RFID Systems: Basic Radio

A short introduction to basic radio concepts.

Why radios work.

Ways of expressing how well they work.

Important parameters with respect to RFID.

Read Chapter 3 in the text.

Physics and radio

The beginning of chapter 3 in the text makes an interesting point about how radio works. What he is saying is that radio works because:

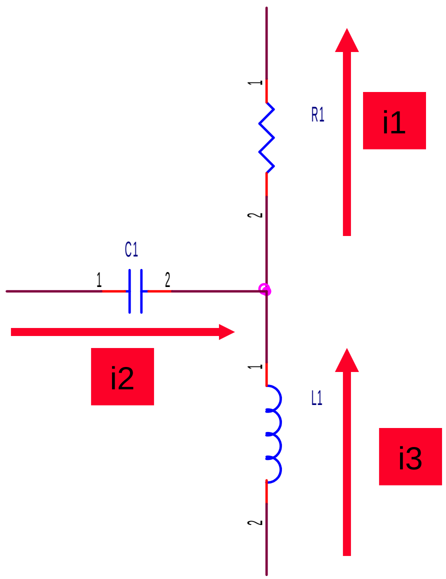
1. Electric circuits obey rules, such as Kirchoff's laws, and ohms law. We will use variants of ohm's law a lot.
2. We have AC circuits as well as DC ones. In AC circuits, current and voltage can change, and can change out of phase.
3. The rate at which EM energy can move or change is finite, and bounded by the speed of light. This includes electron motion in wires.

To see the importance of these, consider what the book says about sending energy to a distant location. This requires a source of non-zero energy that can radiate without being canceled out. The book further points out that the usual state of such energy sources is to be canceled out.

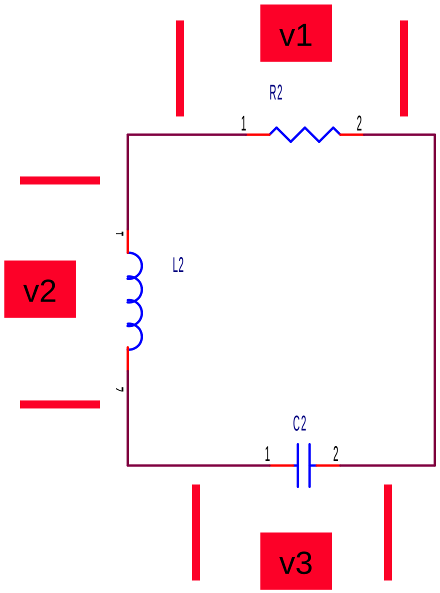
So, how do they radiate???

Example: Kirchhoff's Circuit Laws

Consider Kirchhoff's circuit laws. They illustrate cancellation.

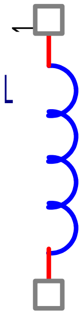


$$\sum_k i_k = 0$$



$$\sum_k v_k = 0$$

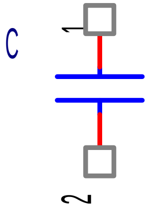
Example: Inductance and Capacitance



$$v = L\frac{di}{dt}$$

$$B = \mu n i \text{ and } L \approx \mu n$$

$$\text{so } i \approx \frac{B}{L}$$



$$i = C\frac{dv}{dt}$$

$$v = \frac{q}{C}$$

These equations are familiar from your physics courses.

But…

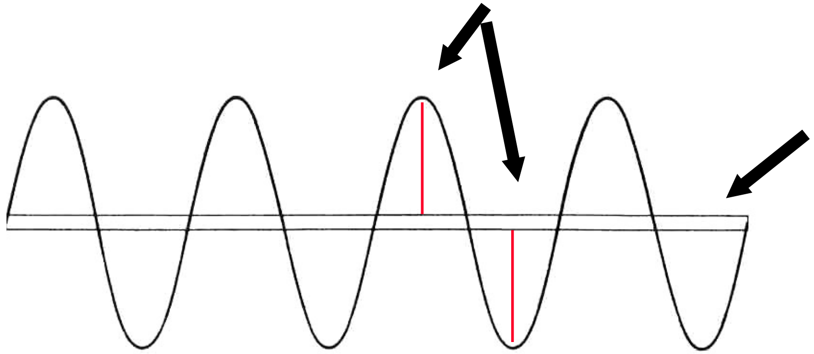
1. Why if a *perfect* DC voltage source is placed across the inductor will the current go towards infinity? What is really happening in the coil? (Or, why can't you have a DC transformer?)
2. Why, if a *perfect* DC current source is placed across the capacitor, the voltage across it will go towards infinity?

It is due to the tendency for things to cancel, as the text claims.

But if the voltage and current sources are AC, then everything works.

AC circuits and long structures

- AC makes it possible for potentials to NOT cancel, and thus be able to propagate and be visible to a distant observer.
- If you have a structure, like a wire, that is long with respect to the *wavelength* of a AC signal that is on it, then at any point in time you can find *significantly different* voltages and currents belonging to that AC signal on the structure.
- A distant observer will be able to see the energy potential differences.

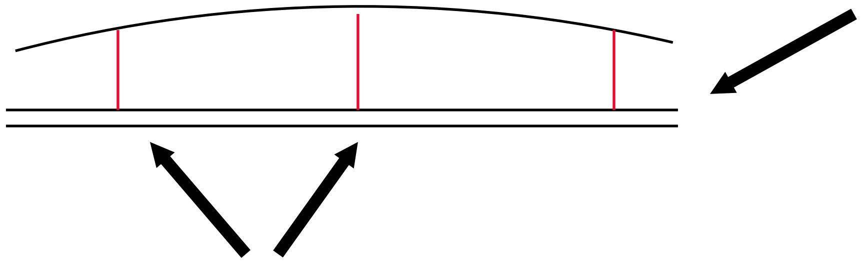


This structure is many wavelengths long.

AC circuits and short structures

- If the structure is short with respect to the wavelength of the AC signal on it, you won't see as significant a difference anywhere on the structure.
- A distant observer will see even less.

This structure is very short compared to a wavelength.



Not much energy potential difference anywhere along the structure.

This doesn't mean that small antennas or low frequencies are bad! It just means that the operating frequency, antenna structure size and intended operating distance will determine if you use an inductive or radiative model.

Signal Voltage and Power

- In RFID we are very concerned with signal voltage and especially power. Here's why.
- Passive tags get their operating power from the energy sent by the reader. How much power is needed? It needs to be enough to run active circuits.
- The receiver has to hear the backscattered signal from the tag, and it has to figure out what it is saying. Is there enough power in the backscattered signal for the receiver to be able to do this?

- Finally, it is necessary to be able to express these power requirements in a way that any engineer can understand.

Radio signal basics
Waves, power, reactance and impedance

- Because RFID deals with RF signal exchange, we need tools to be able to describe exactly the signals and the information they carry.

- For us, a signal is a collection of sin waves, or *harmonic functions*.
- For any frequency, ω, a signal is often expressed as a cosine function, for example: $V_0 \cos(\omega\tau + \phi)$
- This is really just the real part of the complete expression of a harmonic function in the complex plane. If we assume $V_0=1$ and $\phi=0$, then our signal is $\cos(\omega\tau) + j\sin(\omega\tau)$
- Euler's Identity is extremely useful as it converts this harmonic function in the rectangular complex plane to an exponential. In other words, it puts it in polar form.

$$\cos(\omega\tau) + j\sin(\omega\tau) = e^{j(\omega\tau)}$$

This will be useful later. Read over Appendix 2 for more review.

Signal power

Consider a signal going into a circuit. We will just use the real part for now

- For any frequency, ω, the only things variable are amplitude and phase: $V(\tau)=V_0 \cos(\omega\tau + \phi)$
- Angular frequency $\omega = 2\pi f$ (This just means 1 full cycle of 'f')
- Instantaneous power is P = I V
- Using ohms law, $P = I V = V^2/R$
- Average power is the average of P over 1 cycle (2π radians) or

$$P_{ave} = \frac{V_0^{\,2}}{2R} \quad \text{where} \quad ave(COS^2(2\pi)) = \frac{1}{2}$$

The textbook uses this form of average power.

Reactance and impedance

- Resistor behavior is governed by ohms law. R=V/I. Time doesn't appear anywhere. *Good* resistors don't care what ω is.
- Inductors and capacitors do care. Consider a capacitor. We know that:

$$\mathbf{i = C \frac{dv}{dt}}$$

- Time DOES appear. What does that mean for power calculations?
- That depends on what the voltage is doing with respect to time. We know what it is doing. It is varying as a sinusoid with frequency ω. If we normalize the maximum voltage to 1, we can say by using Euler's Identity :

$$v = \cos(\omega\tau) + \mathrm{j}\sin(\omega\tau) = e^{j\omega\tau}$$

Capacitive reactance

Capacitors are interesting because they have a time dependency

- Another identity that is useful here is: $\frac{d}{dx}\left(e^{ax}\right) = ae^{ax}$

- Using this, and substituting our expression for voltage, we get:

$$i = C\frac{dv}{dt} = C\frac{d}{dt}(e^{j\omega\tau}) = Cj\omega e^{j\omega\tau}$$

- From ohms law, we have the effective resistance, R=V/I or:

$$\frac{v}{i} = \frac{e^{j\omega\tau}}{Cj\omega e^{j\omega\tau}} = \frac{1}{j\omega C} = -\frac{j}{2\pi fC} = -jX_C$$

- Xc is the capacitive reactance. The –j indicates that the voltage and current are 90 degrees out of phase. The voltage *lags* the current (-j). It is 0 (thus “imaginary”) when the current is maximum.

Inductive reactance

Inductors also have a time dependency

- The same case applies to inductors. Recall for inductors: $v = L\frac{di}{dt}$
- Current now varies with time. As before, we know it varies as a sinusoid, or $i=e^{j\omega t}$. Proceeding like we did for capacitors:

$$v = L\frac{di}{dt} = L\frac{d}{dt}(e^{j\omega\tau}) = Lj\omega e^{j\omega\tau}$$

- From ohms law, we have the effective resistance, R=V/I or:

$$\frac{v}{i} = \frac{Lj\omega e^{j\omega\tau}}{e^{j\omega\tau}} = jL\omega = j2\pi fL = jX_L$$

- X_L is the inductive reactance. The j indicates that the voltage and current are 90 degrees out of phase. The voltage *leads* the current (+j). It is 0 (thus “imaginary”) when the current is maximum.

Impedance

- X_C and X_L are the time dependent or Reactive component of a capacitor's or coil's resistance.
- However, there is always a DC component, or conventional R associated with these parts (or a network of parts) as well.

- The combination of R and X_C or X_L gives the total *impedance*.

- For example, for a resistance in series with a capacitor:

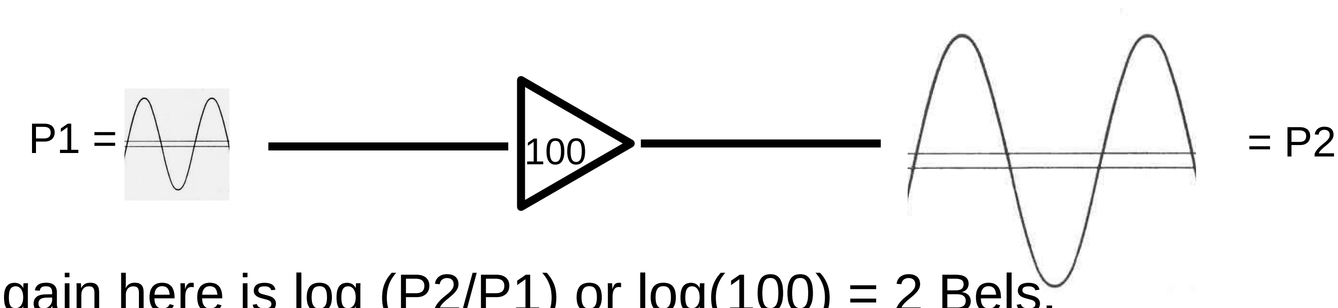
$$\mathbf{R + X_C = Z}$$

- Where Z is the Impedance.
- Like resistance, impedance obeys ohms law, and combine in series and parallel as complex numbers.

- See Appendix 3 in the textbook for more information

Expressing power gain and loss

- *Power* gains and losses are expressed as base 10 logarithmic ratios.
- Base 10 log numbers are used because they are convenient to describe systems with large dynamic range.
- The power ratios are expressed in units of “Bels”. For example:



- The gain here is log (P2/P1) or log(100) = 2 Bels.
- Bels are a bit too coarse a measure, so 1/10 of a Bel or deciBels are much more common.

- In the example above the gain then is just 10 log(100) = 20 dB

Voltage gain and loss

- Engineers find it hard to visualize power, but easy to visualize voltage.
- If we want, we can express *voltage* gain or loss by recalling:

$$P = IV \text{ and } I = \frac{V}{R} \text{ so } P = \frac{V^2}{R}$$

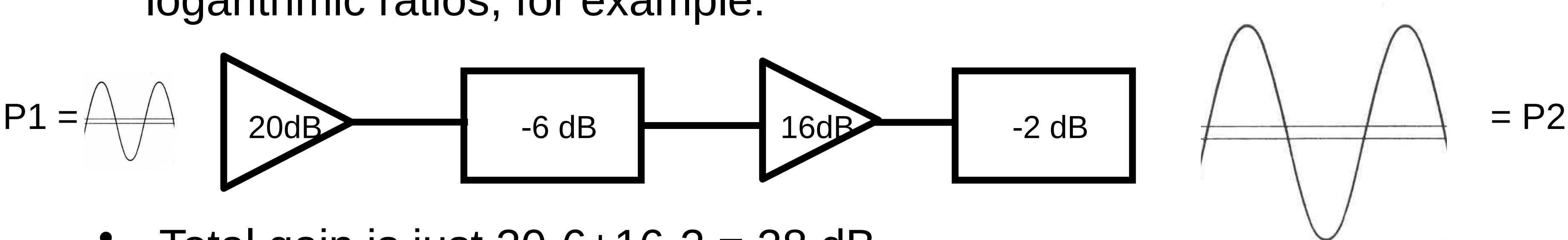
- Substituting this into our equation for power gain gives:

$$G_{dB} = 10\log\frac{P_2}{P_1} = 10\log\frac{V_2^{\,2}/R}{V_1^{\,2}/R} = 10\log\left(\frac{V_2}{V_1}\right)^2 = 20\log\frac{V_2}{V_1}$$

- Note that this ONLY works if 'R' is the same for V_1 and V_2, for example the input and output impedances are the same.

A ‘dB’ for every need

- dB is a great unit to use because it’s easy. Gains or losses that are multiplied to a signal are found by just adding the logarithmic ratios, for example:



- Total gain is just 20-6+16-2 = 28 dB.

- Often gain is expressed with respect to a standard reference
- There are a *lot* of them. For us, the most common will be 1mW.

$$\mathbf{dBm = 10\log\left(\frac{P}{1mW}\right)}$$

We will use this a lot, along with just dB. There are a lot of other forms.

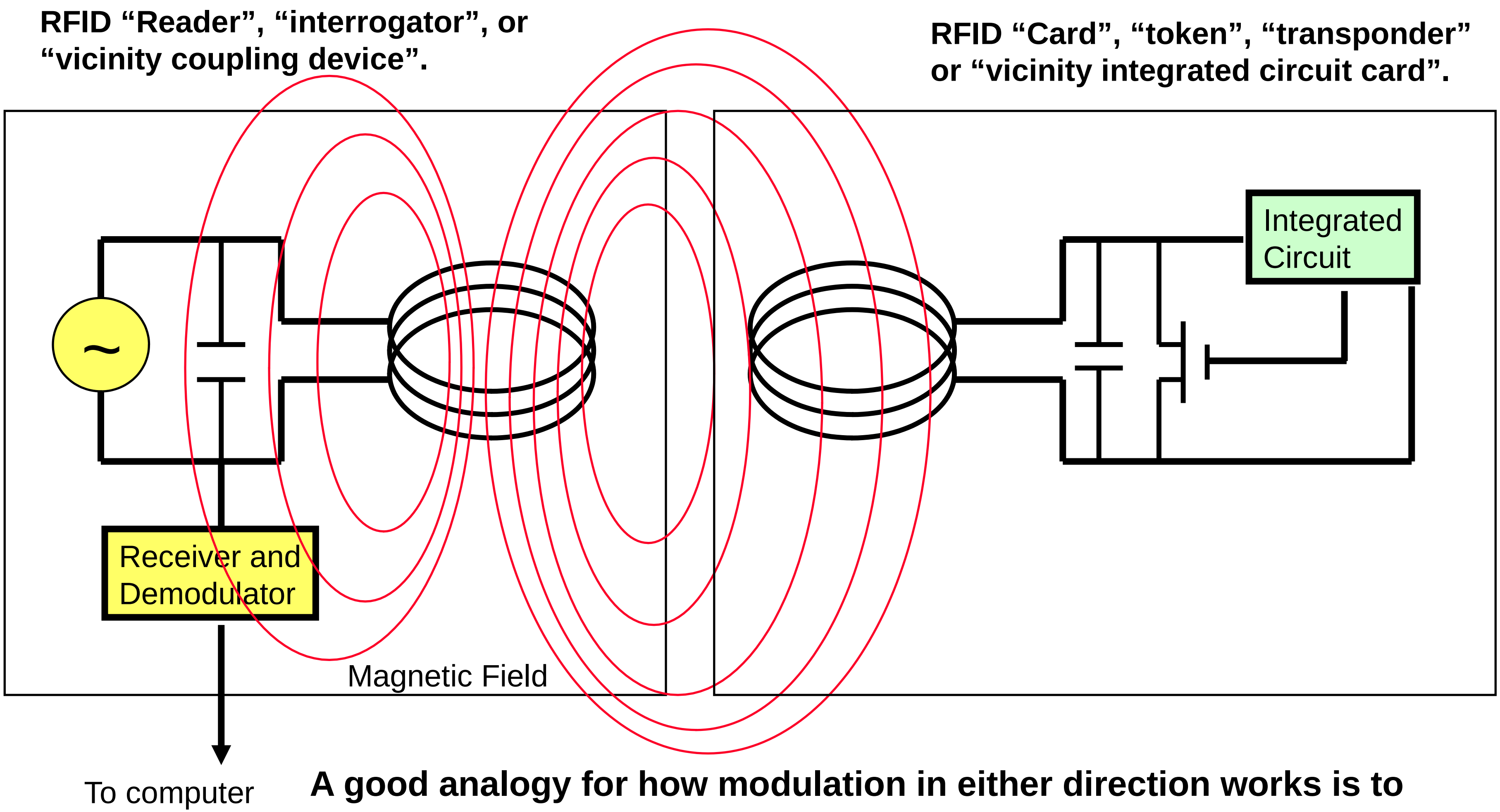
- dBk (1 kilowatt), dbw (1 watt) dBRAP (reference acoustical power 10^-16 watts) dBRN (reference noise) dBv (voltage independent of impedance) dBx (reference coupling) ………..!!!

Inductive Coupling in RFID

With knowledge of reactance, we can explain why inductive coupling works.

- Inductive coupling is similar and different from radiative coupling.
- It is similar in that we still have to defeat the tendency to cancel.
- We still have to have an observable potential.
- It is different in how the energy is transferred.
- Radiative uses the relationship between the size of the antenna and the wavelength of the signal.
- Inductive uses the behavior of magnetic fields, wires and AC.

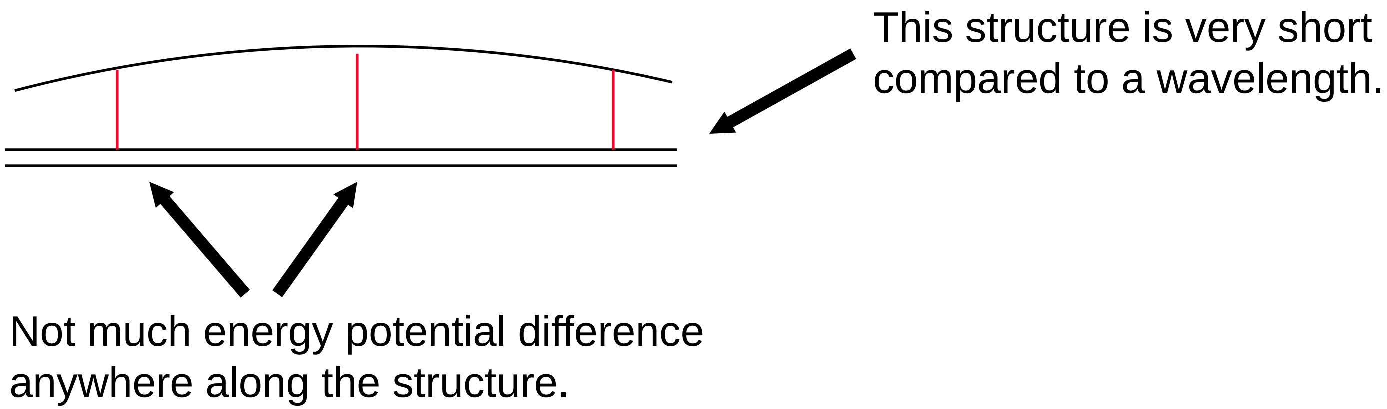
Inductive Coupling overall picture



A good analogy for how modulation in either direction works is to compare the RF voltage link between the reader and the RFID tag as coupled transformer coils.

Recall the conditions to be inductively coupled

- The antenna is physically short WRT the wavelength in use.

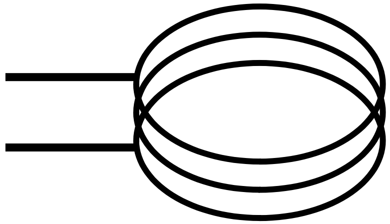


- Consider the case of the RFID we will use in the lab.
- f = 13.56 Mhz
- λ ~= 300e6/13.56e6 = 22.12 meters
- Even at $\lambda/2$ = 11.06 meters, that is a lot of wire for an antenna!

Inductive RFID

Instead of 11.06 meters of wire, lets use a small length and wind it into a coil.

Inductance = L



Coils are really simple. They are just loops of wire.

The coil has an inductance, ‘L’.

It depends on:

- How much wire, and the wire diameter or shape
- How many turns of wire in the coil and the coil dimensions
- The way the turns of the coil are made, ie flat or crossed
- The material in the core of the coil, in our case usually just air.

Recall inductive reactance

Coils allow AC circuits to radiate, and NOT have the electric differences cancel.

- This is because in AC circuits, the voltage across a coil is time dependent on current. We want the current to change with time.

$$v = L\frac{di}{dt}$$

- This allowed us to come up with an expression for inductive AC resistance, or reactance:

$$X_L = 2\pi \mathrm{fL}$$

- This means that with an AC current of frequency *f* flowing through the inductor, we will see an AC voltage *V* across the coil due to Ohms Law

$$V = i * X_L$$

- It doesn't cancel. But how does it radiate?

Inductive signal ‘radiation’

- Ohms law and inductive reactance shows that a signal can be formed in a coil that does not cancel as long as the AC current though it continues.

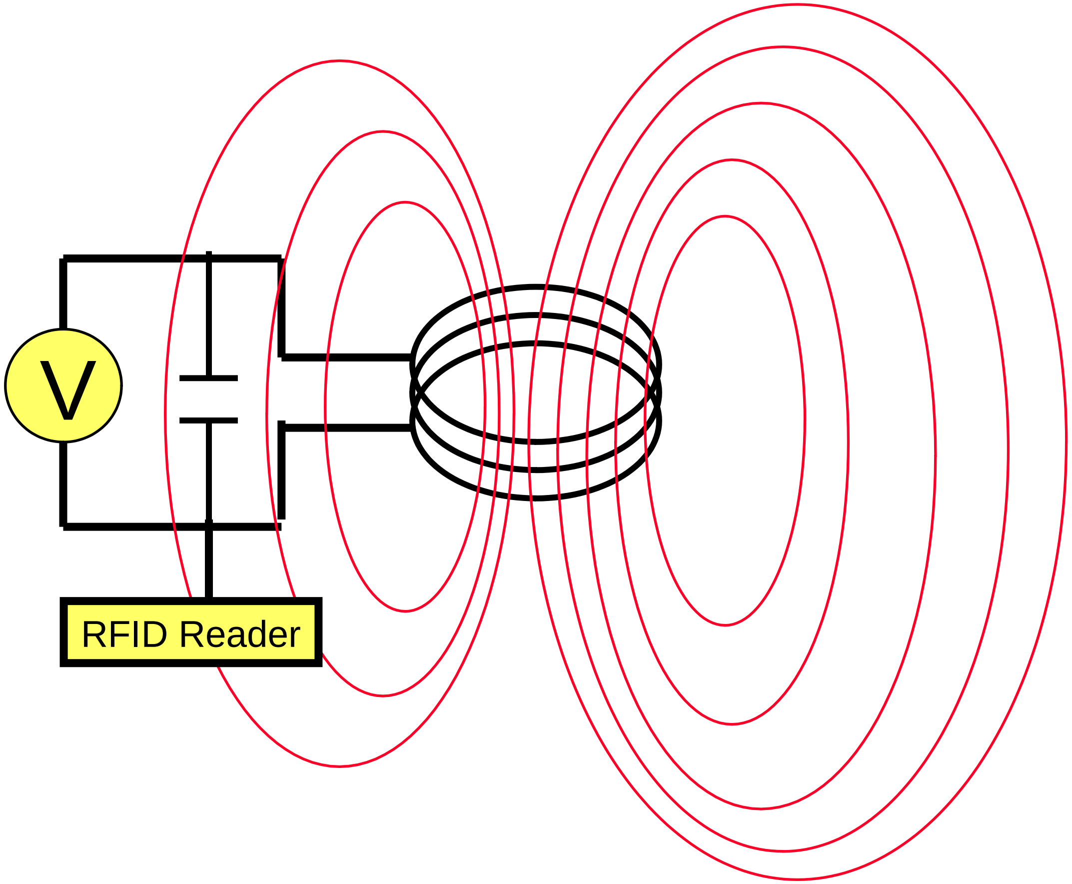
- An RFID reader can easily have such a coil.

- But how does the signal radiate and become visible to another coil?

- To explain this, we need two more laws of physics:
- Oersted’s law
- Faraday’s law of induction

Oersted

- Hans Oersted showed that a current flowing in a wire will generate a magnetic field. It can be AC or DC. If it is DC then the field is static. If it is AC, then the field is changing with time.

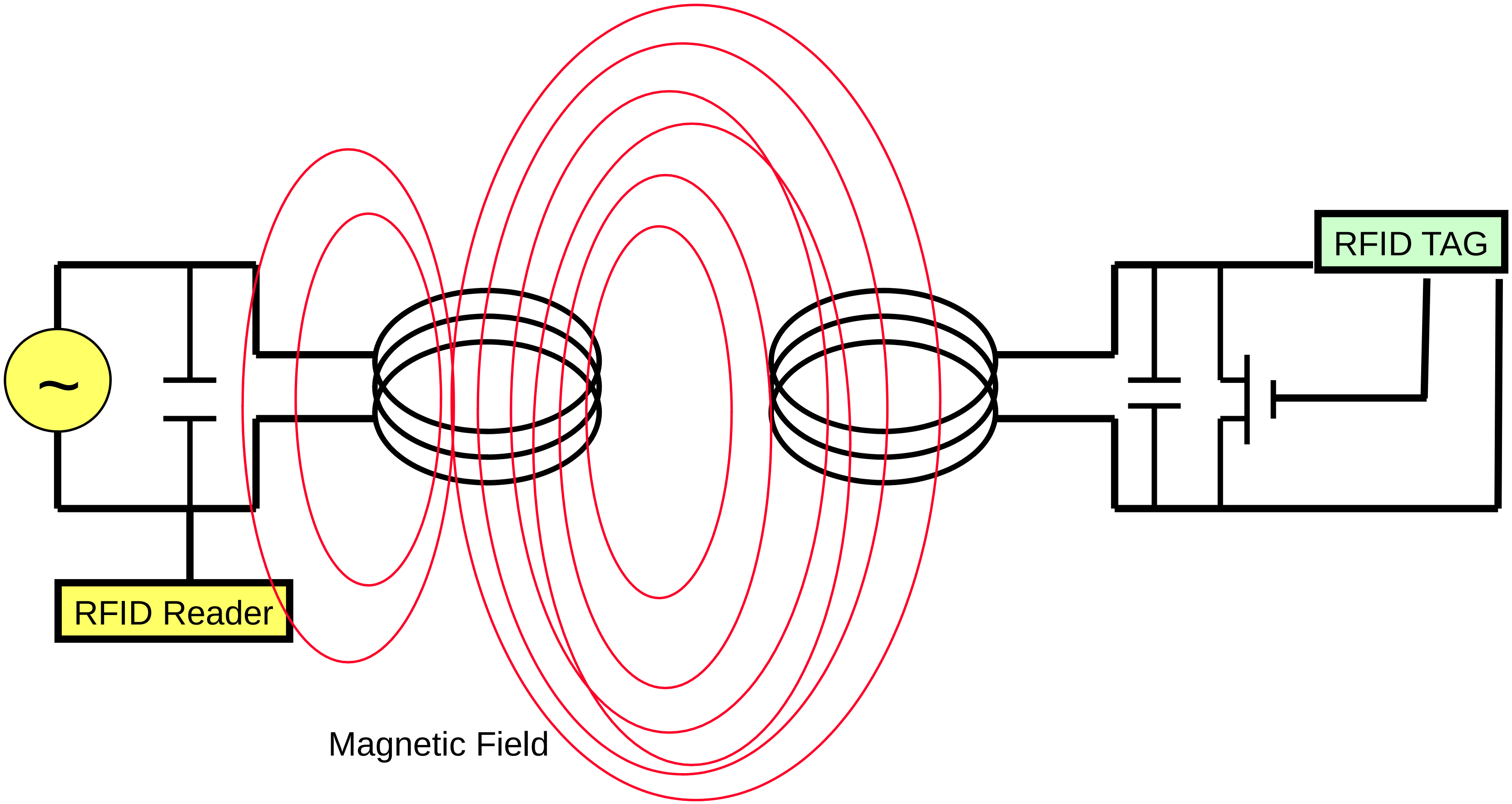


- $B = n\mu i/(2\pi d)$

- B is magnetic field
- *u* is magnetic permeability
- *i* is the AC current in the coil
- d is coil diameter
- n is the number of turns

Couple the coils with the magnetic field

Now, put the tag's antenna close enough so that the B field goes through it.



They should be close together for significant field lines to go through.

Faraday's law of induction

- When one coil generates a magnetic field whose lines of magnetic flux pass though another coil, a voltage will form in the other coil.

- This is described by Faraday's law of induction:

$$|EMF| = |N * d(\Phi(B))/dt|$$

- EMF (Electro Motive Force) is in volts
- N is the number of turns in the coil
- B is the magnetic field
- Φ(B) is the magnetic flux. It is the number of field lines that pass through a given area.
- The greater the coil separation, the lower the magnetic flux

What Faraday's law of induction means

$$|\mathrm{EMF}| = |N * d(\Phi(B))/dt|$$

- Note the dependency on time again.
- What this says is that if a coil of wire is placed in a *changing* (AC) magnetic field, then a voltage will be generated across the coil

- You now have a voltage that is observable across the tag antenna's length.

- More turns in the coil, then more voltage

- Note that it has to be AC. If it is DC the voltage -> zero because

$$d(\Phi(B))/dt = 0$$

- This also explains why you can't have a DC transformer

What Oersted and Faraday together mean to create an Inductively coupled RFID system

1. A magnetic field changing at frequency f can be generated by a coil connected to a RFID reader.
2. A second coil can be placed in this magnetic field, and an observable signal at frequency f can be seen on that coil.
3. This second coil is connected to a tag. This means that a reader can send information to a tag. For example, ask it to send its ID information back.

Otherwise, Inductive and Radiative systems are very similar:

- They both only exist in AC systems. It is the time dependence that allows them to ‘radiate without cancelling’.

- They both exchange electromagnetic energy and have a frequency and so also a wavelength of operation.

- How these systems modulate the signals to exchange data can be, and often are, similar as we will see.

Modulation, symbols and data

- There are some unique concepts in RFID that make it challenging to exchange data.
- For example, the tag gets energy from the reader and reflects some of that energy back with information attached to it.
- But, if that's the case, how can the reader tell the difference between the energy it sends, and the energy it gets back? Isn't it all on top of each other? Isn't there terrible interference?
- Also, if the tag is far away, isn't the energy really weak as well? How can the reader hear it?
- To answer these, we need to look at how radio energy is modulated, and how information symbols are represented.

Modulation and RFID *Readers*

Modulation is the way that a radio signal can carry information. For RFID, there are unique aspects regarding modulation. We start by looking at modulation performed by a RFID *reader*. What is important here?

- Powering the tag. If the tag gets its power from the reader, then energy from the reader can't be turned off. At least for not long.
- Information. The energy used to power the tag has to co-exist with energy used to represent information to and from the tag.
- Robustness. The information must be coded into the radio energy in a way that makes it relatively resistant to errors.
- Speed. We need to have a usefully fast data rate.
- Efficiency. Needs to be efficient with respect to power requirements and use of radio resources

Attaching information

- Recall our basic radio signal, a sinusoid of the form $A\cos(\omega t+\phi)$.
- There are only two things we can do to attach information:
  - Change the Amplitude or the phase (or frequency, same thing).

- For now, consider using Amplitude. The easiest way is to just turn the radio on and off. On-Off Keying (OOK). Morse code!

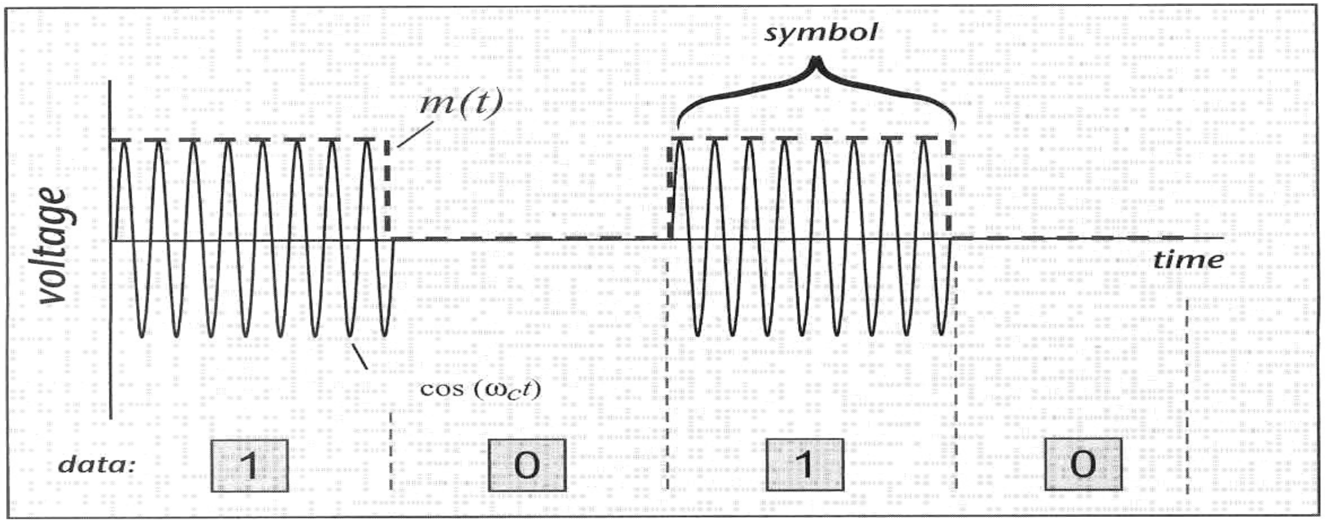


Figure 3.6: On–Off-Keyed Signal.

OOK goes back a long, long time

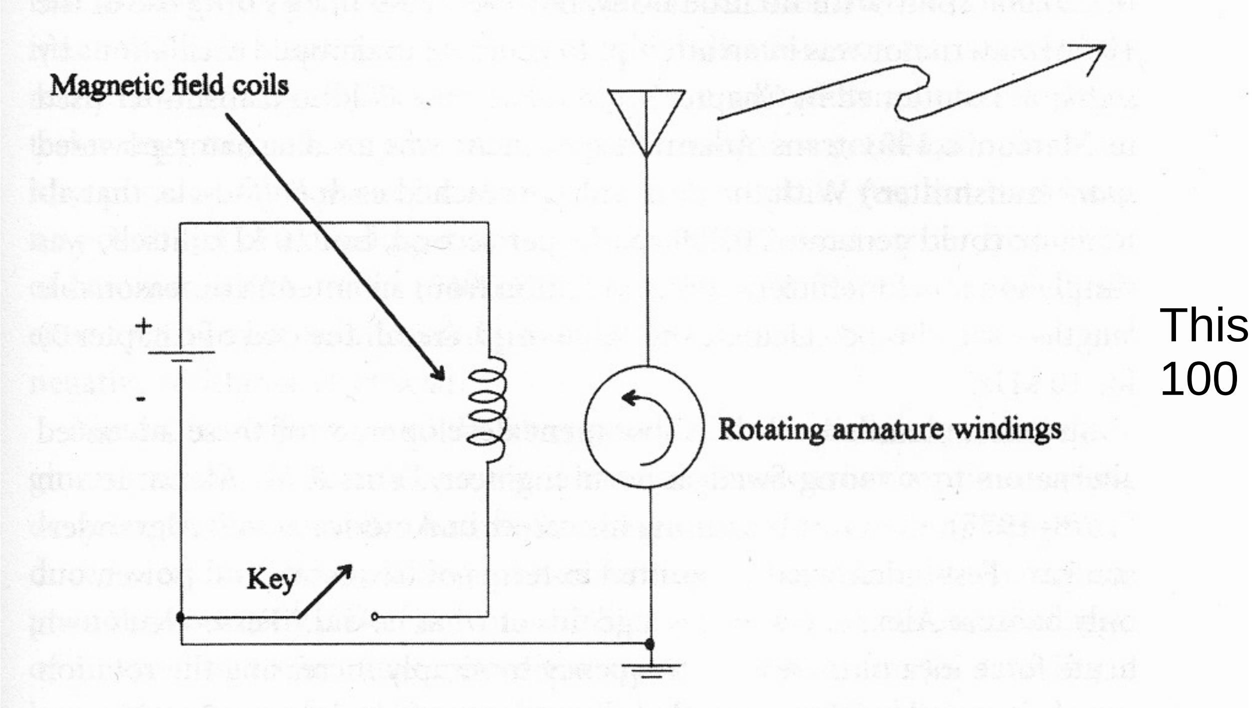


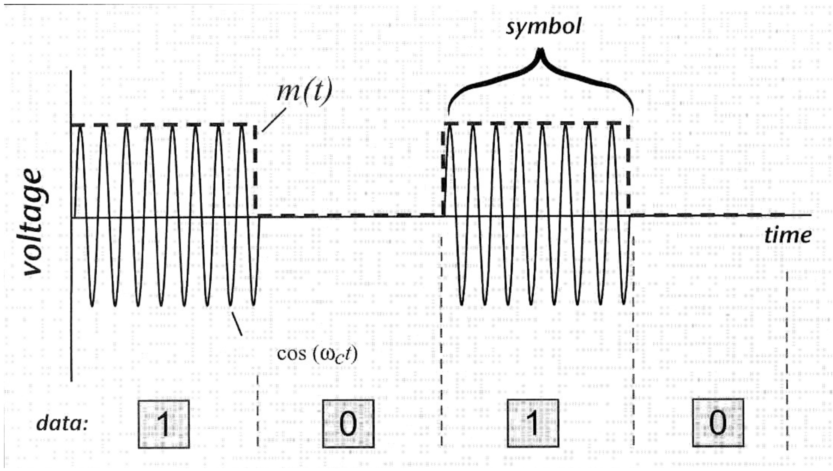
Figure 7.1 A radio-frequency alternator transmitter circuit.

This is from about 100 years ago.

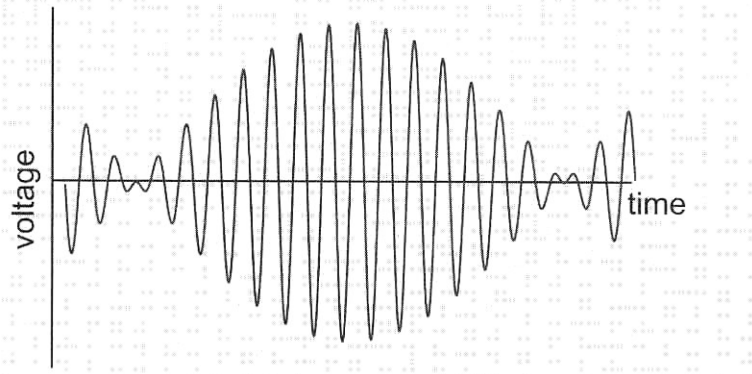
From the beginnings of radio. In this case *f* is a function of the motor speed and number of armature windings. It is based on Faraday's law of inductance AND radiative methods! (The antenna was huge.)

From Nahin, P. The Science of Radio, 1996

Physics of OOK



Or



- Notice that there are now 2 signals here. The first is the <u>carrier</u>.
  - It is abbreviated as ω_c
  - We call it the carrier because it "carries" the signal with the data in it

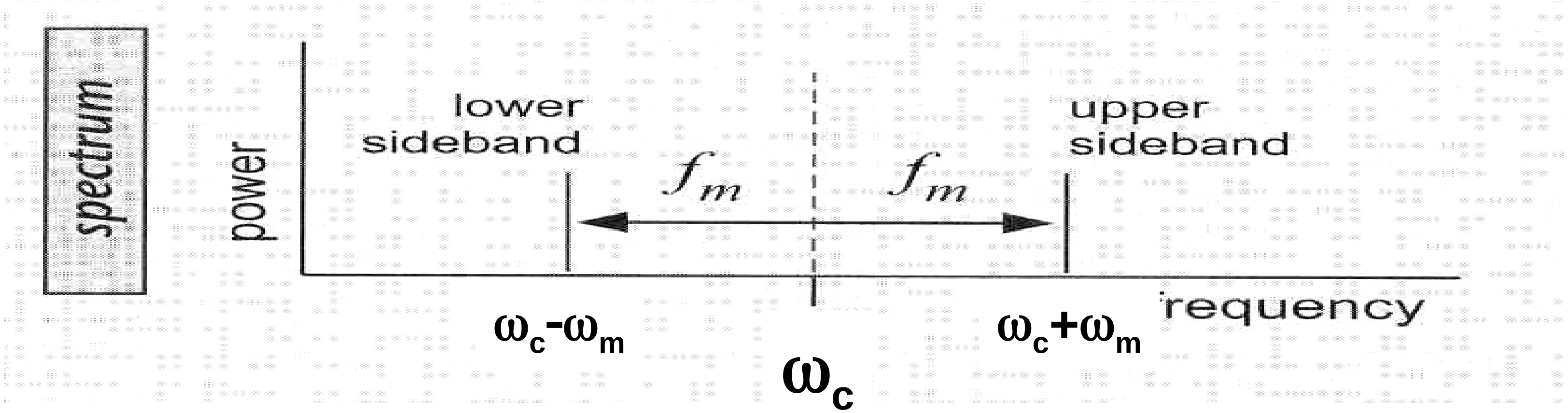
- The second signal is the ON-OFF <u>modulating</u> signal
  - We call it ω_m, and it's frequency is much lower than ω_c.
  - It the modulating signal as it has the data in it. The data "modulates" or "modifies" the carrier using the data.

Modulating ω_c with ω_m

$\boldsymbol{\omega_m}$ modulates $\boldsymbol{\omega_c}$ by scaling the amplitude. Amplitude modulation.

$$V(\tau) = \cos(\omega_m \tau)\cos(\omega_c \tau)$$
$$= \frac{1}{2}\left[\cos([\omega_c + \omega_m]\tau) + \cos([\omega_c - \omega_m]\tau)\right]$$

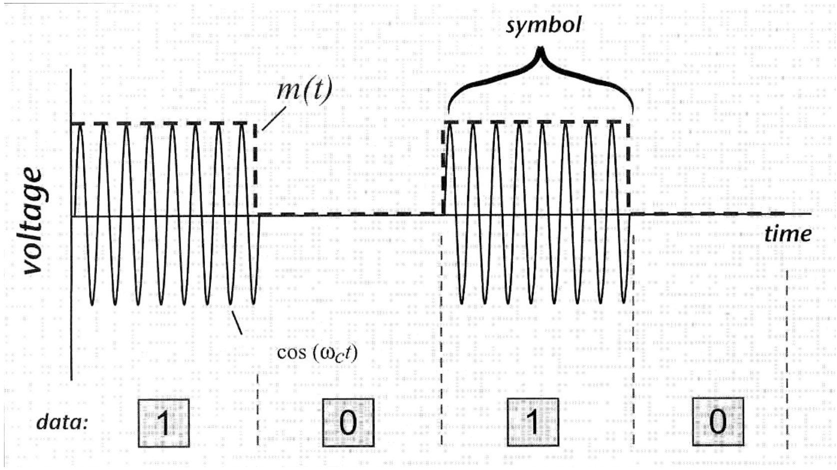
Modulation gives us 2 new signals spaced on each side of the carrier:



These are called *sidebands*. This modulation in this way is related to *mixing*, which is a part of most transmitter and receiver designs.

Problems with OOK

Some interesting things about OOK should be noted:



- First, the carrier is only ON for a logic bit 1. It is OFF for a logic bit 0.
- Remember that if the tag has no battery, it only gets power when the carrier is ON.
- What happens if the reader needs to send a lot of binary 0s to the tag??

Better symbol coding

- In general, with OOK tag power availability is data dependent!
- This is not avoidable
- We can come up with better ways to encode data symbols to ensure there is always some power available to the tag.
- A simple method is Pulse Interval Encoding used with OOK.

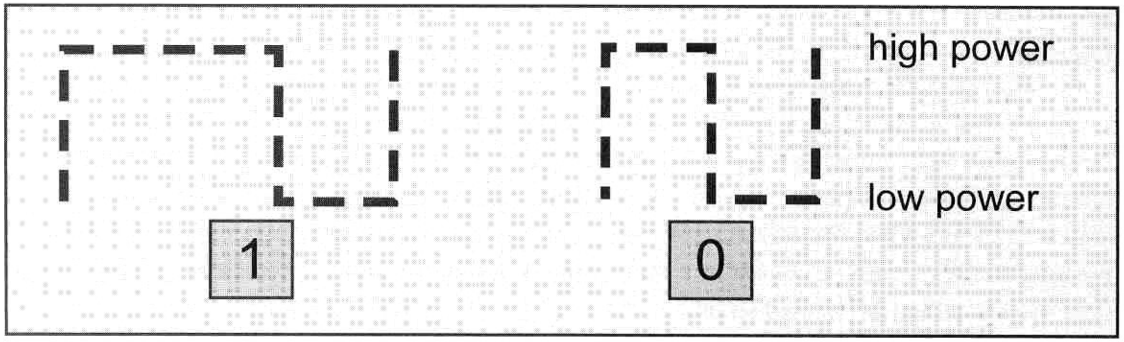
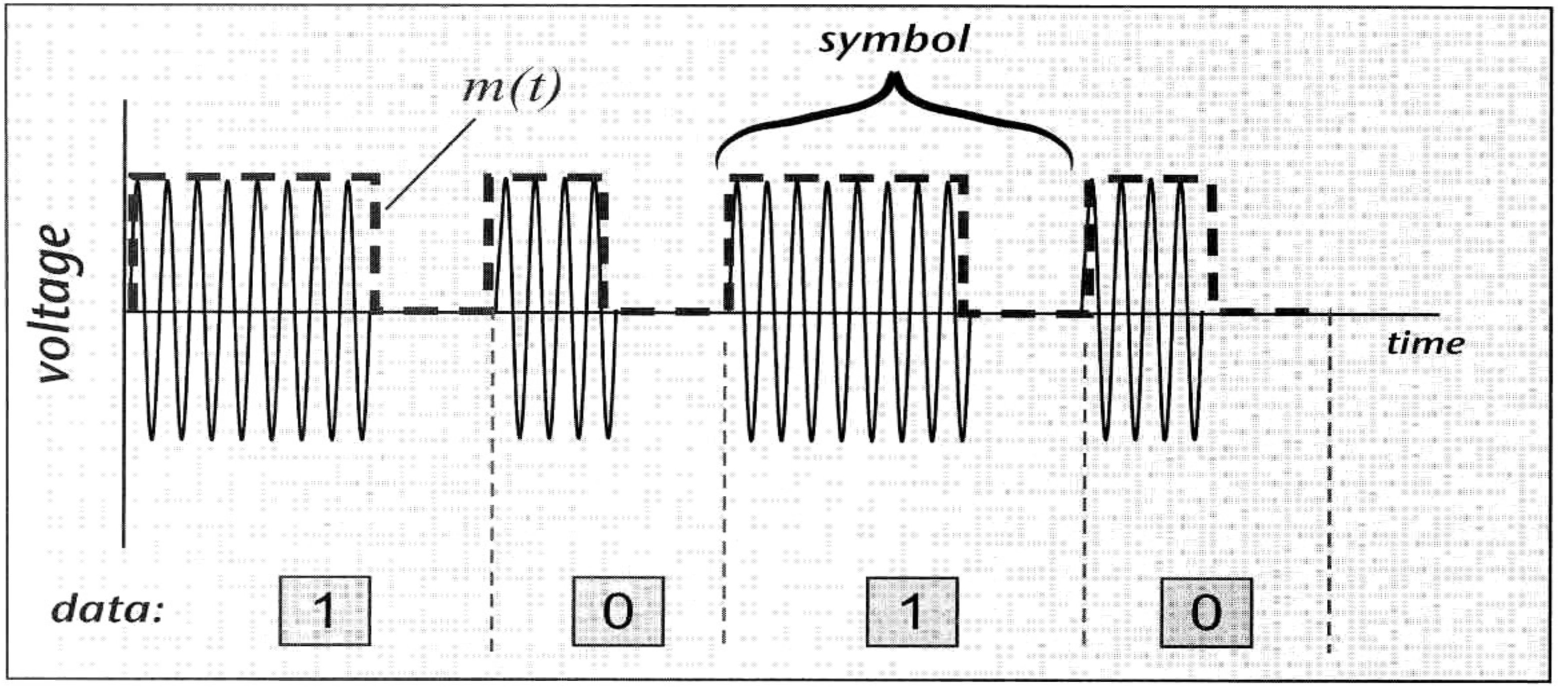


Figure 3.7: Pulse-interval Coding Baseband Symbols (the function $m(t)$).

- It works because there is always some time the carrier is on for both 0 and 1 bits. Logic 1 bits are just on longer.
- This is just one method. There are others.

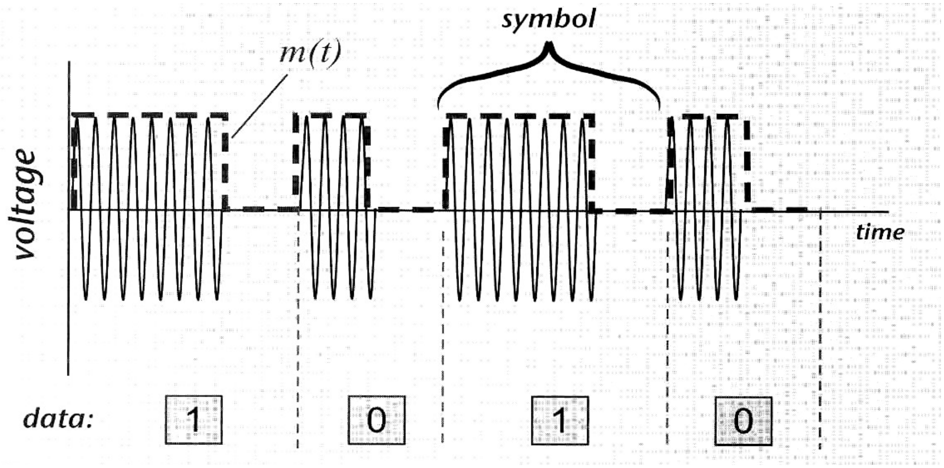
Pulse Interval Encoding (PIE)



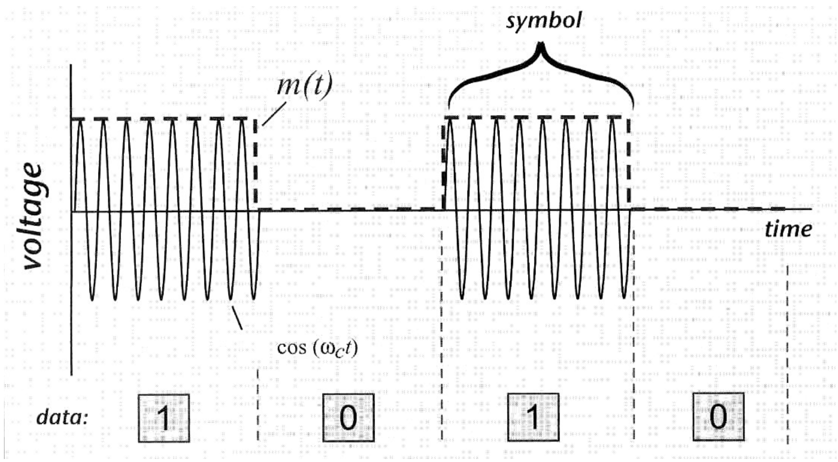
- Another PIE advantage is that both logic 0s and 1s have rising and falling edges. You can tell where each bit begins and ends.
- This makes the OOK data stream more reliable (more robust) than just un-encoded OOK.
- With PIE, the *data rate* is data dependant because 1s and 0s take different amounts of time to send.

Bandwidth and symbols

- How the symbols are defined and formed also has an impact on radiated bandwidth, and data rate. Both are important for RFID.
- Compare un-encoded OOK and PIE for a stream of alternating 0s and 1s:



PIE OOK



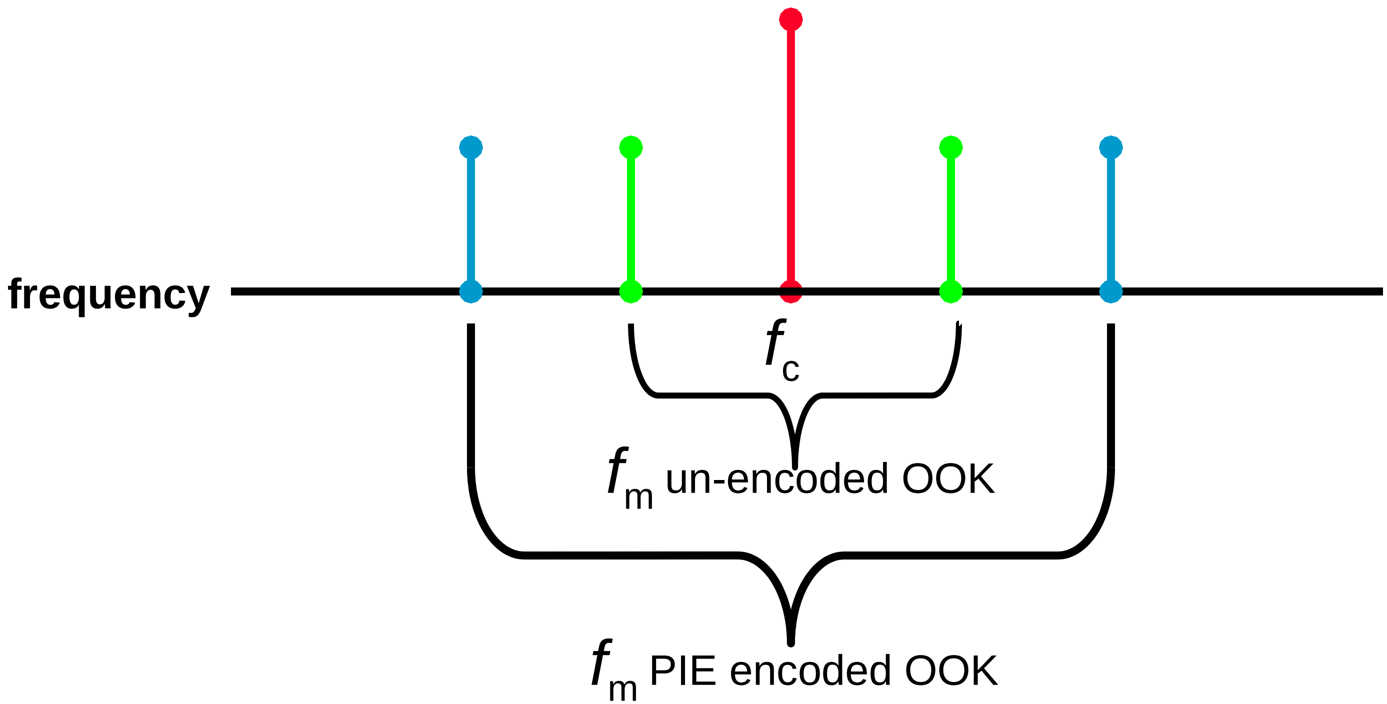
Un-encoded OOK

Note that ω_m for PIE OOK is twice that of un-encoded OOK for about the same data rate!

PIE and bandwidth

- That means that for the same data rate, PIE has double the bandwidth. It is using twice the spectrum resources. Recall that:

$$\mathbf{V(\tau) = \frac{1}{2}\left[\cos([\omega_c + \omega_m]\tau) + \cos([\omega_c - \omega_m]\tau)\right]}$$



Also see figure 3.9

- Note the use of dB to compare sideband power to carrier power.

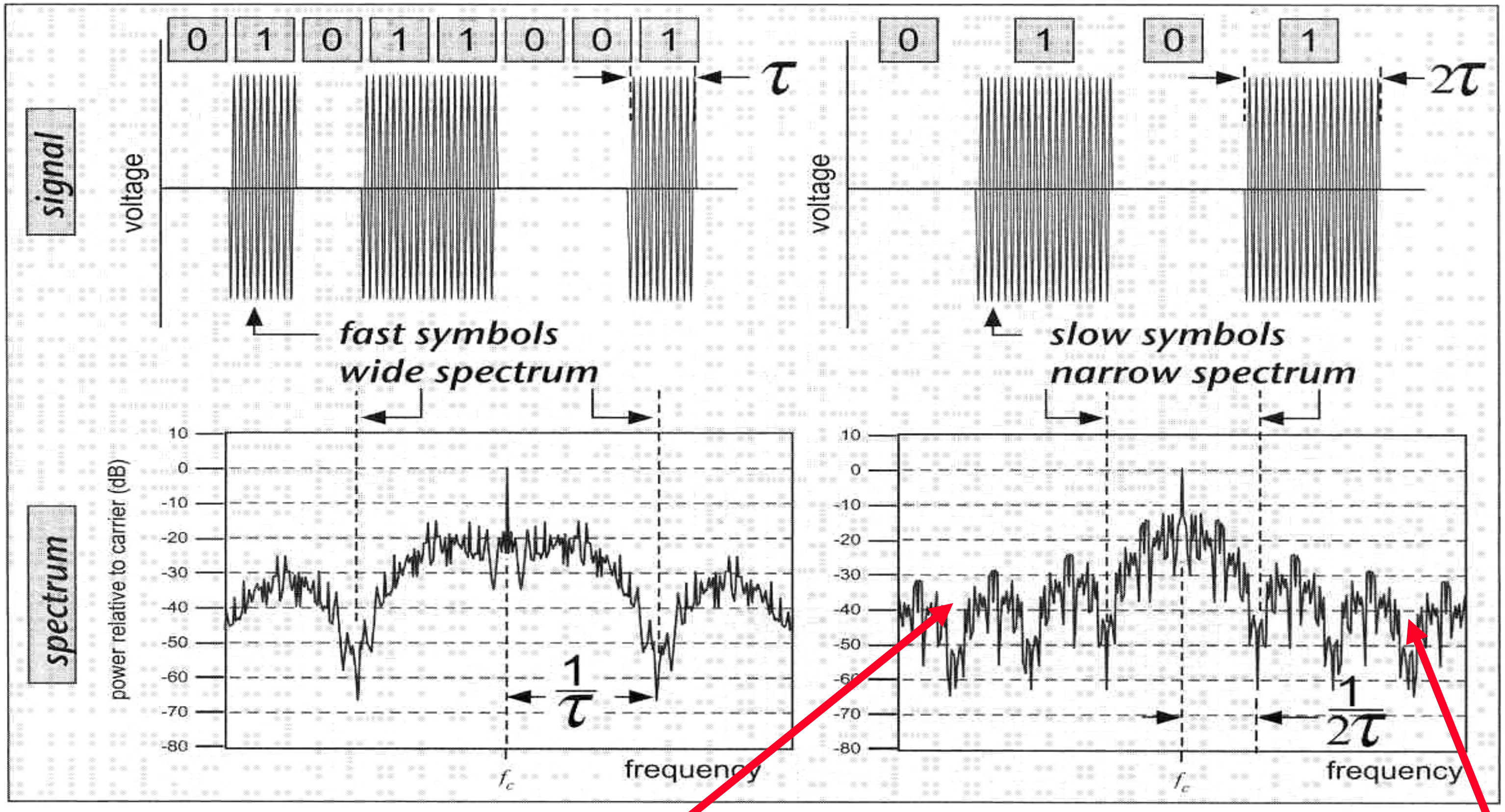
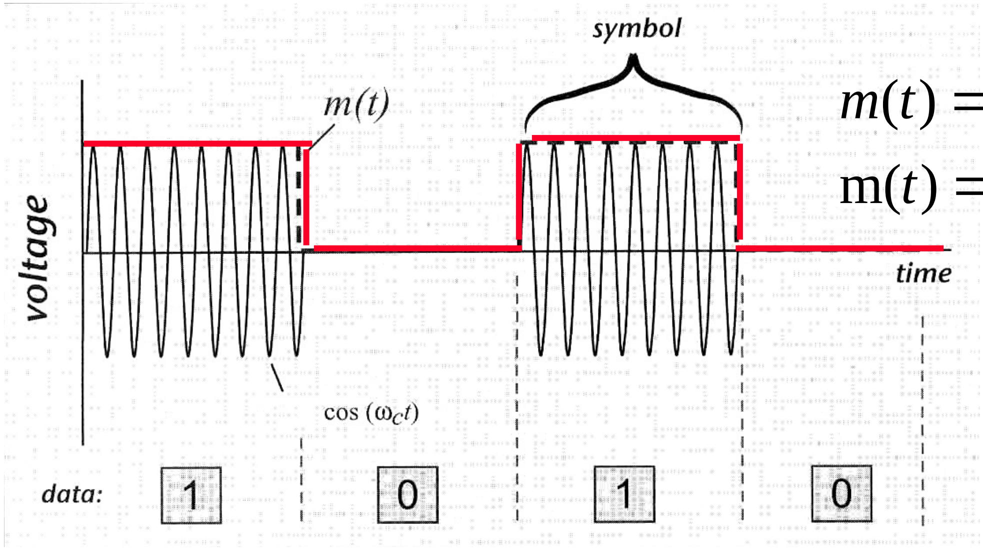


Figure 3.9: Faster Modulation = Wider Spectrum.

What's all this extra spectrum use out here, -30dB from the carrier?

Bandwidth considerations

- Increasing the data rate will also increase the bandwidth because a higher data rate means higher ω_m.
- Also, how you generate the modulating signal m(t) will affect the bandwidth of the signal.
- For example, suppose m(t) works by turning our carrier on and off very fast. In other words, supposed m(t) looks like a square wave:



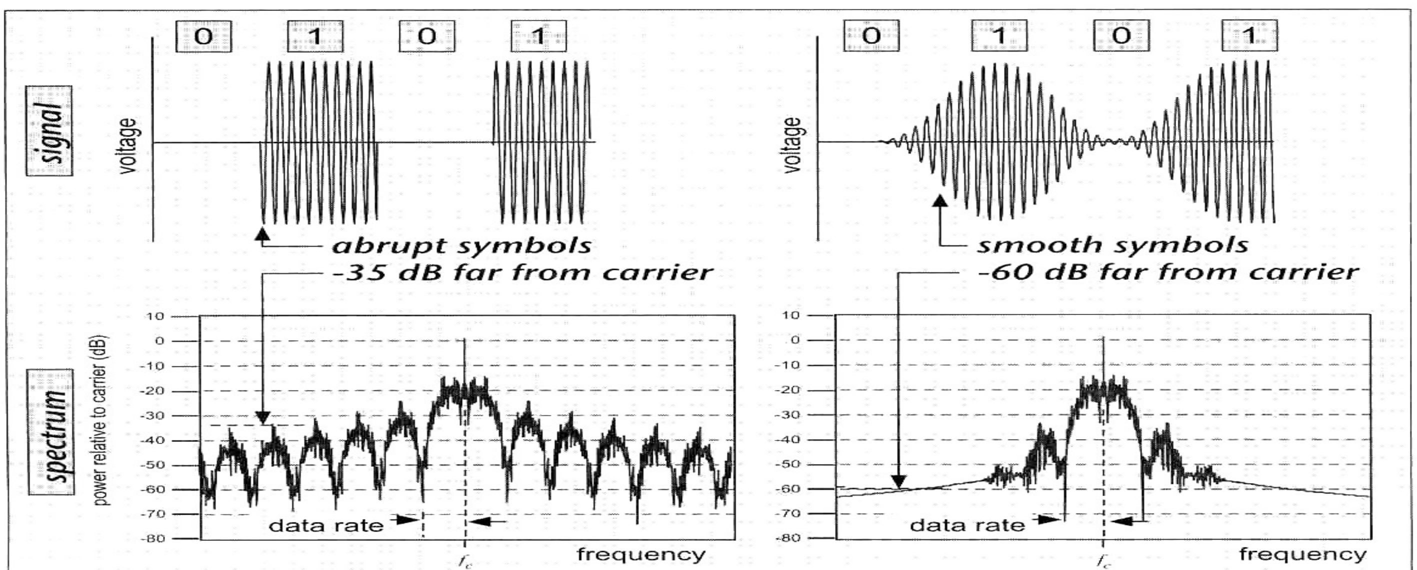
$$\left.\begin{aligned} m(t) &= 1 \quad 0 \le \tau < \pi \\ m(t) &= 0 \quad \pi \le \tau < 2\pi \end{aligned}\right\} \text{ Defined over one cycle}$$

Bandwidth and m(t) shape

- We know from signal processing the Fourier transform of a square wave:

$$H(\omega) = \frac{1}{2} + \frac{2}{\pi}\left(\sum_{n=-\infty}^{\infty} \frac{\sin(b(n)\omega)}{n} \right) \quad \left.\right\} \begin{array}{l} b(n) = 0 \rightarrow \text{for all even } n \\ b(n) = n \rightarrow \text{for all odd } n \end{array}$$

- This shows that when m(t) is a square wave, the modulated waveform will contain sidebands at all odd multiples of ω. Compare to when m(t) is more of a sinusoid (slower changing).



Interference

- There is no real reason to have a fast changing m(t) unless you need a high data rate.
- High data rate requires a high BW. This means significant sidebands far away from the carrier.
- If they are far enough away, they will interfere with other radios.

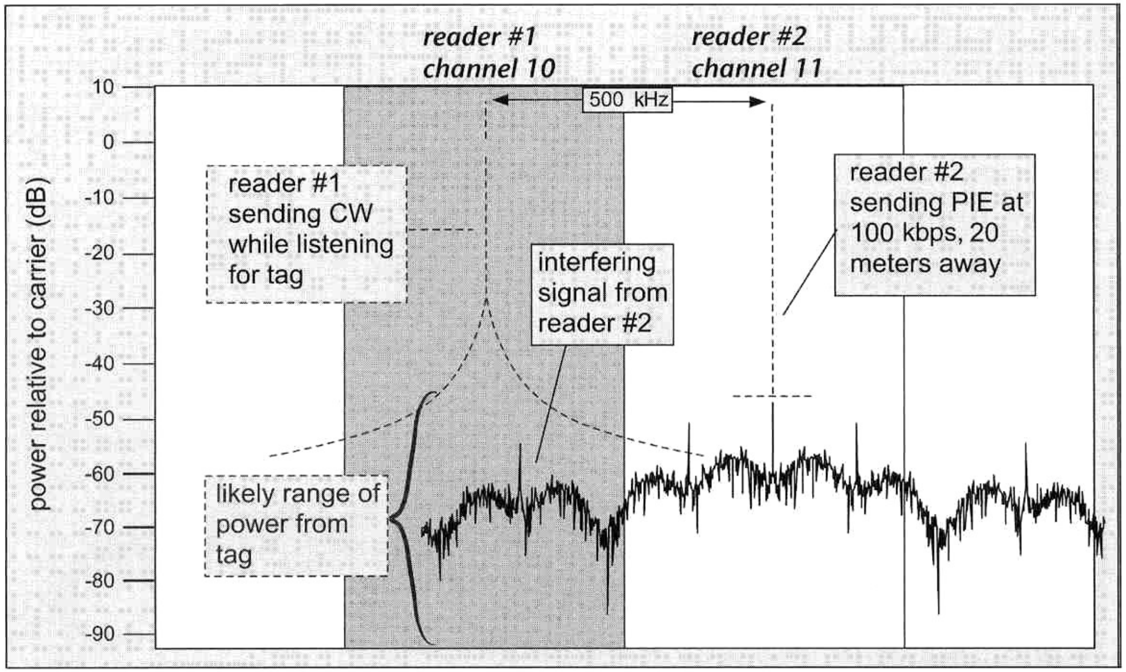


Figure 3.12: Power Far from the Carrier of Reader #2 is in the Channel of Reader #1 if Data Rate is High and Unsmoothed PIE is Used.

This shows how 2 readers can interfere with each other.

This is a channelized RFID standard having carrier frequencies in the 902-928 Mhz band.

Channels are 500 Khz wide. Normal max data rate is 85 kbps (PIE).

RFID limits to what you can do about this

- In theory, you could use filtering to BW limit the spectrum use.
- You could also use a much more sophisticated modulation scheme than PIE. Cell phones and other services like 802.11 do this.
- Readers do have filters, so they can limit their receive or transmit bandwidth.
- But, you are also limited by what the tag can do. It needs to be low power, simple and cheap. It may not be able to handle complicated modulation sent to it by the reader.
- We will see this next as we look at how backscattering works.