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# Radio fundamentals

- What's it good for?
  - Wirelessly delivering data or power
- What are we doing with it?
  - Last two weeks: E-Field sensing lab
  - This week: E-Field ***communication*** lab
  - Later: communication using real radios (that you don't build, but will have a better understanding of)

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# Radio fundamentals

- How does it work?
  - Static electric charges (i.e. a DC voltage) create an electric field nearby
  - Moving charge (i.e. a DC electric current) generates a magnetic field nearby
  - Changing electric field generates a changing magnetic field
  - Changing magnetic field generates a changing electric field
  - In a radio wave, energy oscillates back and forth between electric and magnetic fields, propagating through space

# Symmetries

## Electric Field

- Voltage
- Potential energy

## Magnetic Field

- Current
- Kinetic energy

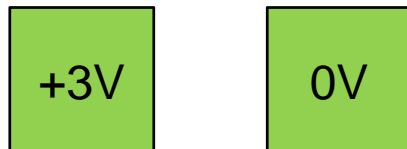
Impedance (Z):

Generalization of  $R$  in  $V=IR \rightarrow R = V/I$

Z (impedance) is ratio of Electric Field to Magnetic Field, or voltage to current

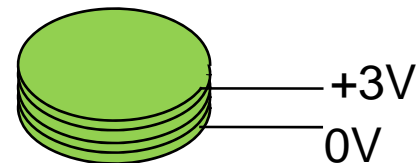
# Static Electric & Magnetic Field “Antennas”

Electric Field “Antenna”  
(Flat electrodes that don’t allow current to flow...voltage only)



High impedance  
Large voltage drop,  
small current flow

Magnetic Field “Antenna”  
(Coil that **does** allow current to flow)



Low impedance  
Small voltage drop,  
large current flow

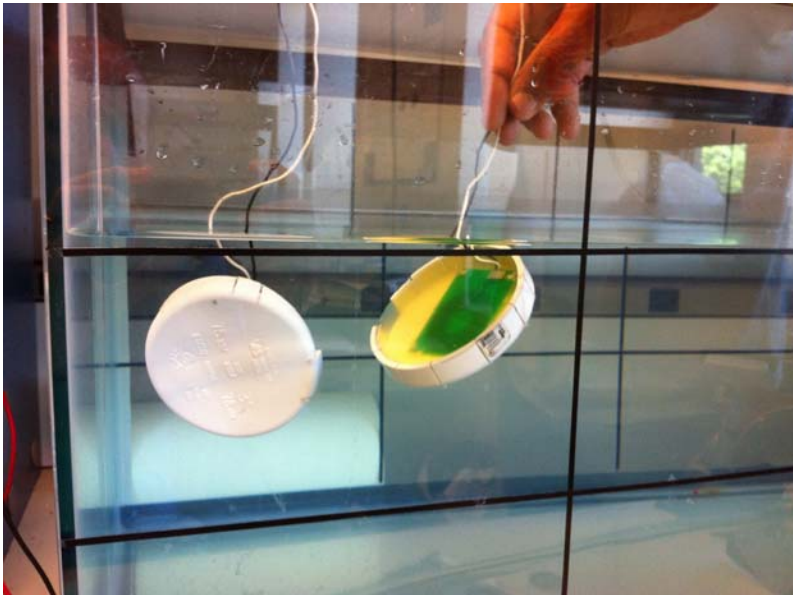
Apply a DC voltage to the electrodes on the left, get a static electric field nearby

Apply a DC current to the coil on the right, get a static magnetic field nearby

# Near field & quasi-statics

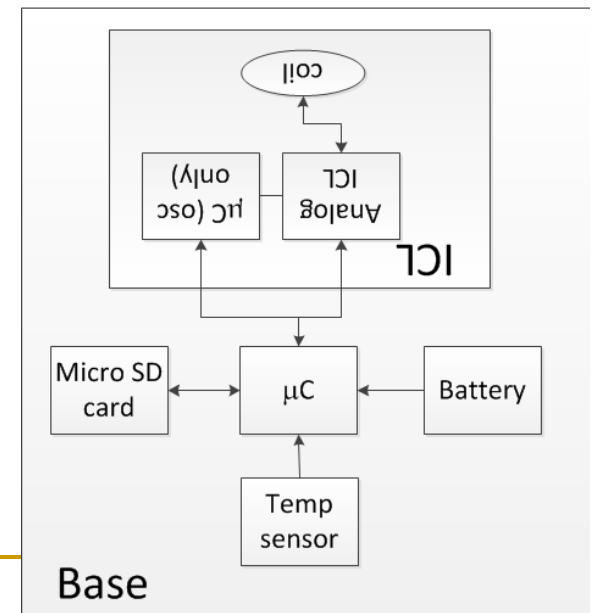
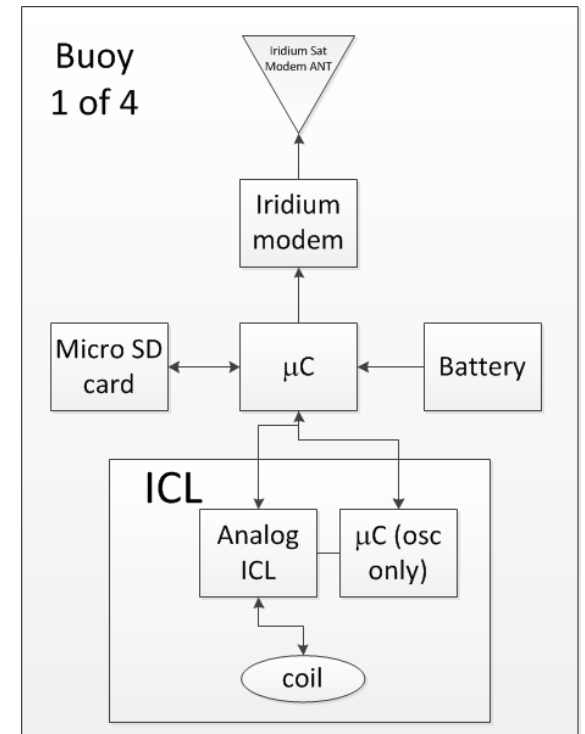
- Instead of applying DC to electrodes / coils, apply AC signals
- If frequency is sufficiently low, energy stays predominantly electric or magnetic...we don't generate propagating radio waves
- How low? Compute wavelength  $\lambda$ 
  - $\lambda$  (meters / cycle) =  $c$  (meters / sec) /  $f$  (cycles / sec)
- If wavelength  $\lambda \gg$  length of antenna, we are in near field
- Oscillating electric field fails to generate magnetic field
- Oscillating magnetic field fails to generate electric field
- Near field / quasistatic “Antennas”:
- Range of nearfield phenomena tends to be  $O(1)$  “antenna” lengthscale
- Nearfield: transmitter “feels” receiver...when receiver sinks more current, transmitter puts out more current

# Near field magnetic communication

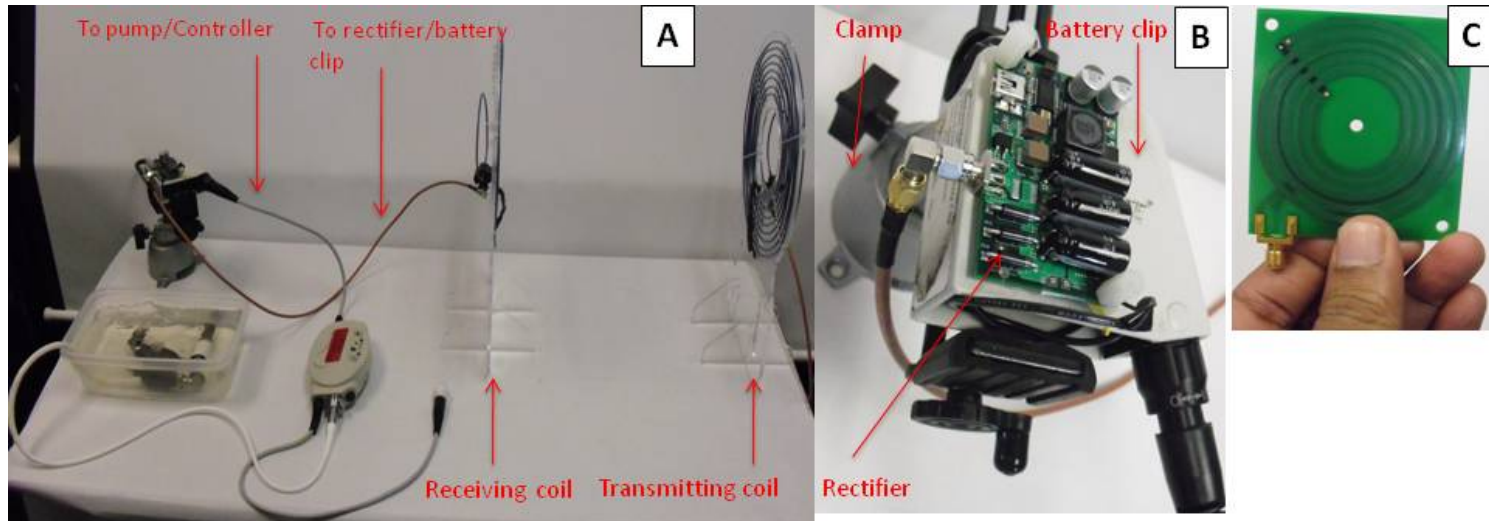


Saltwater is conductive because of ions (dissolved salt)  
 Water has a high dielectric constant  
 These two factors make it bad for electric field communication, or propagating RF communication...think of signal being shunted away

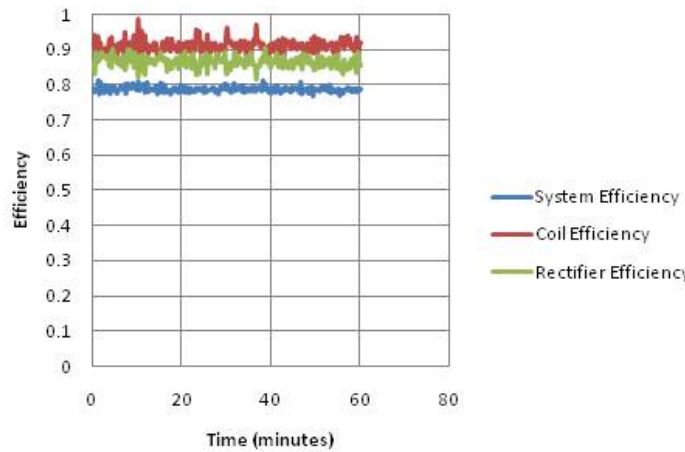
Magnetic field doesn't interact much with water however...this makes it a good choice for short range underwater comms, or wireless power transfer (though the human body, electrically similar to sea water)



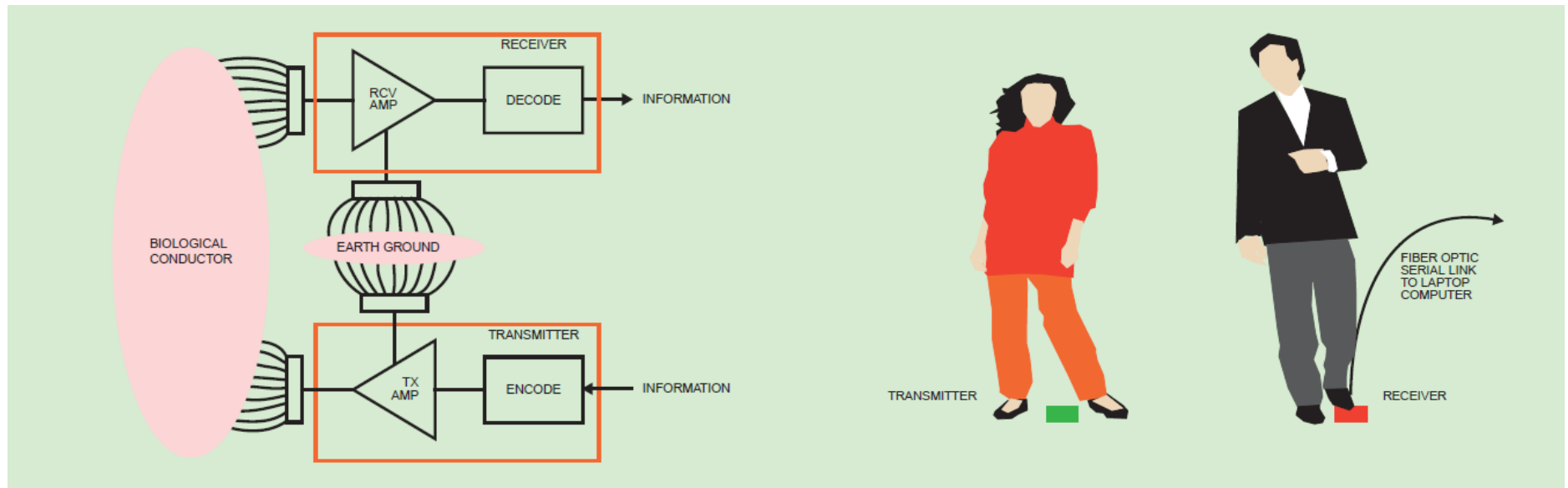
# Near field magnetic power xfer



Efficiency vs. Time: 1hr Continuous Operation



# Near field electric communication



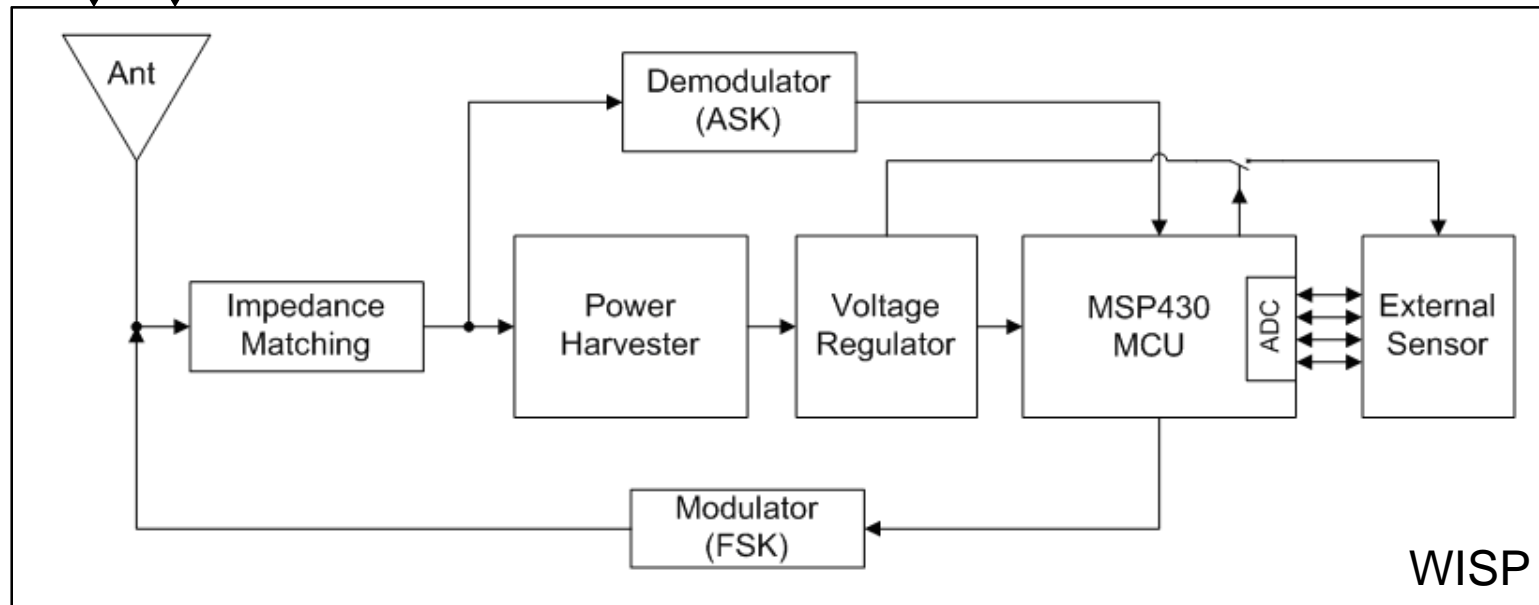
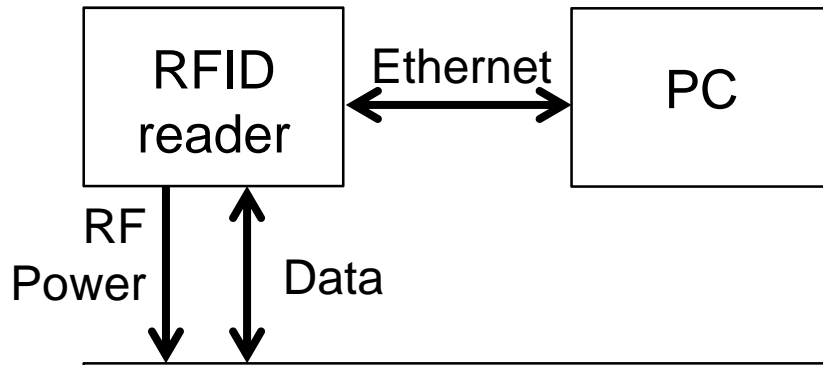
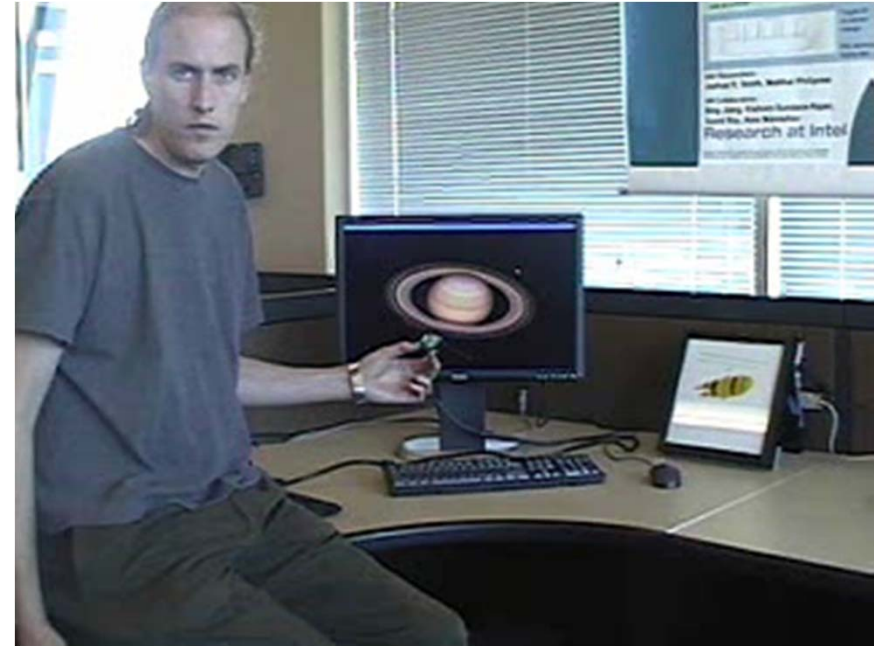
Transfer a business card with a handshake, using your body as a wire.  
This works well built in to shoes...but only built in to shoes...that's why you've never heard of it

*Thomas G. Zimmerman. Personal Area Networks: Near-Field Intrabody Communication. IBM Systems Journal, 1996: pp. 609-617*



# WISP: (Far field pwr & data)

Wireless Identification and Sensing Platform



Board design:  
Alanson Sample,  
Dan Yeager

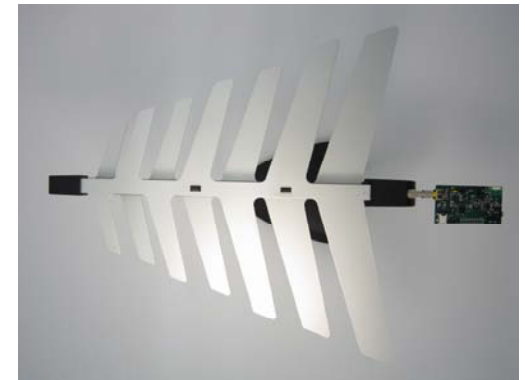
Embedded SW:  
Polly Powledge

WISP

# WARP: Wireless Ambient Radio Power

## Far field power

- ❑ KING-TV
- ❑ Channel 48: 674MHz – 680MHz
- ❑ 960kW
- ❑ 4.1km
- ❑ 5dBi log periodic antenna
- ❑ Front end 30MHz BW
- ❑ Open circuit: 5V
- ❑ 8kOhm load  $\rightarrow$  0.7V  $\rightarrow$  60uW
- ❑ Friis formula predicts 280uW



*Experimental results with two wireless power transfer systems*

A.P. Sample and J.R. Smith

Proceedings RAWCON 2009

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# End of lecture

# Lab 3 tips & questions

- What's wrong with this IIR filtering scheme?
  - x: sensed value
  - y: filtered value
  - $y = 0.2*x + 0.8*y$
  - A: floating point multiplication is very slow
- Faster:
  - $y = 0.25*x + 0.75*y$
  - $y = \frac{1}{4}*x + (\frac{1}{4} + \frac{1}{2})*y \rightarrow y = (x \gg 2) + (y \gg 2) + (y \gg 1)$
  - $y = \frac{1}{4}*x + (1 - \frac{1}{4})*y \rightarrow y = (x \gg 2) + y - (y \gg 2)$

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# Lab 4

- Electric field communication
- Bits encoded in frequency

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# Frequency Modulation

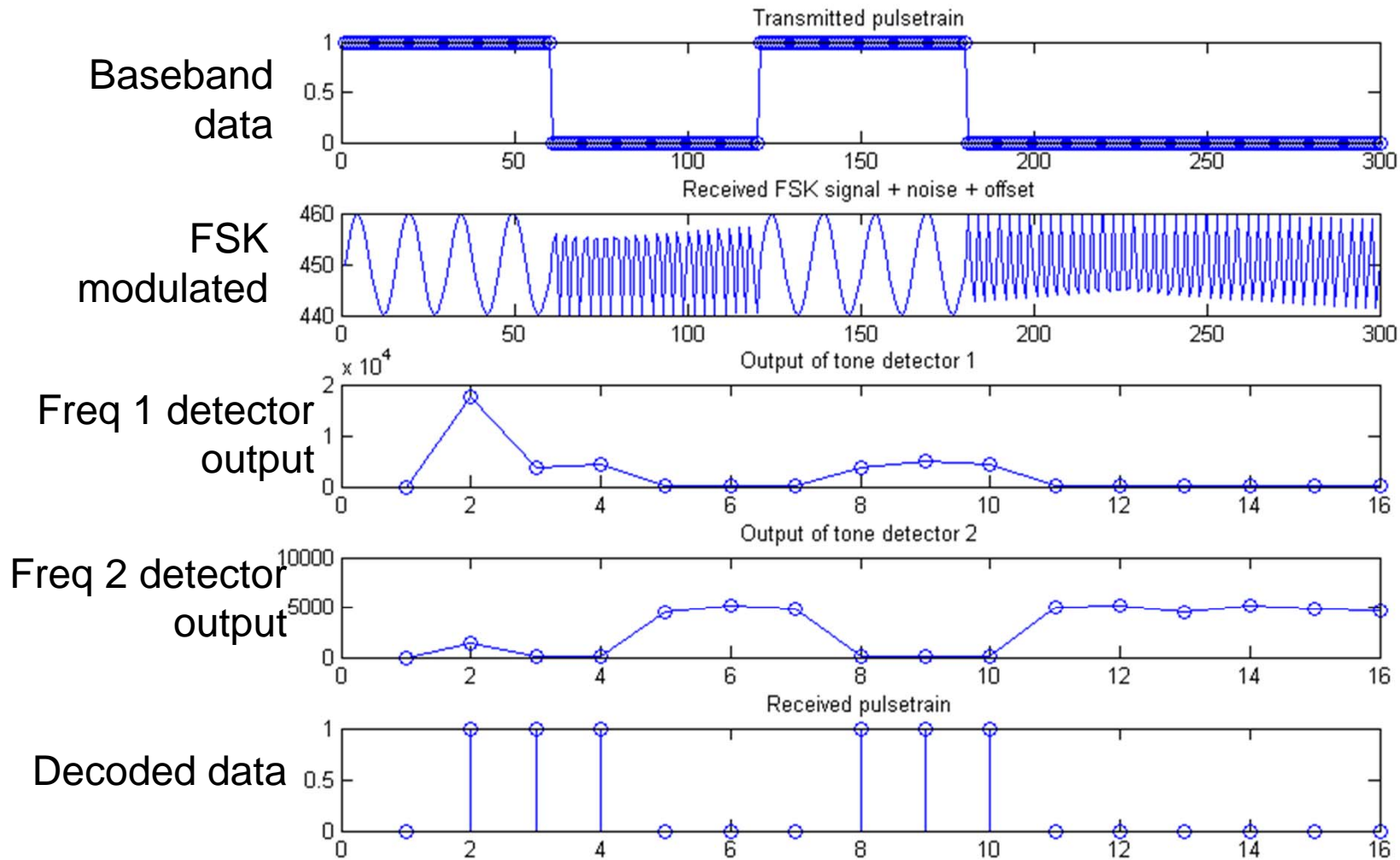
- Analog frequency modulation
  - Baseband (slowly varying) data signal such as voice controls [modulates] frequency of TX osc [carrier]
  - At RCV, a Phase Locked Loop (PLL) tracks received frequency
  - Output signal is tracking control value
  - Advantages: additive noise doesn't affect signal
  - Often used to encode analog sensor values
  - Disadvantages: non-linear modulation scheme (unlike everything else we've discussed)
    - Used for sound synthesis ("FM synthesis")...nonlinear behavior produces rich sounds

# Frequency Shift Keying

- Digital Frequency Shift Keying: encode digital data in frequency...can be implemented in Lab 4
  - Example: 0 → 2kHz, 1 → 10kHz
  - Can decode in a linear fashion
    - “What is the amplitude of 2kHz? 10kHz? Which is larger?”
    - This is the same projection (inner product) operation we’ve been doing throughout the course
    - Could in principle take DFT, look at 3kHz and 8kHz bins
    - DFT is a fast algorithm for projecting a signal onto a list of basis functions (sinusoids)
    - Since we only want 2 frequency bins, there is a faster way
    - Goertzel algorithm will do this efficiently
    - Essentially a filter that asks “How much energy is there in 1 frequency bin”?

# Goertzel frequency detector

A computationally efficient single-frequency detector





# Goertzel (initialization)

```
% FSK Frequencies:
w1 = 2000;% 2kHz
w2 = 10000;% 10kHz
Fs = 30000; %30kHz
A0 = 450; % Amplitude of DC offset
A1 = 10; % Amplitude of w1
A2 = 10; % Amplitude of w2
A3 = 0; % Amplitude of noise
endTime = .01;%sec
lpfCoeff = 0.9; % DC offset removal filter coefficient
n = 20; % Number of samples per sample block
%%
N = endTime*Fs; % Total number of samples
t = linspace(0,endTime,N); % Build time vector
```

Frequency bin width:  $\text{sampling freq} / \text{\#bins} = F_s / n = 30000 / 20 = 1.5\text{kHz}$

# Goertzel (simulated rcv signal)

```
% Bitstream to transmit
signal = [ones(1,N/5) zeros(1,N/5) ones(1,N/5) zeros(1,2*N/5)];

% Generate simulated received signal
dc_offset = A0;
tone1 = A1*sin(2*pi*w1*t) .* signal;
tone2 = A2*sin(2*pi*w2*t) .* (1-signal);
noise = A3*rand(1,N);

in = tone1 + tone2 + dc_offset + noise;
```

# Goertzel (build-time calcs)

## Constants that you pre-compute

```
% K computation
k1 = 0.5 + n*w1/Fs;
k2 = 0.5 + n*w2/Fs;

% Algorithm constants computation
coeff1 = 2*cos((2*pi/n)*k1);
coeff2 = 2*cos((2*pi/n)*k2);

% Initialize buffer values
P2=0; P1=0; P0=0;
Q2=0; Q1=0; Q0=0;
mag1=0;
mag2=0;
```

# Goertzel (the algorithm)

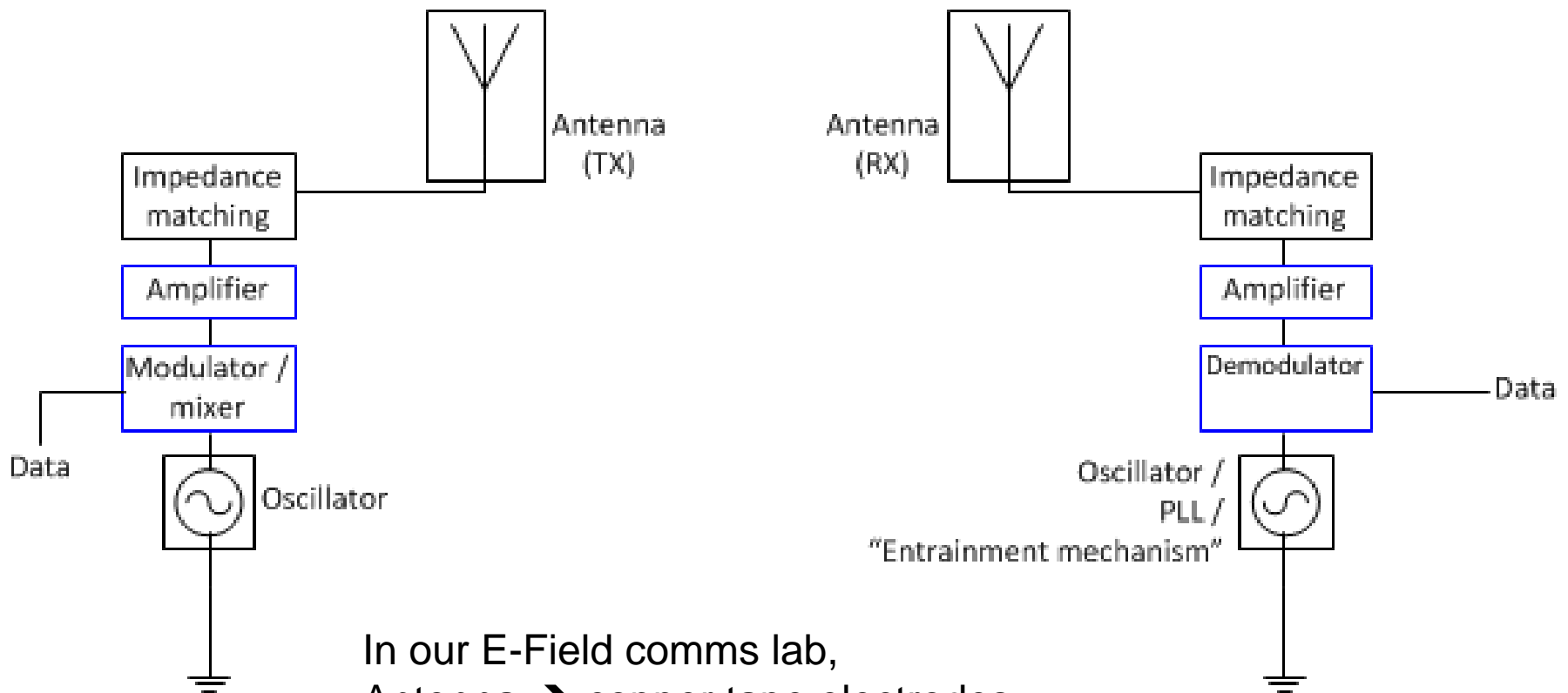
```
for i = 1:1:N
    % For each sample, do the following:
    % 1) Compute Q0 using current sample
    P0 = coeff1*P1 - P2 + in(i) - offsetAdjust; % Goertzel 1
    Q0 = coeff2*Q1 - Q2 + in(i) - offsetAdjust; % Goertzel 2

    % 2) Rotate buffer values and decrement
    Q2=Q1; % Goertzel 1
    Q1=Q0;
    P2=P1; % Goertzel 2
    P1=P0;

    % 3) Update offset adjustment
    offsetAdjust = (1-lpfCoeff)*in(i) + lpfCoeff*offsetAdjust;
    % 4) If n samples taken, compute magnitude and reset buffers
    if(mod(i, n) == 0)
        mag1= [mag1 (P1*P1 + P2*P2 - P1*P2*coeff1)];
        mag2= [mag2 (Q1*Q1 + Q2*Q2 - Q1*Q2*coeff2)];
        Q2=0;Q1=0;Q0=0;
        P2=0;P1=0;P0=0;
    end
end
```

end

# Radio components



Note: in FM case, modulator and oscillator are combined, via voltage-controlled oscillator

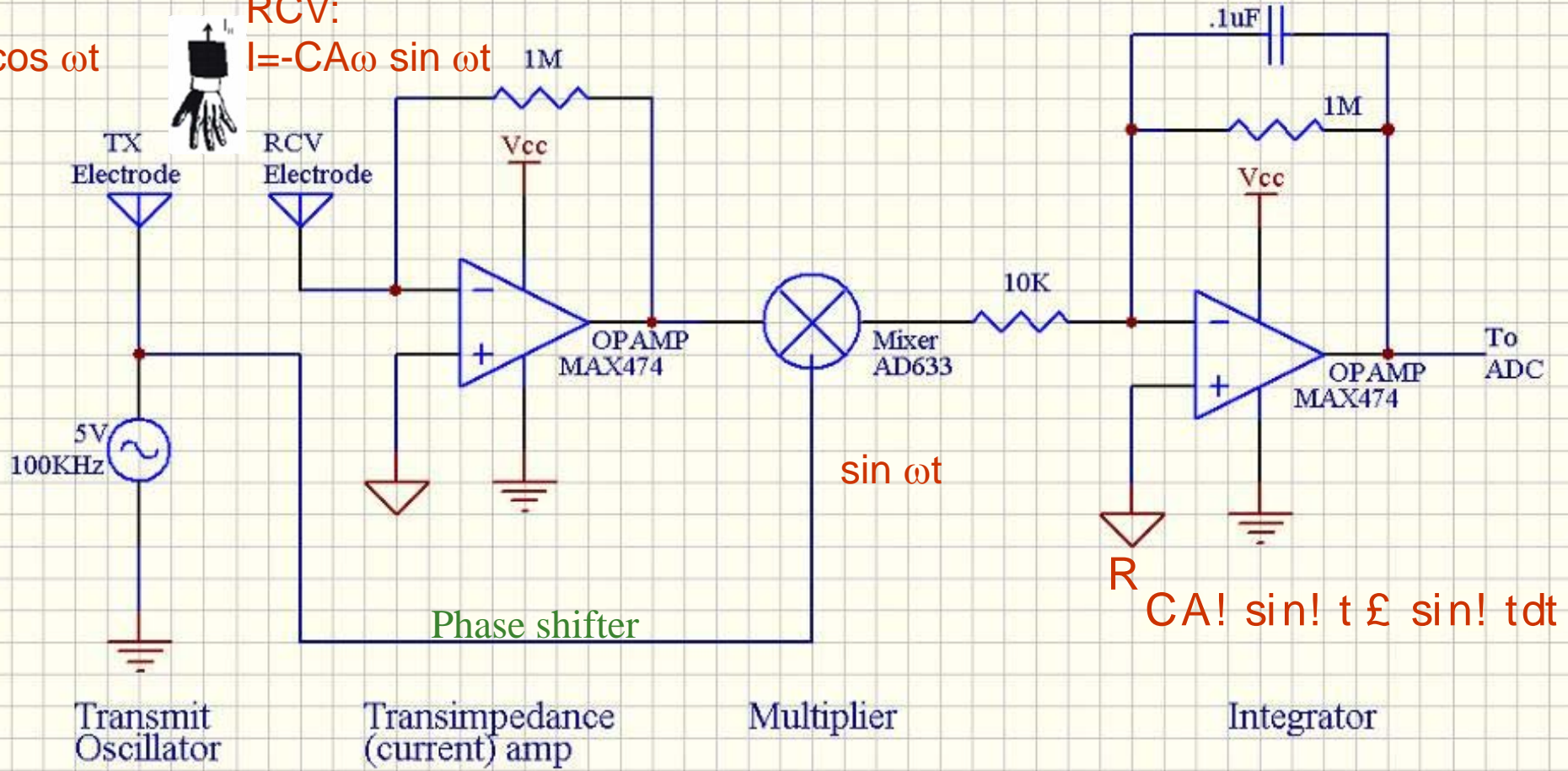
In our E-Field comms lab,  
Antenna → copper tape electrodes  
Impedance matching → not needed  
Amp: TX → none; RCV → op-amp  
Modulator / demodulator → software  
Oscillator → SW or PWM toggling output pin

Compare components of conventional radio to analog E-Field sensing circuit

## Basic Electric Field Sensing Circuit (Analog)

TX  
Acos ωt

RCV:  
 $I = -CA\omega \sin \omega t$

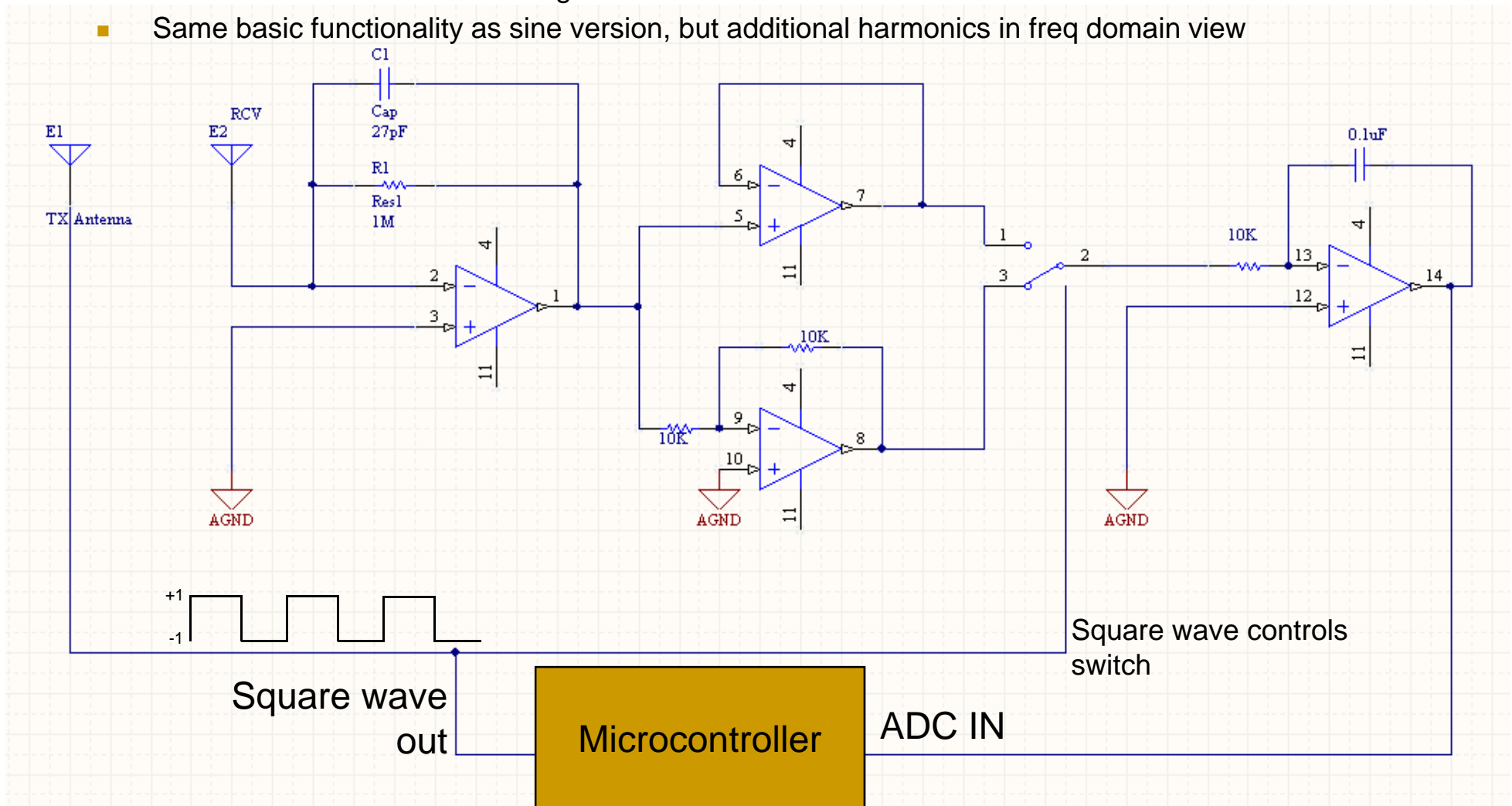


$CA \int \sin t \, dt$

# Electric Field Sensing circuit

## Variant 2 (no analog multiplier)

- Replace sine wave TX with square wave (+1, -1)
- Multiply using just an inverter & switch (+1: do not invert; -1: invert)
- End with Low Pass Filter or integrator as before
- Same basic functionality as sine version, but additional harmonics in freq domain view

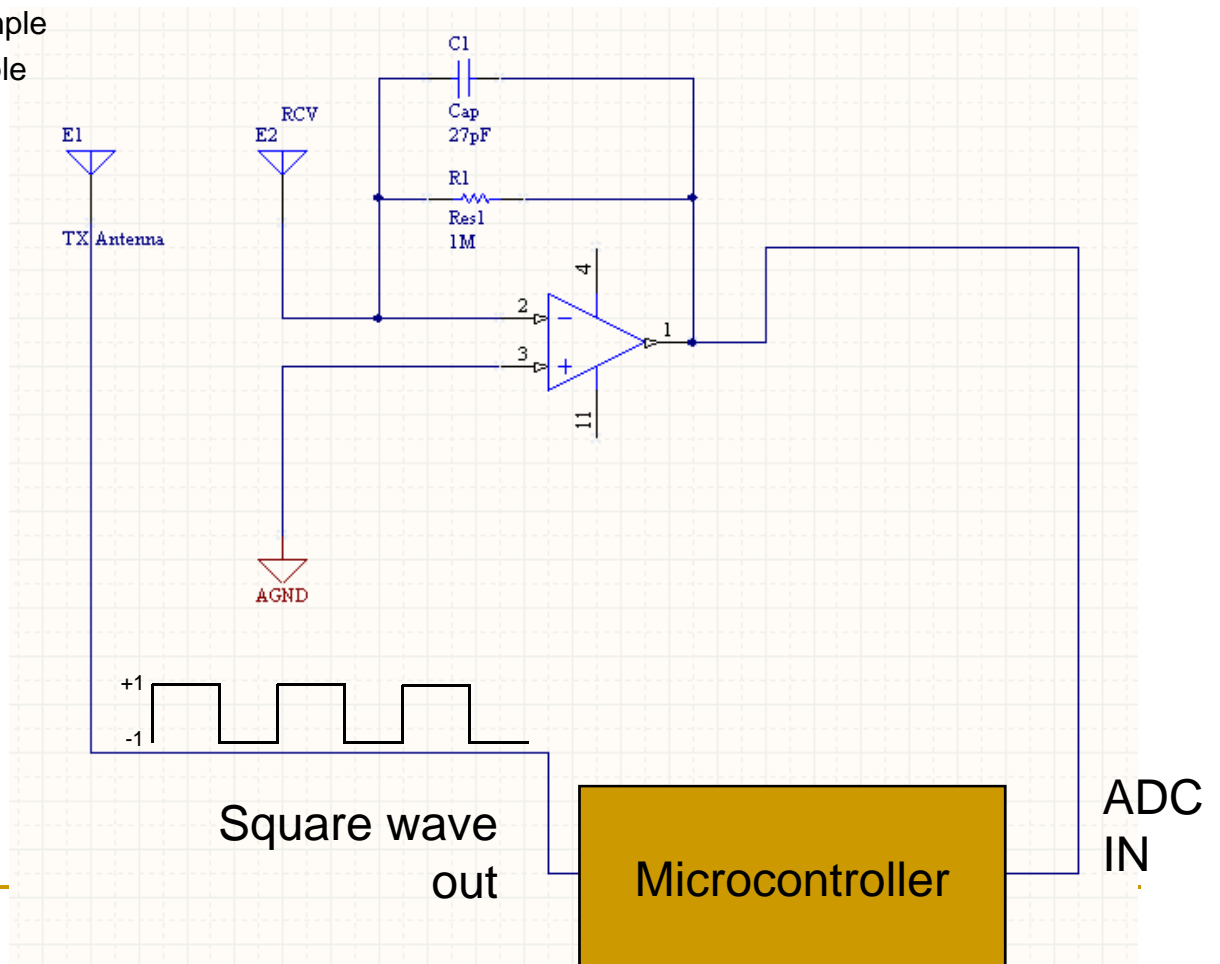


# Electric Field Sensing circuit

Variant 3 (implement demodulation in software)

- For nsamps desired integration
- Assume square wave TX (+1, -1)
- After signal conditioning, signal goes direct to ADC
- $Acc = \sum_i T_i * R_i \rightarrow$ 
  - When TX high,  $acc = acc + sample$
  - When TX low,  $acc = acc - sample$

This is what you built in Lab 3. By comparing to the pure analog implementation, we are trying to illustrate the connection to conventional radio. In the pure analog implementation, more of the pieces of a conventional radio are present. In the scheme on this slide, several of the blocks have been replaced by software.





# Antenna issues

- Using near field (electric or magnetic) radios, we don't need to worry about antennas or impedance matching
- The next few slides illustrate the antenna & impedance matching issues that arise in conventional far field radio
- The designers of the radios we will be using in lab 5 had to deal with these issues

# Transmission line

e-tl.html

# Standing wave

# Termination

e-tlterm.html

# Impedance matching

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End