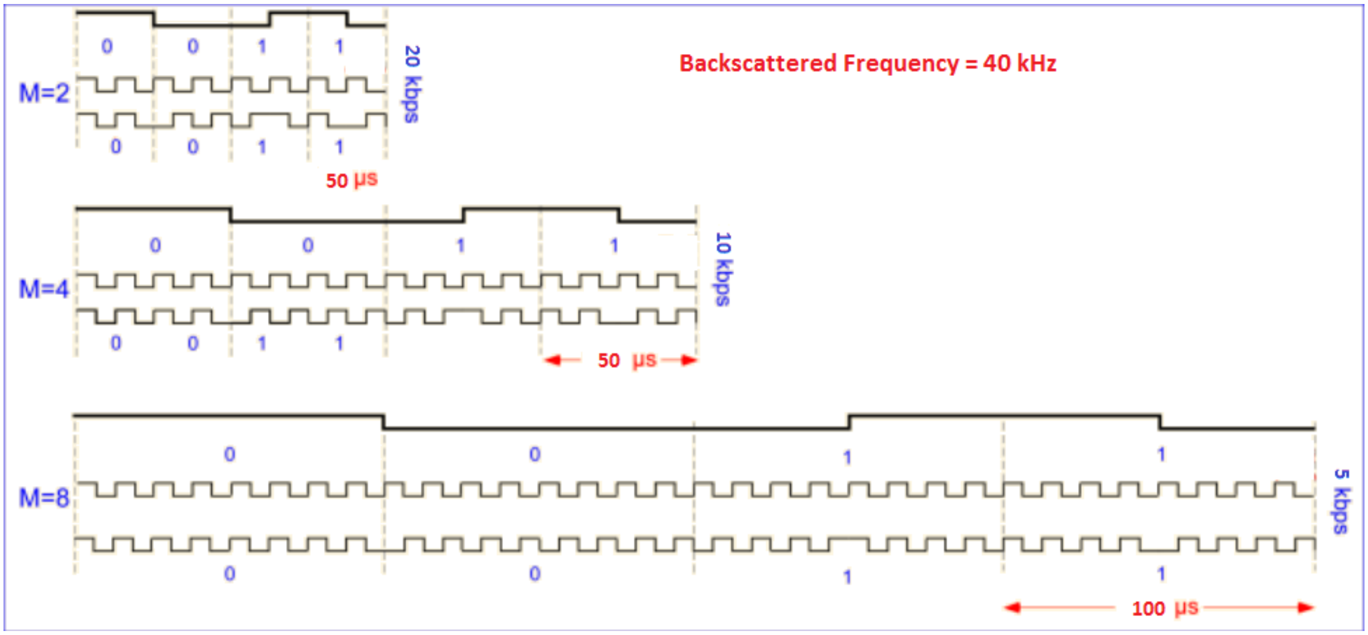


Fig. 12: Miller Modulated Subcarrier signals

The backscattered signal is a sum of two sinusoidal signals (s_1(t) and s_2(t)) each at a frequency of 40 kHz away from the original CW carrier frequency. The backscattered signal s(t) is described in equation 14. A_1 and A_2 are the amplitude of the sidebands and f_s is the frequency of the subcarrier which is 40 kHz.

$$s(t) = s_1(t) + s_2(t) = A_1 \cos(2\pi(\mathrm{f_c} - \mathrm{f_s})\mathrm{t}) + A_2 \cos(2\pi(\mathrm{f_c} + \mathrm{f_s})\mathrm{t}) \qquad \text{Eq. 14}$$

The specific reason for using MMS encoding along with subcarrier modulation is explained in section 2.2.2 on the RFID reader receiver.

2.1.10 Signal Processing Unit

The signal processing unit's main components are the controller and the memory unit. The function of the controller is to receive the demodulated signal from the demodulator and the clock signal from the clock generator in order to find the number of pulses needed in one cycle to generate the incoming signal. The controller then responds appropriately depending on the instructions provided by the instruction register. For example, the controller may need to fetch data, which will be stored in the memory unit that needs to be transmitted back to the reader (i.e. random 16-bit number or EPC number). It may also need to write data to memory. The second important function of the controller is to send a "wake up" call to make sure that the tag is on.

2.2 RFID Reader

An RFID reader is essentially a radio transceiver. It transmits a modulated signal at a particular carrier frequency, and then receives and demodulates a response. One of the few distinctions of a passive RFID reader is that aside from transmitting a modulated signal at the carrier frequency, the reader always transmits a continuous wave at the carrier frequency to provide power to the passive RFID tag. The RFID reader is a full-duplex receiver meaning that it transmits and receives signals simultaneously. This full-duplex transceiver, however, is different than most full-duplex devices like cell phones because it can transmit and receives signals at the same carrier frequency. We will discuss in detail how a RFID reader works by first explaining the transmitter side and then explaining the receiver side. Figure 14 depicts a full duplex system where the transmitter antenna transmits a CW to the tag and the tag backscatters the response to the receiver antenna. The important thing to note is that the receiver not only receives the backscattered signal from the tag but also the transmitted CW from the transmitter. The CW has much higher amplitude than the backscattered signal so the receiver has the task of differentiating the backscattered signal from the CW.

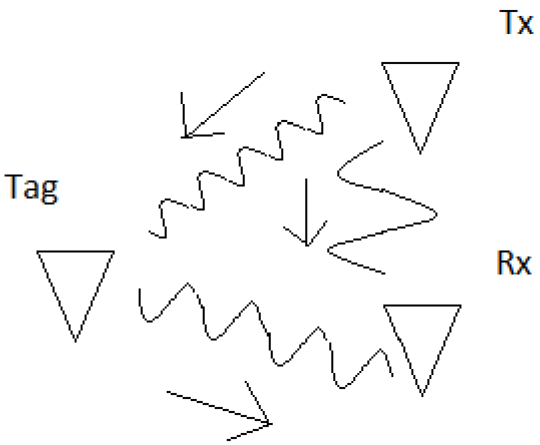


Fig. 13: Full Duplex RFID System

2.2.1 Transmitter

The RFID transmitter is much simpler than the RFID receiver. It's main goal is to send the ASK modulated messages to the tag and then in between the messages, send a continuous 915 MHZ (adjustable) wave to allow the tag to back-scatter the signal and send data back to the receiver. We can represent the transmitter in Figure 14 as a 915 MHz oscillator, two amplifiers, and a transmitting antenna. The messages are amplitude modulated by varying the DC power supplied to the second output amplifier. A logical "1" is sent with maximum DC power supplied to the second output amplifier and a logical "0" is send with the minimum DC power supplied to the second output amplifier. All RFID readers use some sort of encoding scheme to transmit data, but we will not go into any further explanation on that topic. When the CW is being sent, the DC power to the output amplifier is left constant. In this transmitter, only the amplitude of the transmitted signal is altered and not the phase, although other RFID reader designs are able to send phase modulated signals.

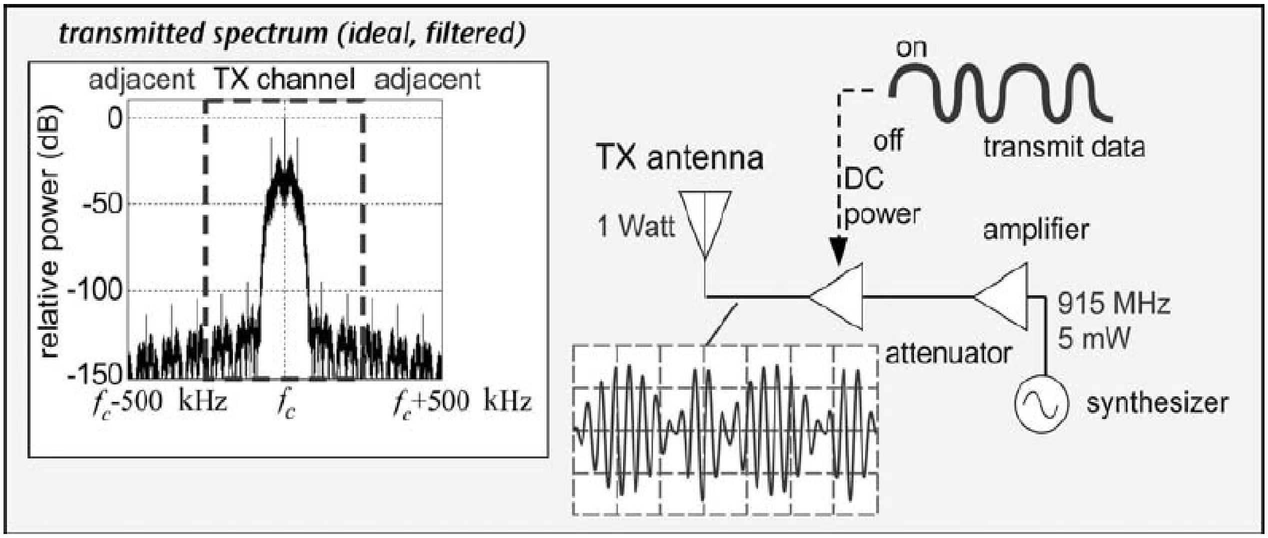


Fig. 14: RFID reader transmitter and modulated signal frequency response.

2.2.2 Receiver

The main challenge of the receiver is to differentiate the backscattered signal from the CW despite the fact that the CW is at a significantly higher power level than the backscattered signal. The answer to this challenge lies in the backscattered modulation technique described in section 2.1.9. The backscattered signal is subcarrier modulated so that it is received at a frequency offset compared to the CW signal. Equation 14 in section 2.1.9 depicted the backscattered signal. The signal entering the antenna at the receiver is a combination of the backscattered signal and reflections of the transmitted CW. Since the transmitter radiates the CW outwards, multiple paths of the signal are able to reach the receiver antenna. This is depicted in equation 15. We will denote r(t) as the signal seen at the receiver antenna. A_C is the amplitude of the CW signal and θ is the phase shift of the CW signal. Note that there are n CW signals received by the antenna all at a different amplitude and phase shift.

$$r(t) = A_1\cos(2\pi(\mathrm{f_c} - \mathrm{f_s})\mathrm{t}) + A_2\cos(2\pi(\mathrm{f_c} + \mathrm{f_s})\mathrm{t}) + A_{C1}\cos(2\pi f_c t + \theta_1) + A_{C2}\cos(2\pi f_c + \theta_2) + \ldots + A_{Cn}\cos(2\pi f_c t + \theta_n) \qquad \text{Eq. 15}$$

For future purposes we will lump all of the CW signals received at the receiver antenna as n(t) as described below in equation 16.

$$n(t) = A_{C1}\cos(2\pi f_c t + \theta_1) + A_{C2}\cos(2\pi f_c t + \theta_2) + \ldots + A_{Cn}\cos(2\pi f_c t + \theta_n) \qquad \text{Eq. 16}$$

Equation 15 can then be written as the follows in equation 17. The resulting signal can then be seen graphically in figure 15. The CW from the transmitter is depicted as an impulse at the carrier frequency and the backscattered signals are shown at their frequency offsets.

$$r(t) = A_1\cos(2\pi(\mathrm{f_c} - \mathrm{f_s})\mathrm{t}) + A_2\cos(2\pi(\mathrm{f_c} + \mathrm{f_s})\mathrm{t}) + n(t) \qquad \text{Eq. 17}$$

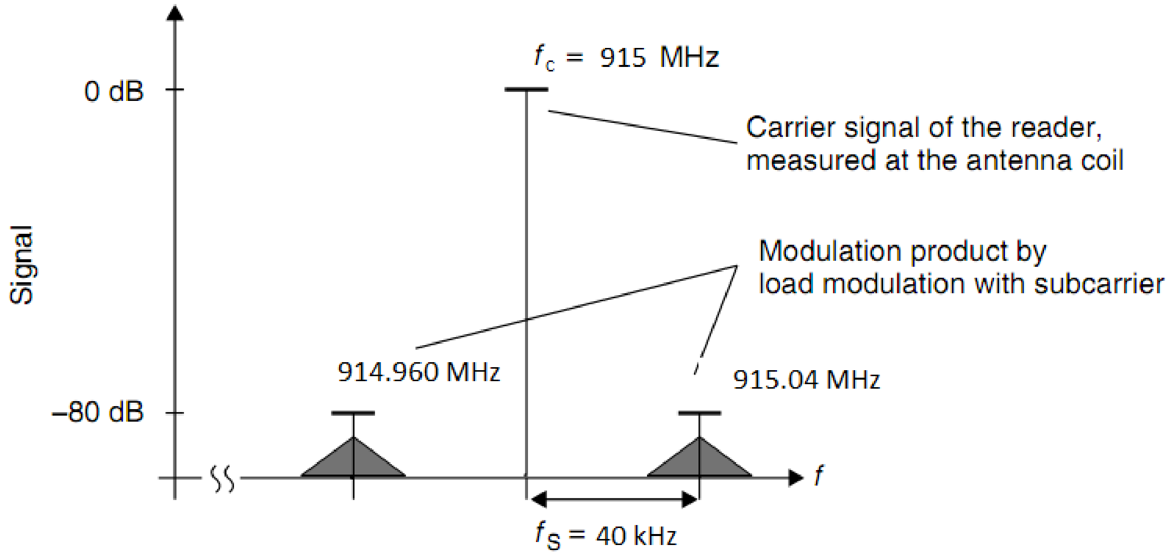


Fig. 15: Frequency spectrum of signal at receiver

The next step would be to remove the CW reflections from the transmitter would be to use a band pass filter surrounding one of the backscattered sidebands. This, however, would be very difficult and costly because narrow band pass filters in the 900 MHz range are not cheap. The easiest thing to do is down convert the signals to baseband and then use a filter to remove the CW component. This is achieved using a homodyne receiver structure as shown in figure 16.

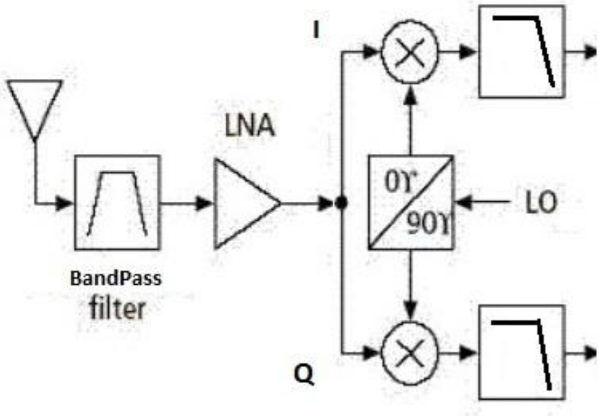


Fig. 16: Homodyne Receiver

The received signal is first fed through a band pass filter to reduce outside noise and then through a low noise amplifier (LNA) which amplifies the weak backscattered signals. The received signal is then split and multiplied by the CW signal or a 90° phase shifty of the CW signal. The output of the I and Q branches are shown in the following equations. We will denote the output of the mixer in the I branch as $y_I(t)$ in equation 18 and the output of the mixer in the Q branch as $y_Q(t)$ in equation 19.

$$\begin{aligned} y_I(t) &= r(t)\cos(2\pi f_c t) \\ &= A\cos(2\pi(\mathrm{f_c}-\mathrm{f_s})\mathrm{t})\cos(2\pi f_c t) + A\cos(2\pi(\mathrm{f_c}+\mathrm{f_s})\mathrm{t})\cos(2\pi f_c t) \\ &\quad + n(t)\cos(2\pi f_c t) \end{aligned}$$

Eq. 18

$$\begin{aligned} y_Q(t) &= r(t)\sin(2\pi f_c t) \\ &= A\cos(2\pi(\mathrm{f_c}-\mathrm{f_s})\mathrm{t})\sin(2\pi f_c t) + A\cos(2\pi(\mathrm{f_c}+\mathrm{f_s})\mathrm{t})\sin(2\pi f_c t) \\ &\quad + n(t)\sin(2\pi f_c t) \end{aligned}$$

Eq. 19

We will then show the simplification of the equations 18 and 19 using trigonometric identities. In order to read the equations better, we have excluded the CW noise analysis. The simplification for the I branch is shown in equation 20 and the simplification for the Q branch is shown in equation 22. Equations 21 and 23 show the CW noise analysis for the I and Q branches respectively.

$$\begin{aligned} y_I(t) &= r(t)\cos(2\pi f_c t) \\ &= \frac{A}{2}[\cos(-2\pi f_s t) + \cos(2\pi(2f_c - f_s)t)] \\ &\quad + \frac{A}{2}[\cos(2\pi(2f_c - f_s)t) + \cos(-2\pi f_s t)] \\ &= A[\cos(2\pi f_s t) + \cos(2\pi(2f_c - f_s)t)] \end{aligned}$$

Eq. 20

$$\begin{aligned} n(t)\cos(2\pi f_c t) \\ &= \frac{A_{C1}}{2}[\cos(\theta_1) + \cos(4\pi f_c t)\cos(\theta_1) - \sin(4\pi f_c t)\sin(\theta_1)] + \cdots \\ &+ \frac{A_{Cn}}{2}[\cos(\theta_n) + \cos(4\pi f_c t)\cos(\theta_n) - \sin(4\pi f_c t)\sin(\theta_n)] \end{aligned} \qquad \text{Eq. 21}$$

$$\begin{aligned} y_Q(t) = \frac{A}{2}[\sin(2\pi(2f_c - f_s)t) - \sin(-2\pi f_s t)] \\ + \frac{A}{2}[\sin(-2\pi f_s t) - \sin(2\pi(2f_c - f_s)t)] = 0 \end{aligned} \qquad \text{Eq. 22}$$

$$\begin{aligned} n(t)\sin(2\pi f_c t) &= \frac{A_{C1}}{2}[\sin(4\pi f_c t)\cos(\theta_1) - \sin(\theta_1) + \cos(4\pi f_c t)\sin(\theta_1)] + \cdots \\ &+ \frac{A_{Cn}}{2}[\sin(4\pi f_c t)\cos(\theta_n) - \sin(\theta_n) + \cos(4\pi f_c t)\sin(\theta_n)] \end{aligned} \qquad \text{Eq. 23}$$

There are a few things to notice from the above equations. First, the backscattered signal in the Q branch is equal to zero. This is because we did not assume there was any phase shift in the backscattered signal. If there was a phase shift, then there would be a term in the Q branch as well along with a phase constant. When the backscattered signal is 90^o out of phase from the CW signal, then the term in the I branch of receiver will be zero and the term in the Q branch of the receiver will look like the result of equation 20.

After the signal passes through the mixing phase, it is sent through a low pass filter. This low pass filter will remove any signal components with frequencies greater than f_s. The outputs of the I and Q branches after passing through the low pass filter will be shown in equations 24 and 25 respectively.

$$y_I(t) = A\cos(2\pi f_s t) + \left(\frac{A_{C_1}}{2}\right)\cos(\theta_1) + \cdots + \left(\frac{A_{C_n}}{2}\right)\cos(\theta_n) \qquad \text{Eq. 24}$$

$$y_Q(t) = -\left(\frac{A_{C_1}}{2}\right)\sin(\theta_1) - \cdots - \left(\frac{A_{C_n}}{2}\right)\sin(\theta_n) \qquad \text{Eq. 25}$$

Now we wish to remove the DC components of the signal which are caused by the CW reflections into the receiver. There are two ways we can do that. The first is to place a capacitor in series with the I and Q branches. A capacitor will block any DC components and will not affect the desired signal at the subcarrier frequency, f_s. The other method is to use a high pass filter to remove the DC components. A high pass filter will be more beneficial because if there were any nonlinear affects on the CW when it was received, then there would be CW noise present at frequencies higher than or lower than DC. The high pass filter would not remove these frequency fluctuations, but it would reduce them more so than the capacitor would. After the filtering phase, the I and Q branches are squared and then added together to produce the final received signal. Equation 26 shows the received backscattered signal. Note that it is a squared version of the actual backscattered signal. This is due to the I and Q separations. This is used to allow for a backscattered signal to be received with a phase difference then the CW signal.

$$y_R(t) = A^2 \cos^2(2\pi f_s t) \qquad \text{Eq. } 26$$

Probability of Error

We will now determine the probability of error for the received signal once passes through figure 16. We will assume that the DC components from the CW were filtered out and all that remains is the backscattered signal and white Gaussian noise. We can split up the decoded signal into a possibility of two signals depending on whether a “1” or a “0” was sent. We will denote the received signal as y(t) and n(t) as the white Gaussian noise and it is shown in equation 27.

$$y(t) = \begin{cases} As_1(t) + n(t) & when\ "0"\ is\ sent \\ As_2(t) + n(t) & when\ "1"\ is\ sent \end{cases} \qquad \text{Eq. } 27$$

The signal will then pass through a matched filter to maximize the SNR. After passing through the matched filter, the signal will be sampled at rate of t = T. We will denote the output of the sampler as x(T) and it is depicted in equation 28.

$$x(T) = \int_0^T h(\tau) y(T-\tau) d\tau \qquad \text{Eq. } 28$$

The probability of error is the probability that a “1” is detected when a “0” was sent plus the probability that a “0” is detected when a “1” was sent. We will assume the probability of sending a “1” or a “0” is ½. This is depicted in equation 29.

$$P_e = \frac{1}{2} P(say\ 1 | sent\ "0") + \frac{1}{2} P(say\ 0 | sent\ "1") \qquad \text{Eq. } 29$$

To determine the probability that we decode a “1” when a “0” was sent we will use equation 28. The output of the sampler can be split up into a sum of two convolutions. The first convolution is between the backscattered signal s(t) and the matched filter and the second is between the white Gaussian noise and the matched filter. Equation 30 shows a further simplification of equation 28 . In the equation we removed the matched filter and replaced it with s(T-τ) because we will chose the matched filter to be the time reversed representation of the backscattered signal.

$$x(T) = \int_0^T s(\tau)s(T-\tau)d\tau + \int_0^T n(\tau)s(T-\tau)d\tau = \Gamma + W \qquad \text{Eq. 30}$$

To proceed any further we must elaborate on equation 30. The right part of the equation is a Gaussian random variable. The left side of the equation reduces down to a number. We can therefore characterize the signal x(T) as a Gaussian random variable with a mean of Γ (we will assume that the white Gaussian noise, n(t), is of mean 0). We then need to figure out the variance of the Gaussian signal to determine the probability of error. Equation 31 depicts the variance of the Gaussian signal. T denotes the period of the bit being transmitted.

$$variance = E[W^2] = \frac{1}{T^2}E\left[\int_0^T\int_0^T n(\tau)n(z)s(T-\tau)s(T-z)d\tau\,dz\right] \qquad \text{Eq. 31}$$
$$= \frac{N_0}{2T}\int_0^T s^2(T-\tau)d\tau$$

Before we can finish determining the probability of error for the system, we need to take a look at the signal to noise ratio for the Gaussian signal out of the sampler. The signal in this case is the left side of equation 30 and the noise is the standard deviation of equation 31. This is shown in equation 32.

$$SNR = \left(\frac{\Gamma}{\sigma}\right)^2 = \frac{2T\left(\int_0^T s(\tau)s(T-\tau)\,d\tau\right)^2}{N_0\int_0^T s^2(\tau)d\tau} \qquad \text{Eq. 32}$$

To simplify this equation we can use the Cauchy Schwarz inequality. This will simplify equation 32 into equation 33.

$$SNR = \left(\frac{\Gamma}{\sigma}\right)^2 = \frac{2T\left(\int_0^T s(\tau)\,d\tau\right)^2\left(\int_0^T s(T-\tau)\,d\tau\right)^2}{N_0\int_0^T s^2(\tau)d\tau} = \frac{2T\left(\int_0^T s(\tau)\,d\tau\right)^2}{N_0} \qquad \text{Eq. 33}$$

This means that the signal to noise ratio only depends on the energy of the signal being transmitted. We can determine the energy in the backscattered signal based on our definition of the Miller modulated subcarrier encoding described in section 2.1.9. In that type of encoding, a logical “0” is sent with energy A^2 and a logical “1” is sent with energy $A^2/2$. With this we can show the probability density function of the received signal and then describe it in equation form. Figure 17 depicts the probability density function for the received random variable X.

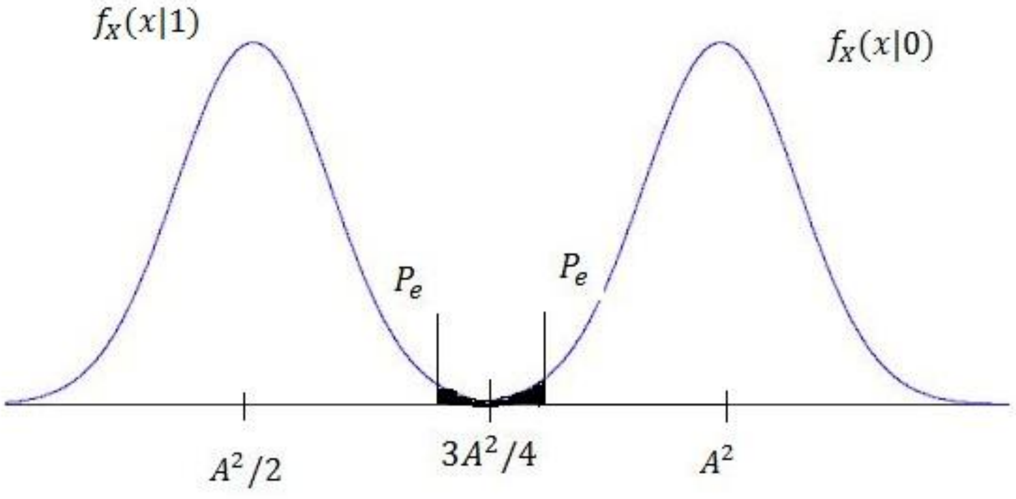


Fig. 17: Probability Density Function for Gaussian Random Variable X

The probability density functions are then shown below in equations 34 and 35.

$$f_X(x|1) = \frac{1}{\sqrt{\pi N_0/T}} exp\left(-\frac{(x-\frac{A^2}{2})}{N_0/T}\right) \qquad \text{Eq. 34}$$

$$f_X(x|0) = \frac{1}{\sqrt{\pi N_0/T}} exp\left(-\frac{(x-A^2)}{N_0/T}\right) \qquad \text{Eq. 35}$$

The previous two equations denoted the probability density functions. The probability of error is the area under the curves in figure 17 where the two density functions overlap. The final probability of error is depicted in equation 36.

$$P_e = \frac{1}{\sqrt{\pi N_0/T}} \int_{3A^2/4}^{\infty} exp\left(-\frac{(x-\frac{A^2}{2})}{N_0/T}\right) dx \qquad \text{Eq. 36}$$

Dynamic Range

When the CW is transmitted from the RFID reader, some objects in the environment reflect the CW and is picked up by the receiver. These unwanted “echoes” are clutter noise and could potentially interfere with the subcarrier frequency of the desired backscattered signal. The clutter noise may be picked up by the receiver with such high power that it saturates the receiver and prevents detection of tag response. This can be prevented if the receiver has a large dynamic range. Dynamic range of a receiver, usually expressed in decibels, is defined as a ratio of the maximum to the minimum signal input power levels over which the receiver can operate with some specified performance. The maximum signal level might be set by the nonlinear effects of the receiver response that can be tolerated, and the minimum signal may be the desired backscattered signal. If the receiver's dynamic range is small, then a relatively strong "echo" can cause the receiver to saturate. Some of the more important characteristics of the receiver's dynamic range are described below.

Receiver Input Noise Level

It is very important to understand and specify the noise level at the receiver input. This is set by the antenna noise temperature and its total effective noise gain or loss. The noise level can be specified either as an RMS power in a specified bandwidth or as a noise power spectral density.

System Noise

The system noise consists of both the antenna and receiver noise. Usually with RFID systems, the receiver input noise exceeds that of the noise due to the receiver itself. This proves that the receiver has only a small impact on the system noise temperature. It is very important while defining dynamic range parameters such as signal to noise ratio to specify whether the noise is the receiver noise or the system noise.

Spurious Free Dynamic Range (SFDR)

The ratio of the maximum signal level to that of the largest spurious signal created within the receiver is called SFDR. This parameter is determined by a variety of factors such as the mixer intermodulation spurious, the spurious content of the receiver local oscillators, the performance of Analog to Digital converter, and the paths that many result in unwanted signals coupling onto the receiver signal path. An ideal mixer acts as a multiplier that produces an output proportional to the product of the two input signals. In passive mixers, the modulation is performed using Schottky barrier diodes where increased dynamic range is required. What happens is that the input RF signal at f_R is modulated by the LO signal f_L. The resulting output signal frequencies [f_R+f_L and f_L-f_R] are the sum and difference of the two input frequencies. All mixers produce unwanted intermodulation spurious responses with frequencies $\pm nf_L \pm mf_R$, and the degree to which these spurious precuts impact the RFID performance depends upon the type of mixer and overall RFID performance requirements.

Clutter Noise

As mentioned above, the receiver picks up the backscattered signal in addition to unwanted reflected signals. The reflected signals are actually the transmitted signal that gets reflected by its surroundings (these reflected signals are also known as clutter). These reflections carry power that will also be picked up by the receiver. The problem with this is that the sidebands of the clutter noise can potentially spillover into the frequency range of interest. The phase of the sidebands of the clutter is related to each other and the carrier by either amplitude or frequency modulation. AM components are generally much lower in power than the FM components, and less problematic. As such, we will discuss the complications of the

FM components. Let's take f_{ns} as the modulating frequency in the noise sidebands and Δf to be maximum frequency deviation. Then the peak amplitude of the carrier and the nearest noise sidebands can be described by equations 37 and 38, respectively, using the Bessel function

$$J_0(\beta) \qquad \text{Eq. 37}$$

$$J_1(\beta) \qquad \text{Eq. 38}$$

The modulation index β = $\frac{\Delta f}{f_{ns}}$.

The Bessel functions can then be approximated given that the modulation index is small. This simplifies the equations shown above to the equations 39 and 40.

$$J_0(\beta){\sim}1 \qquad \text{Eq. 39}$$

$$J_1(\beta){\sim}\frac{\beta}{2} \qquad \text{Eq. 40}$$

We can now find the ratio of the power in the nearest sidebands to that of the carrier. This will be

$$\mathrm{P} = \frac{\Delta f^2}{2f_m^2} \qquad \text{Eq. 41}$$

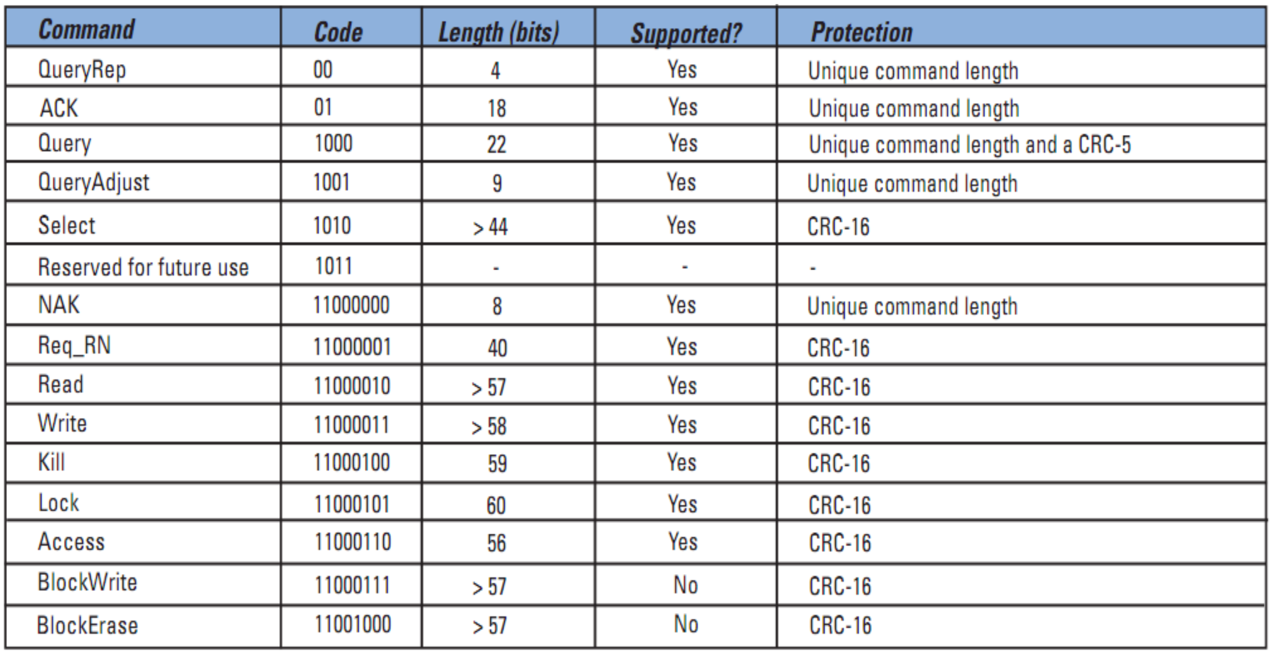
Our RFID reader is implemented using bi-static antennas greatly reduces the spillover and clutter effects.

Interference Canceling

There is one method that is used in some RFID readers to reduce the unwanted signals produced by the transmitter. The method is called interference cancelling and is a dynamic method that mixes the received signal with a CW that is phase shifted to cancel out the received CW signal. The idea is that if the received CW signal is multiplied by a signal that is orthogonal to it and then integrated, the CW noise will be effectively removed from the received signal. The problem lies in not knowing exactly what signal to multiply the received signal by to remove this CW noise. One method is to first multiply the received signal by a 90^{o} phase shifted CW signal and then measure the amount of CW noise present after the integration process. The multiplied signal is then continuously adjusted (either in its phase, frequency, or amplitude) to further reduce the CW noise. It is an iterative process that continuously measures the amount of noise present and then changes parameters to try and further reduce the noise.

2.2.3 Protocol

The RFID reader / tag system that we are using utilizes the Generation 2 Class 1 protocol as outlined by the EPC global organization. The Gen 2 protocol is a handshake based protocol where the reader initiates the communication and the tag responds. A response cannot be generated by either the reader or the tag until the incoming message is decoded. The RFID tag can respond to a certain amount of predefined commands and responds with predefined commands. Table 1 lists all of the commands in the Gen 2 protocol and shows which commands are supported by our RFID tags.



Command	Code	Length (bits)	Supported?	Protection
QueryRep	00	4	Yes	Unique command length
ACK	01	18	Yes	Unique command length
Query	1000	22	Yes	Unique command length and a CRC-5
QueryAdjust	1001	9	Yes	Unique command length
Select	1010	> 44	Yes	CRC-16
Reserved for future use	1011	-	-	-
NAK	11000000	8	Yes	Unique command length
Req_RN	11000001	40	Yes	CRC-16
Read	11000010	> 57	Yes	CRC-16
Write	11000011	> 58	Yes	CRC-16
Kill	11000100	59	Yes	CRC-16
Lock	11000101	60	Yes	CRC-16
Access	11000110	56	Yes	CRC-16
BlockWrite	11000111	> 57	No	CRC-16
BlockErase	11001000	> 57	No	CRC-16

Table 1: EPC Gen 2 Commands

The EPC Gen 2 protocol works by transitioning the RFID tag into states. When the tag has not received any commands, then it is in the “ready” state. When the tag is in this state, it will only respond to certain commands sent by the reader. After each subsequent command sent by the reader, the tag change its state. The handshake protocol is based on the slotted aloha protocol used in certain wireless communications. In slotted aloha, the reader sends the tag a command notifying it of how many slots will be in this current round. The tag generates a random integer between zero and the number of slots in the round and responds to the reader based on the random number. If the tag randomly selects 0, then it will respond immediately to the reader when it first receives the command. If the random number selected is anything other than 0, then the tag waits for another command from the reader indicating that it is the beginning of a new slot and it decrements its random number by one.

Figure 18 shows a typical handshake protocol for communicating with one tag. The reader, or interrogator, begins by sending a query command. This is the first command that must be sent and the tag will not respond to any other command when it is in this state. The query command includes how many slots will be in the round, the bit rate the tag must use, in our case its 40 kHz, and a cyclical redundancy check to ensure the message was received without error. The tag will respond if it received the query without error and if it randomly selected slot 0. The tag responds with a RN16, a 16 bit random number that differentiates it from any other tag within range. The reader will then respond with an ACK that includes the RN16 number sent by the tag. If the tag receives the ACK with the correct RN16 number, it will backscatter its EPC number which is a 96 bit number that identifies the tag. When the reader receives the EPC number, it could refrain from sending any more commands to the tag or send additional commands to write data to the tag if necessary.

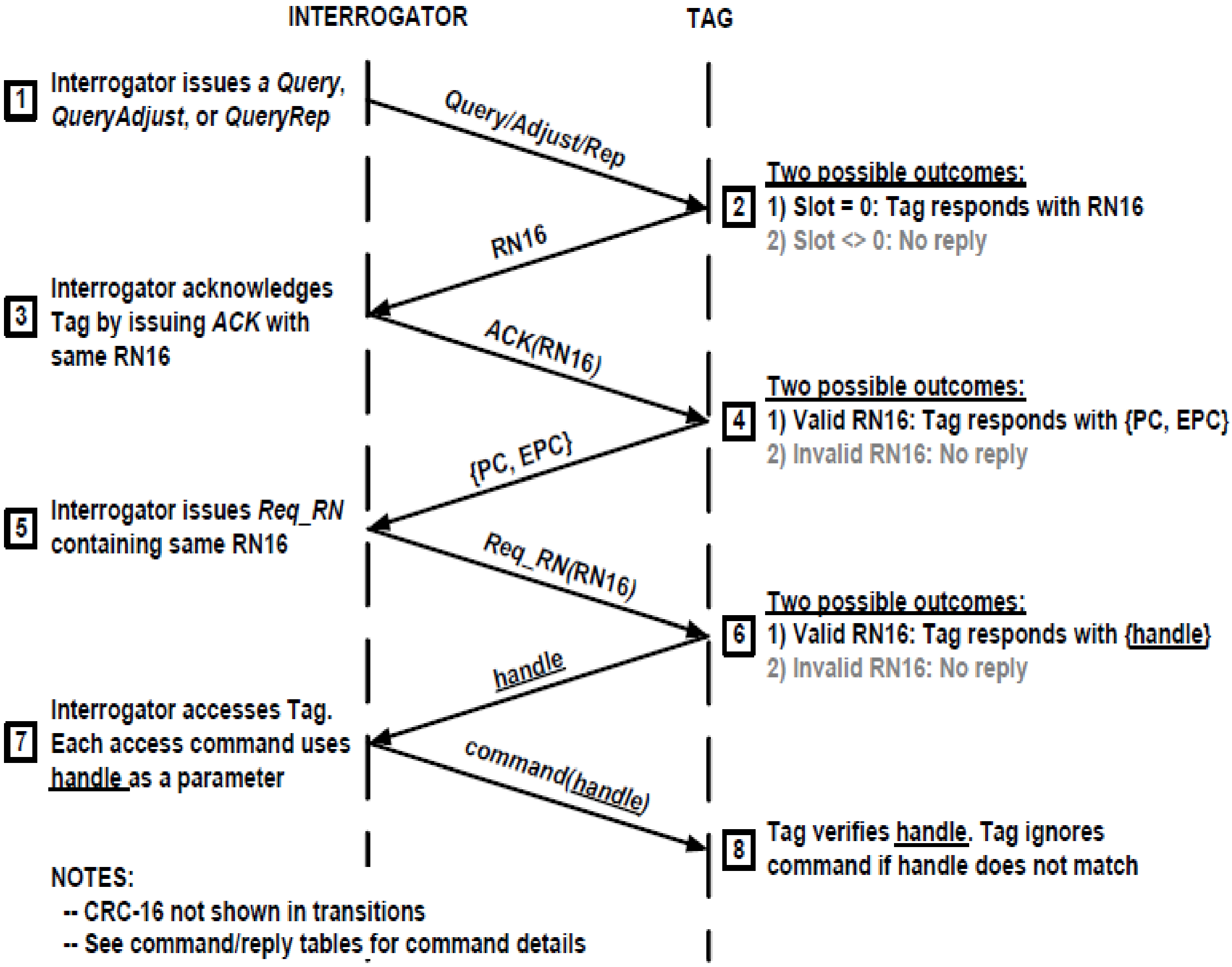


Fig. 18: Handshake Protocol for EPC Gen 2

3. Procedure

3.1 Initial Procurement and Installation

Since we did not have access to a commercial RFID reader, we did some research into how we can build our own RFID reader. Upon doing research, we realized we could use GNU Radio to implement an RFID reader. GNU Radio is open source software that performs communications processing at the software level, instead of at the hardware level. It is defined by signal processing blocks and flow graphs. Each block handles a specific signal processing operation (i.e. filtering), and graphs call these blocks, set their parameters, and connect them together. Next, we researched the Universal Software Radio Peripheral (USRP), which is essentially an RF front end used to transform the RF signals designed in software to the real world.

The next steps involved configuring and installing GNU Radio and USRP. We found that GNU Radio operates easily and is supported by Linux operating systems. So we installed Ubuntu on a laptop and started the dissection of the GNU Radio code.

We focused our attention next on making an RFID reader. While we were researching this topic, we came across the work of a PhD student, Michael Buettner from Washington University, who had designed an RFID reader using GNU Radio and USRP. We installed this code and began implementing the necessary changes. This task itself took majority of our time due to the fact that we had to first understand what the purpose of each file was and understand the code. The Appendix provides the exact steps that we took to install and configure the USRP, GNU Radio, and RFID code.

3.2 Testing / Adjustments

Initially, when we started the testing, our RFID reader did not detect the presence of any tags. Using the software plotting tool, Octave, we were able to see if the reader received any modulated back-scatter signal from the tags. We initially bought Gen 2 Inlays from TI which were not be detected by the RFID reader. Upon further research we found out that the tags were outdated and discontinued. Therefore, we bought Alien Omni-Squiggle Sticker Labels, which we referred to us by Michael Buettner, as these were the tags he originally tested his RFID reader. The new RFID tags gave us the result we expected as we were able to detect the RFID tag.

For us to properly test the device, we made a pair of stands (using PVC pipes) for our antennas which we taped to a cardboard box and cut a hole out in the center so as to slip the box through the individual stands. Then we took a rotating chair and taped the tag on the back and tested the distance of which a tag can be read. Since the antennas we are using have a beam-width of 40º we took string and measured out the angle from the center of the antenna. We then moved the chair around and ran the device and came to a conclusion that the tag can only be read from 9 inches away within the 40º width. We had to go back to the code and adjust the amplitude of the transmitting signal to realize that the best fit was 27,000 at 915 MHz. Refer to the section labeled Pictures to view our setup.

3.3 Code Modifications

When we first started testing the Alien Omni-Squiggle Sticker Labels we noticed that all of the tags had the same pre programmed EPC code on them. This made it impossible to test the RFID reader with multiple tags within range because we were not be able to distinguish one tag from another. Our solution was to program the tags ourselves using our RFID reader. As shown in table 1 in the RFID theory section of the report, the RFID tags can respond to a write command, and we then can program there non volatile memory (NVM) with a new EPC code. The problem with the solution is that Michael Buettner, the PhD student who wrote the code, had not seen any value in writing to an RFID tag so had not implemented the code.

Our next step was to write the code to send the command. The hardest thing about writing the code was to implement the CRC-16 (cyclical redundancy check) which is a 16 bit word that ensures the data was sent without error. The CRC-16 circuit diagram is depicted in figure 19. Once the code was finished and tested we had to see if the tag would respond to the new commands. Another problem arose when we realized that the tags will only respond to the command needed to be sent prior to the write command, if it is received within 500 μs of the tag's previous response. This became very difficult to overcome because of the data rates of the USB connector and slow speed of the USRP. The semi solution we came up with was to send the command before the tag's previous response was completely decoded (since that response from the tag was not needed to send the command). This solved the timing issue and we were able to send the command within 500μs. As a backup plan, we also order a few randomly programmed tags with different EPC numbers.

We then came to know that Professor Marsic's TA, Siddika Parlak, had a commercial RFID reader. She programmed our RFID tags, each with a unique EPC identifier. This enabled us to begin our testing with multiple RFID tags.

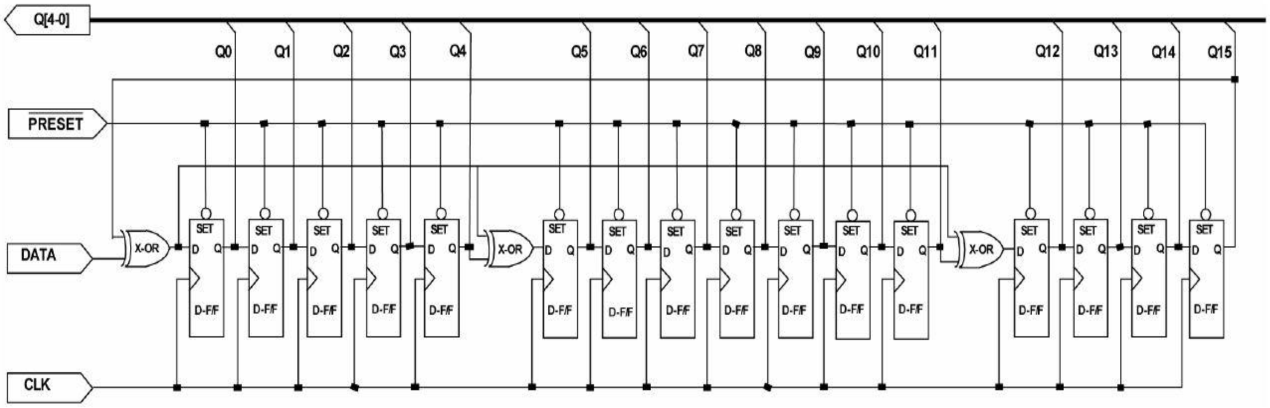


Fig 19: CRC-16 circuit diagram

3.4 GUI Application

In our approach in making a GUI Application, we had two things that we wanted to tackle. One was to integrate the RFID reader with the application and the other was to make a user friendly application so our users would not have difficulty navigating through it. The setup of our application is set so the user selects a product from a drop down box. Initially, the user would have to manually input what products they want the RFID reader to track, and also assign it with the appropriate tag (text file). When a product is selected by the user, if the EPC number is detected in the *log_out* file of the RFID reader, then the EPC, Purchased date, and the time of detection will appear in the appropriate fields. Along with that, there is a field called availability that would be filled saying “Available.” In the case where the EPC has not been detected, the availability field will be set to “Not Available” and you will see the EPC field and Purchased date empty so there is no confusion. The application also allows the user to update / change the purchased date of the individual product by using an option on the application called “Update Date Purchased.” We also have a clear button which can clear all the fields.

A separate text file is created so the user can initially put in the products and given EPC number. Our algorithm compares each EPC number in the text field to the EPC number in the *log_out* file that has been last updated. Since the *log_out* file does not delete itself after every scan and logs underneath the previous scan, we had to make sure our application only reads the “latest” scan instead a previous scan. We wrote an algorithm that reads the file from the bottom up and stops when it hits a particular string that indicates a scan has been started. Then it reads that particular block of data and scans to see if it finds a match with the EPC number from the text file. Our algorithm also keeps track of the time and day when the RFID reader runs by checking when the log_out file was last modified. Along with all this, we thought it would be useful if by a click of a button the application showed a list of products that is recommended to buy. The list would display all the products not detected by the recent scan. The simplicity of our application makes it enjoyable for the user to navigate.

4. Technical Specifications

4.1 USRP

- Four high-speed analog-to-digital converters - 64 MS/s at a resolution of 12 bits
- Four high-speed digital-to-analog converters- 128 MS/s at a resolution of 14 bits
- Two digital up converters with programmable interpolation rates
- Two digital down converters with programmable decimation rates
- Capable of processing signal up to 16 MHz wide
- An Altera Cyclone
- A Cypress EZ-USB FX2 high-speed USB 2.0 controller
- 4 extension sockets (2 TX, 2 RX) in order to connect 2-4 daugtherboards
- 64 GPIO pins available through 4 Basic TX/Basic RX daughterboards

4.2 RFID Tags

Alien Omni-Squiggle Sticker Label
Dimensions (W x H mm): 101.6 x 101.6
RFID Chip: Monza
Air Interface: EPC Class 1 Gen 2
EPC Memory: 96-bits
Read Range: 3-5 meters

Gen 2 Inlay
Dimensions (W x H mm): 95.25 x 38.1
Air Interface: EPC Class 1 Gen 2
User Memory: 96-bits
Operating Frequency: 860-960 MHz
Data sheet: http://www.ti.com/rfid/docs/manuals/pdfSpecs/epc_inlay.pdf
Read Range: 3-5 meters

4.3 Antenna

Alien Antenna
Frequency Range: 860-930 MHz
Polarization: Circular
3dB Beam-width: 40º nominal
Return Loss: -15dB across frequency range

5. Cost Analysis & Comparison

In order for a project to be truly successful, it must ultimately be economically feasible, and be marketable to a larger audience (e.g. the one in question for this project is the everyday user). Shown below is a table outlining the necessary parts ordered and its associated costs.

Item	Quantity	Cost
Universal Software Radio Peripheral (USRP)	1	$700.00
RFX900 Daughterboard	2	$550.00
Alien RFID Circular Antenna	2	$363.98
RFID Gen 2 Inlay	25	$21.75
Alien Omni-Squiggle Sticker Label	10	$12
Shipping and Handling		$60
Stands	2	$67

Total Cost: $1774.73

The UHF RFID tags are relatively inexpensive, which is important considering there can be many food products that a person may need to track within his/her refrigerator. However, the combination of the cost of the USRP, daughterboards, and antennas is a steep one.

Implementation of this system in the real world would maintain a fixed cost of $1613.98 (includes USRP, daughterboard, and antennas). The variable cost in this would be the RFID tags. The number of tags bought by the user depends on his or her needs, and these needs vary from person to person. As such, it is questionable as to whether or not this product could provide revenues if made available to the public.

Commercial Gen 2 RFID Reader

A commercial Gen 2 RFID Reader as seen below is roughly **$1500**. The specifications to this RFID is similar to the RFID we built using the USRP, RFX900 Daughterboard, and GNU Radio. The main difference lies in the fact that this commercial reader supports more LAN protocols and uses monostatic antennas. Commercial readers generally have hardware to isolate the receive chain from the CW signal, use sharp cut-off filters to suppress all but the tag response, and transmit at a higher power. Using the USRP and GNU Radio gives a high degree of flexibility with respect to both the MAC and PHY layers of the system. The level flexibility is only possible with this setup and not with commercial readers which allows low-level RFID research.

6. Conclusion

The implementation of the RFID reader using GNU Radio and USRP was successful, but difficult. We were successfully able to read multiple RFID tags, and design a Java application to recommend the user to buy food products based upon availability. Our main difficulties included learning how to use Linux, GNU Radio, and USRP. In addition, we had to make changes to the RFID code to enable reading and writing of the tags. The main drawbacks of the RFID reader was the read range, which was only 9 inches and the large amplitude we had to use to successfully read the tags at that range. As a result, we believe the implementation of this system in the real world is not yet practical as the USRP is still in its developmental stages, and the costs of such a system are expensive. We do, however, believe that this implementation would be useful for anyone interesting in testing changes to the RFID system. But as a commercial product, this implementation falls short.

7. Division of Labor

We distributed the work in our project as follows.

RFID Reader code configuration / compilation --> Nishit and Eric

RFID testing past and future --> Nishit, Hiran, and Eric

RFID Reader code modifications/enhancements --> Eric

GUI / Application --> Hiran and Nishit

Report --> Nishit, Hiran, and Eric

8. References

[1] Wikipedia: The Free Encyclopedia.
<http://en.wikipedia.org/wiki/Envelope_detector>
< http://en.wikipedia.org/wiki/Maximum_power_transfer_theorem>

[2] Daniel M. Dobkin. Elsevier, 2008. *The RF in RFID Passive UHF RFID in Practice.*

[3] Meng-Lin Hsia, Yu-Sheng Tsai, Oscal T-C. Chen. *An UHF Passive RFID Transponder Using A Low-Power Clock Generator without Passive Components.* Dept. of Electrical Engineering, National Chung Cheng University. IEEE, 2006.

[4] Merrill Skolnik. McGraw-Hill Professional, 2008. *Radar Handbook.*

[5] Merrill Skolnik. McGraw-Hill College, 1980. *Introduction to Radar Systems.*

9. Pictures

Fig. 20: USRP and Laptop with GNU Radio

Fig. 21: 2 Alien Antennas on stands

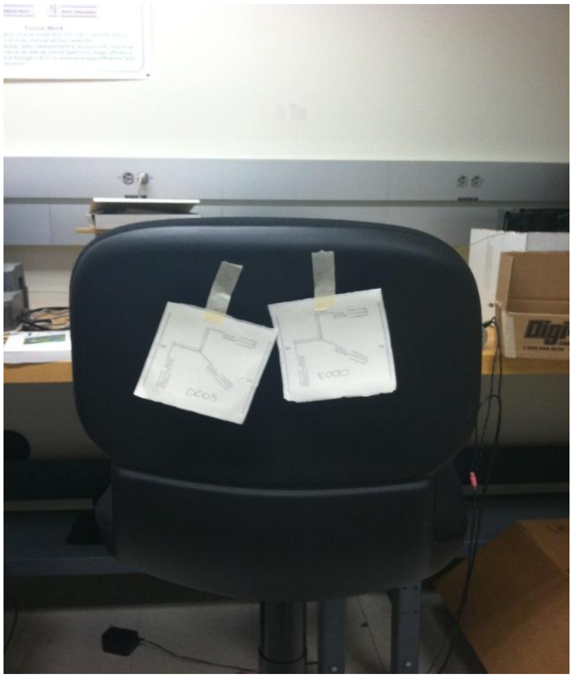


Fig. 22: Gen 2 Tags on Chair

Fig. 23: Tags 9 inches away from Receiver

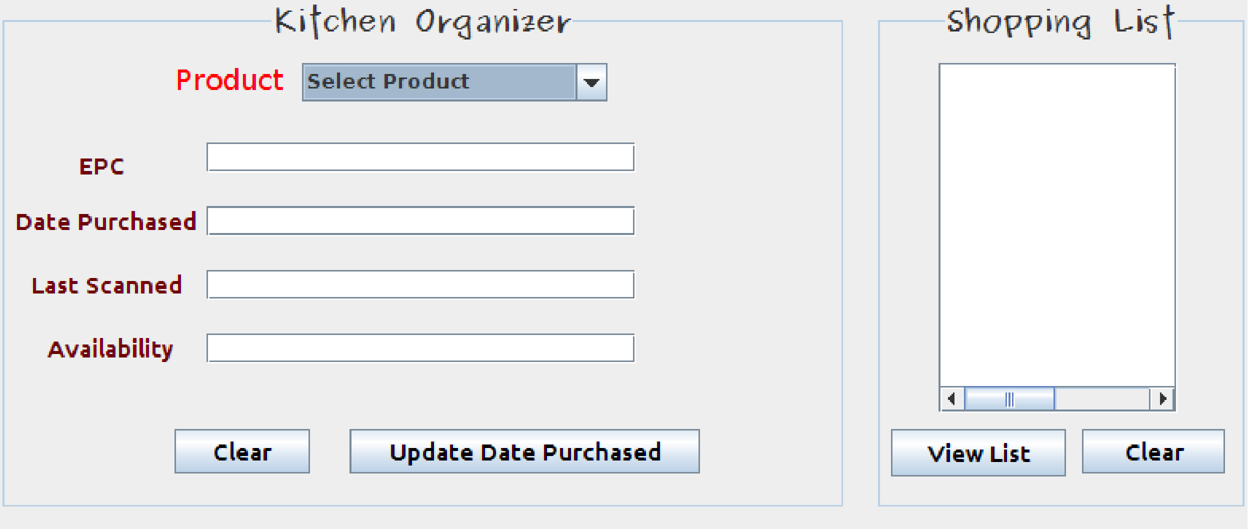


Fig. 24: Default View of GUI Application

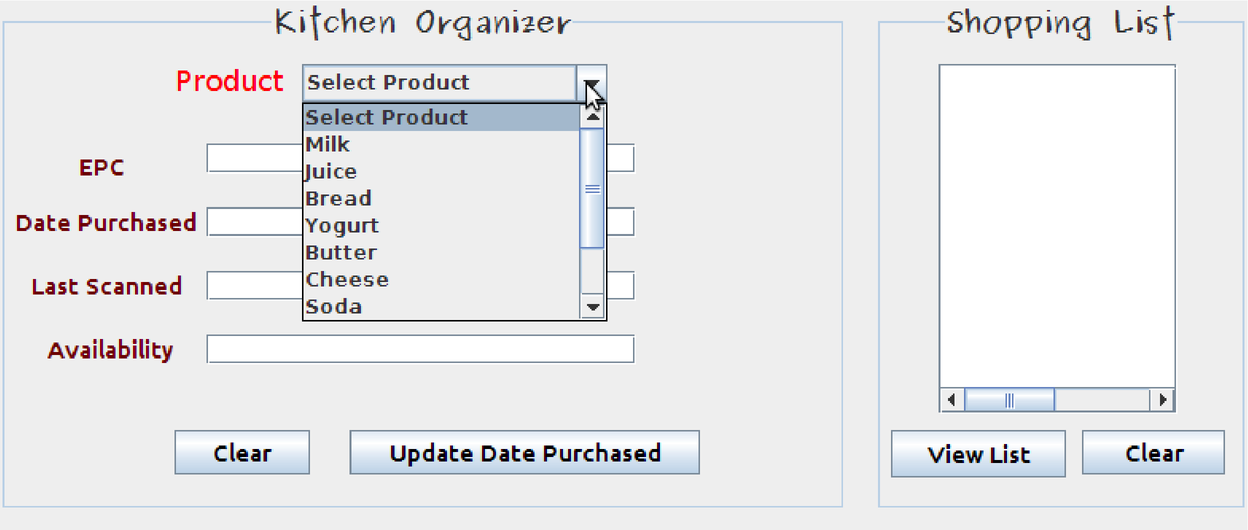
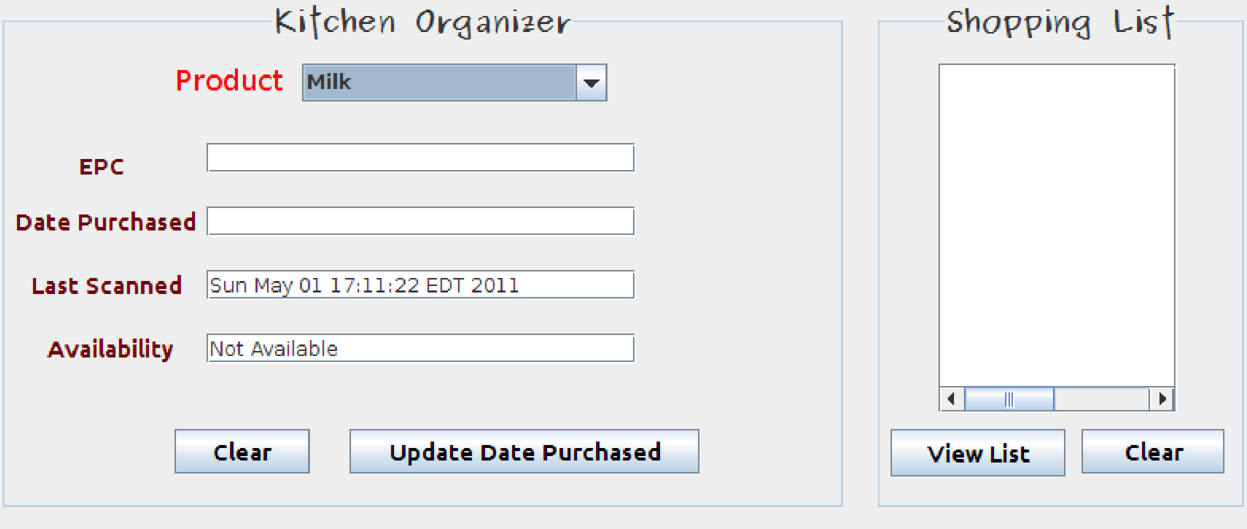
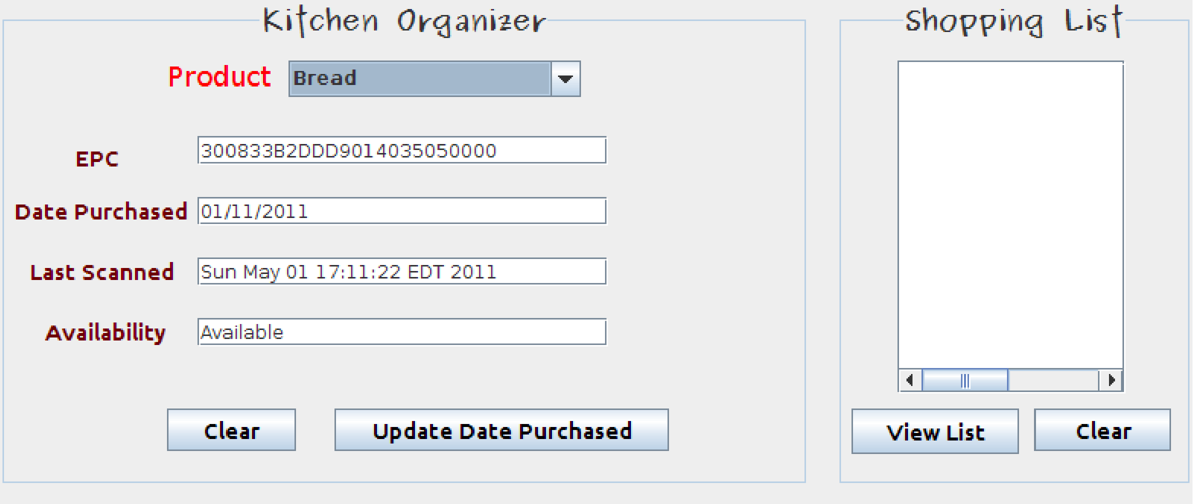


Fig. 25: Drop Down Box of Products



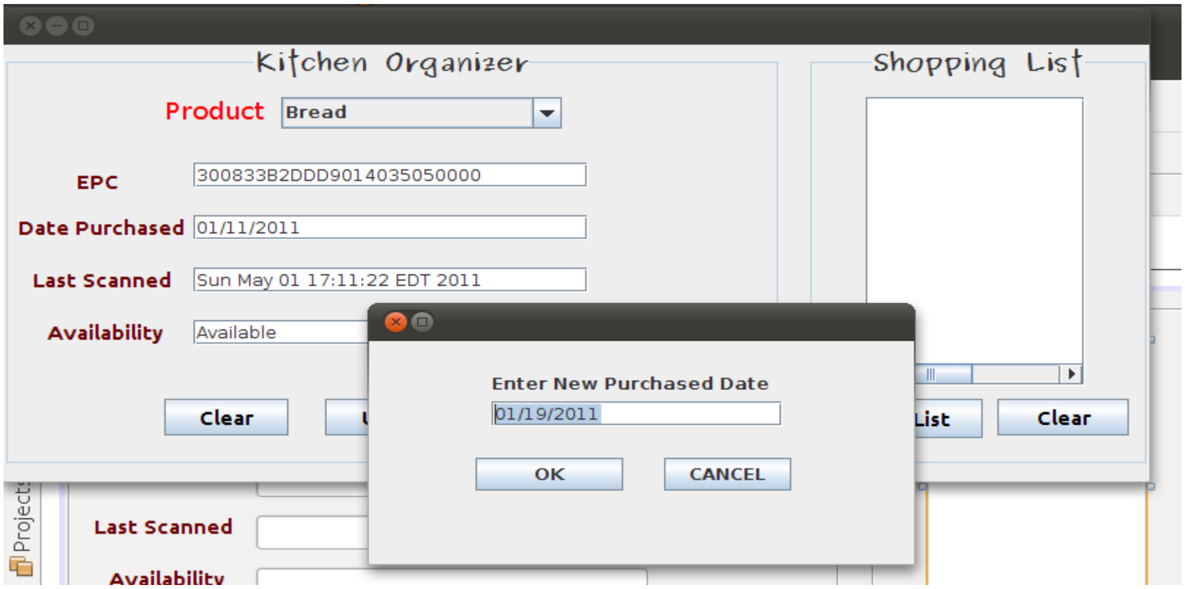
Product: Milk
EPC:
Date Purchased:
Last Scanned: Sun May 01 17:11:22 EDT 2011
Availability: Not Available

Fig. 26: Display When Product Has Not Been Detected



Product: Bread
EPC: 300833B2DDD9014035050000
Date Purchased: 01/11/2011
Last Scanned: Sun May 01 17:11:22 EDT 2011
Availability: Available

Fig. 27: Display When Product Has Been Detected



Product: Bread

EPC: 300833B2DDD9014035050000

Date Purchased: 01/11/2011

Last Scanned: Sun May 01 17:11:22 EDT 2011

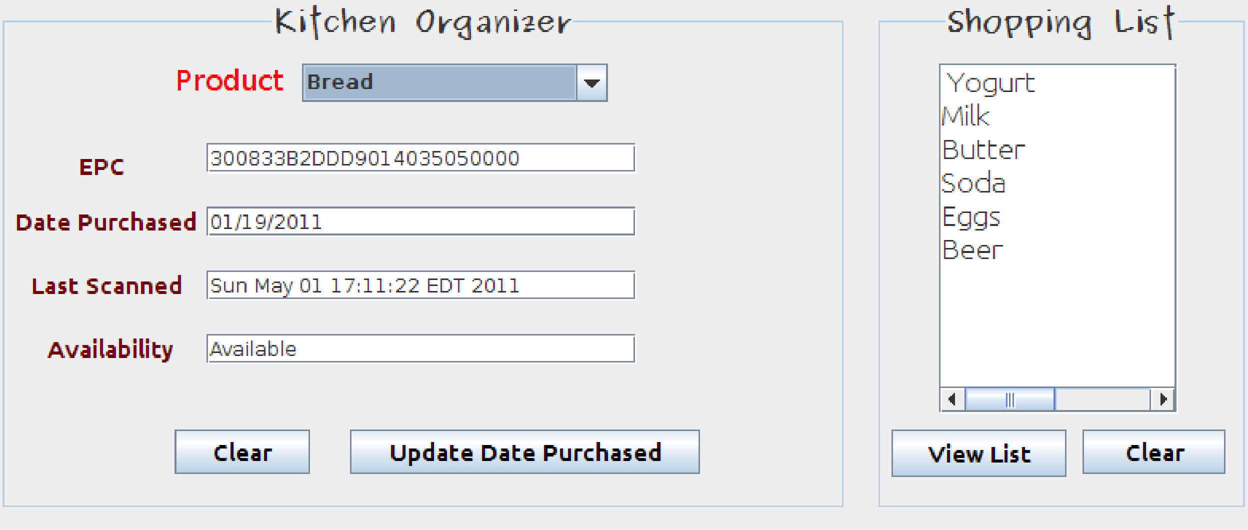
Availability: Available

Enter New Purchased Date: 01/19/2011

Last Scanned

Availability

Fig. 28: Display to Enter New Purchased Date



Product: Bread

EPC: 300833B2DDD9014035050000

Date Purchased: 01/19/2011

Last Scanned: Sun May 01 17:11:22 EDT 2011

Availability: Available

Yogurt
Milk
Butter
Soda
Eggs
Beer

Fig. 29: List of Products User Should Buy

Appendix

1. Install software dependencies for GNU Radio.

```
sudo apt-get -y install libfontconfig1-dev libxrender-dev libpulse-dev swig g++ automake autoconf libtool python-dev libfftw3-dev \
libcppunit-dev libboost-all-dev libusb-dev fort77 sdcc sdcc-libraries \
libsdl1.2-dev python-wxgtk2.8 git-core guile-1.8-dev \
libqt4-dev python-numpy ccache python-opengl libgsl0-dev \
python-cheetah python-lxml doxygen qt4-dev-tools \
libqwt5-qt4-dev libqwtplot3d-qt4-dev pyqt4-dev-tools python-qwt5-qt4
```

2. Configure and install GNU Radio

```
git clone http://gnuradio.org/git/gnuradio.git
cd gnuradio
git branch --track next
git checkout next
git branch
export PKG_CONFIG_PATH=/usr/local/lib/pgkconfig:${PKG_CONFIG_PATH}
./bootstrap
./configure
make
make check
sudo make install
```

3. Configure USRP Hardware

```
sudo addgroup usrp
sudo usermod -G usrp -a ece
echo 'ACTION=="add", BUS=="usb", SYSFS{idVendor}=="fffe",
SYSFS{idProduct}=="0002", GROUP:="usrp", MODE:="0660"' > tmpfile
sudo chown root.root tmpfile
sudo mv tmpfile /etc/udev/rules.d/10-usrp.rules
```

The open source RFID reader code was downloaded from the following website: https://cgran.org/wiki/Gen2.

4. Configure, Install, and run RFID reader

```
./configure --prefix=/usr/local/rfid/gnuradio/lib
make
sudo make install
PYTHONPATH=/usr/local/rfid/gnuradio/lib/python2.6/site-packages GR_SCHEDULER=STS nice -n -20 ./gen2_reader.py
```