Transmit Mode vs. Loading Mode in Electrostatic Tags

Babak Nivi

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Abstract

We compare the AC current amplitudes seen at the reader in the loading and transmit modes of an electrostatic radio frequency identification tag. The goal is to determine which method is best for tag to reader communication. Preliminary results indicate that loading mode may be the best communication method.

1 Electrostatic Tags

We have developed a new type of electrostatic radio frequency identification (RFID) tag at the Physics and Media group of the MIT Media Lab. Specifically, we use body capacitance and earth ground to send data and power through the body to the tag. Figure 1 shows the general circuit topology. This type of data transmission through the body has been studied in [2, 1].

RFID tags may communicate with the reader in two ways

Transmit Mode The tag *actively transmits* data to the reader by applying a voltage to its electrodes (Figure 2).

Loading Mode The tag sends data to the reader by modulating the load (complex impedence) that it presents to the tag (Figure 4).

Most commercial magnetostatic RFID systems use loading mode communication. Our goal is to determine whether transmit mode or loading mode is the best method for the tag to communicate with the reader in the context of electrostatic tags. We proceed by approximating the changes in the amplitude of the AC current that the reader sees due to the tag.

2 Transmit Mode

The goal here is to get a rough idea of how much current we can expect to see at the tag reader from an electrostatic shoe tag that is *actively transmitting* a signal. Figure 2 shows a model of the system with approximate capacitances. $C1$ is the

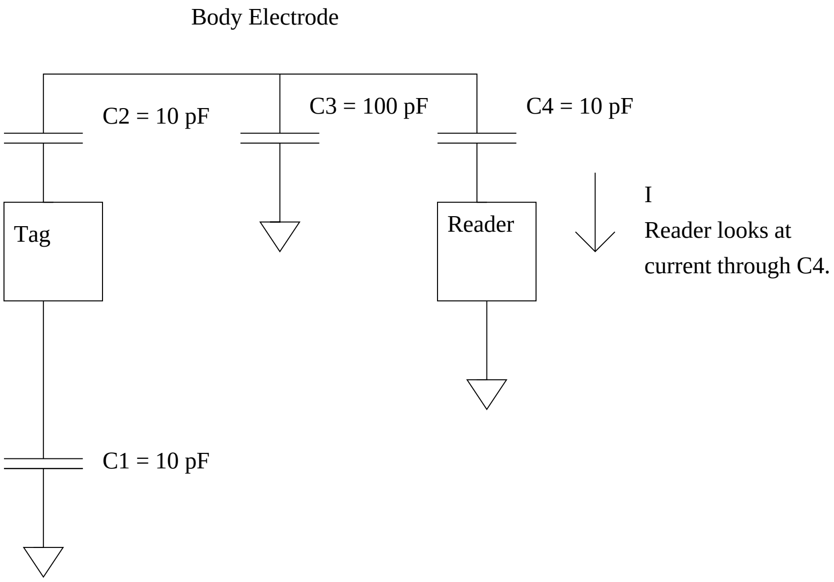

Figure 1: Electrostatic Tag Circuit Topology

capacitance of the bottom tag electrode to ground, $C2$ is the capacitance of the top tag electrode to the body, $C3$ is the capacitance of the body to ground, and $C4$ is the capacitance of the body to the reader. We model the tag as a voltage source V operating at a fixed frequency ω.

2.1 Transmit Mode Thevenin Equivalent

Figure 3 shows the Thevenin equivalent of the circuit from the viewpoint of $C4$ looking to the left. The explicit formula for C_{Th} and V_{Th} are

$$\begin{aligned} C_{Th} &= \frac{C_1 + C_2}{C_1C_2 + C_1C_3 + C_2C_3} \\ &= 9.5 \text{ fF} \end{aligned}$$

$$\begin{aligned} V_{Th} &= \frac{C_1C_2}{C_1C_2 + C_1C_3 + C_2C_3} V \\ &= .05 \text{ V} \end{aligned}$$

The series capacitance of $C_{Th} = 9.5$ fF and $C_4 = 10$ pF is approximately 9.5 fF. Therefore, the voltage source sees a capacitance of approximately 10fF.

2.2 Transmit Mode Current Calculations

If we assume that the tag can generate a 10V amplitude sinusoidal voltage swing at some angular frequency ω, then the magnitude of the current through the

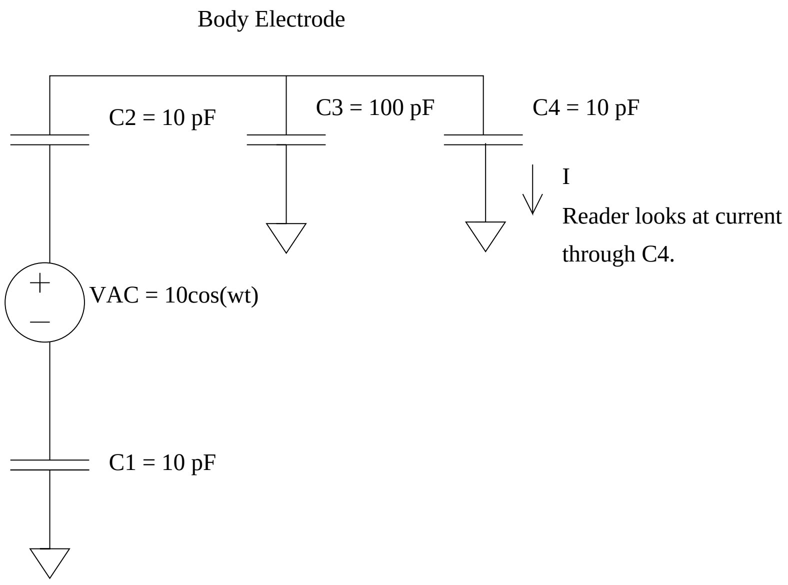

Figure 2: Trasmit Mode Circuit Topology

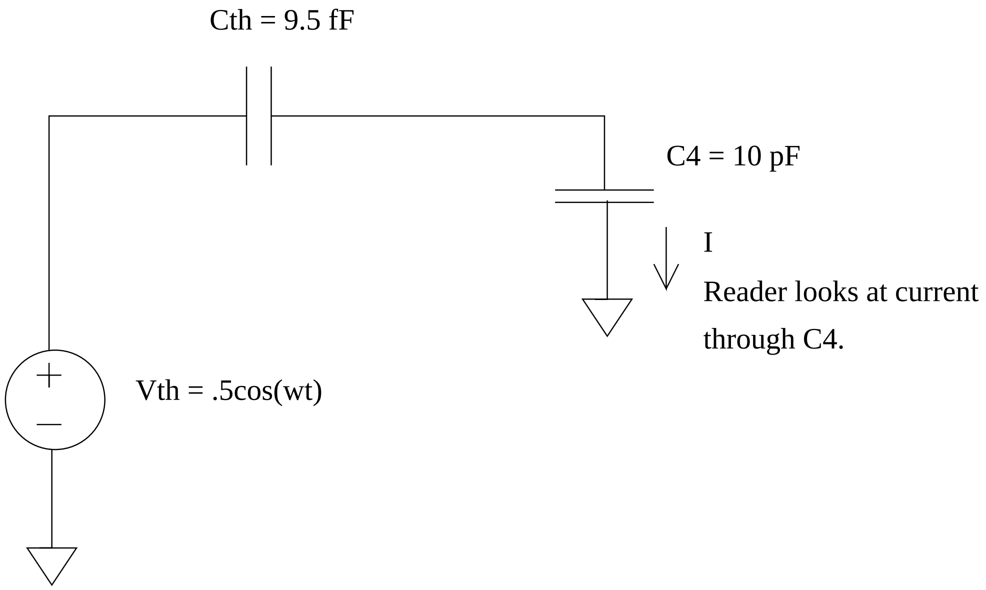

Figure 3: Trasmit Mode Thevenin Equivalent

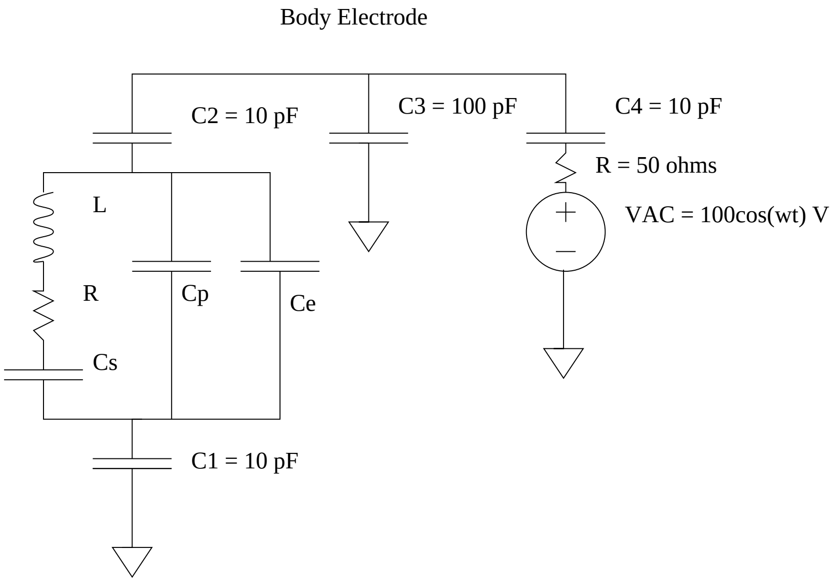

Figure 4: Loading Mode Model

reader is[1]

$$I = \frac{.05(10\mathrm{V})}{\frac{1}{\omega 10\cdot\ 10\mathrm{pF}}} = 5 \cdot 10^{-12} \omega \mathrm{VF}$$

If we assume low frequency operation at $\omega = 2\pi \cdot 10^5$ radian/s^{-1} (the current at the tag is linear with frequency but we keep frequencies low to prevent the body from radiating like an antenna), then $I = 3.14$ μA Therefore the reader can expect to see currents on the order of a microamp.

3 Loading Mode

The goal here is to get a rough idea of how large of a change in the amplitude of AC current we can expect to see at the tag reader by modulating the load that the tag presents to the reader. Figure 4 shows a model of the system with approximate capacitances.

3.1 Crystal Model

We model the tag as a quartz crystal where L, C_s, R model the *motional* reactance and resistance of the crystal and C_p is the parallel plate capacitance formed by the two metal electrodes separated by the quartz dielectric. Table 3.1 lists the values of L, C_s, R, C_p and Q for 100 kHz and 1 MHz crystals. C_e is the

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[1] Since we do not care about phase in any of these calculations, throughout this paper V and I are the real amplitude of signals with $e^{j\omega t}$ time dependence.

f (MHz)	L (H)	C_s (pF)	$R(\Omega)$	C_p (pF)	Q
.1	2.9	.1	300	13.5	50,000
1	25	.0085	260	3.4	72,000

Table 1: Crystal Parameters

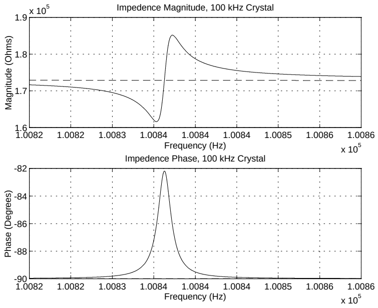

Figure 5: Phase and magnitude of impedence seen by reader near 100 kHz crystal resonance.

capacitance between the top and bottom tag electrodes. We also assume that the reader has a source impedence of 50 Ω.

3.2 Impedence Calculation

Now we calculate the impedence that the reader source sees. It is straightforward but extremely menial to calculate this impedence symbolically. Rather than calculate the impedence symbolically, we use Matlab (see Appendix B for source code) to calculate the magnitude and phase of the impedence near the resonance of the crystal (Figures 5 and 6). The solid lines in the figures indicate the magnitude or phase of the impedence seen by the reader when the crystal is part of the circuit as in Figure 4. The dashed lines indicate the magnitude or phase of the impedence seen by the reader when the crystal is replace by a short.

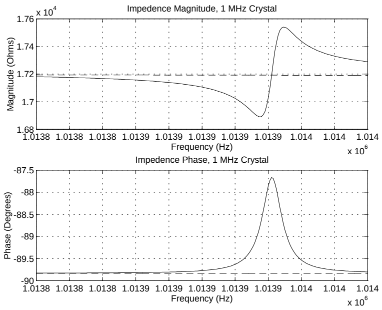

Figure 6: Phase and magnitude of impedence seen by reader near 1 MHz crystal resonance.

3.3 Choosing the Crystal Resonant Frequency

At high frequencies, C_3 shorts the body to ground and destroys the communication link from the tag to the reader. At low frequencies, C_1, C_2, and C_4 do not pass current from the reader to the tag again destroying the communication link from the tag to the reader. For example, the Q of the system that the reader sees increases as the resonant frequency of the crystal is reduced (visually compare the Qs in Figures 5 and 6). There is some optimal crystal resonant frequency or frequencies where the reader sees the highest Q system. Therefore, I evaluated the system at 2 crystal resonant frequencies: 100 kHz, and 1 MHz.[2]

3.4 Current Calculations

Note that Figures 5 and 6 do not indicate that the impedence that the reader sees resonates near the resonant frequency of the crystal. Rather, the reader sees a capacitance (the phase is $-\pi/2$ off resonance) that is slightly perturbed near the resonant frequency of the crystal. If the reader actually saw a resonant system, the phase of the impedence that the tag sees would be 0 at resonance.

Let us calculate the change in load magnitude $\Delta Z = Z_1 - Z_2$ required to create a change in reader current amplitude $\Delta I = I_1 - I_2$ for a given reader

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[2] I only had crystal data for 100 kHz and 1 MHz crystal resonant frequencies. Otherwise I would have evaluated the model at other frequencies as well.

voltage amplitude V. Let $V/Z_1 = I_1$ and $V/Z_2 = I_2$. Then

$$V\left(\frac{1}{Z_1} - \frac{1}{Z_2}\right) = I_1 - I_2$$

We will take $V = 100$ V. In the case of the 1 MHz crystal we might hope that the reader can switch frequencies between the dip and the peak of the impedence magnitude in Figure 6 resulting in

$$\Delta I = 100\text{V}\left(\frac{1}{16900\Omega} - \frac{1}{17500\Omega}\right) = .2\text{mA}$$

However this ΔI rides on top of a current amplitude of approximately $100\text{V}/17200\Omega =$ 5.8mA. Thus ΔI perturbs the current amplitude by only 4%. In the case of the 100 kHz crystal, $\Delta I = 77\mu\text{A}$, the steady state current amplitude is .6 mA giving a perturbation of 13.3%.

4 Transmit Mode vs. Loading Mode

Detection in transmit mode requires detecting microamp amplitude currents at the reader. Detection in transmit mode requires detecting changes in amplitude of 100 μA, 2 orders of magnitude larger than the currents in transmit mode. However these changes in current are less than 10% of the amplitude they ride on. But there is the possibility of constructing a bridge circuit to cancel out the constant amplitude in loading mode. However this might be difficult or impossible because changes in the coupling between the body and ground, body and the reader, and the body and tag might perturb the bridge's rejection properties because they will affect the DC impedence the reader sees.

Assuming that we can reject the DC current amplitudes in loading mode, loading mode is the winner of this contest. Note however that we assumed that the crystal in loading mode was unloaded, i.e. the tag will require one crystal for power recovery and one crystal for data transmission.

A Possible Improvements in this Calculation

There are many possible improvements to this calculation and many things left to figure out:

- Find the optimal crystal resonant frequency.
- Get more parameter data on crystals at a wider range of frequencies.
- Determine why in the lab we see phase dispersion but out impedence graphs do not indicate phase dispersion.
- How can we use impedence phase to get more reliable communication in loading mode?
- Calculate the noise floor in transmit mode.

B Matlab Source Code

```
% Calculate complex impedence seen by the tag reader in loading mode.
function Z = tag(f,x)

w = 2*pi*f;
x = 1e5/x;

ivector = ones(size(w))*i;

% Crystal L
L = 2900e-3; % 1 MHz

% Crystal R
R = 260;

% Crystal series C
Cs = .0085e-12;

% Crystal parallel C
Cpc = 3.4e-12;

% Tag electrode capacitance
Ce = 10e-12;

% Crystal parallel C plus electrode capacitance
C = Cpc + Ce;

% Tag impedence

Ztag = ((i*w*L + R + -ivector./(w * Cs)) .* -ivector./(w * C)) ./
((i*w*L) + R + -ivector./(w * Cs) -ivector./(w * C));

Ztag = 0;

% Tag bottom electrode to ground
C1 = 10e-12;

% Tag top electrode to body
C2 = 10e-12;

% Everything so far.
Z2 = -ivector./(w*C1) - ivector./(w*C2) + Ztag;

% Body to ground.
C3 = 100e-12;
```

```
% C3 parallel to Z2
Z3 = ((-ivector./(w * C3)) .* Z2)./(-ivector./(w*C3) + Z2);

% Reader to body.
C4 = 10e-12;

% C4 in series with Z3.
Z4 = -ivector./(w * C4) + Z3;

% Source impedence.
Rs = 50;

% Total impedence
Z = Rs + Z4;
```

References

[1] Matthew Gray. Physical limits of intrabody signalling. Master's thesis, MIT, MIT Media Lab, 20 Ames Street, Cambridge, MA 02139, May 1997.

[2] Thomas Guthrie Zimmerman. Personal area networks (pan): Near-field intra-body communication. Master's thesis, MIT, MIT Media Lab, 20 Ames Street, Cambridge, MA 02139, Sep 1995.