RFID Systems: Radio Architecture

A discussion of radio architecture and RFID.

What are the critical pieces?

Familiarity with how radio and especially RFID radios are designed will allow you to make correct choices when designing an application system.

Read Chapter 4.1 through 4.3 in the text.

Radio architecture parameters

What makes a “good” radio good? Radio designers take into account a lot of parameters. Here is a reasonable list of parameters for good RFID design.

1. Getting the signal you want:
   - Selectivity
   - Stability
   - Sensitivity and dynamic range

2. Quality of the information
   - Accuracy during modulation and de-modulation
   - Low noise and low distortion

3. Good performance with respect to information speed
   - Adequate bandwidth

Radio architecture parameters

4. Cost
   - Can anyone afford it?
5. Complexity
   - Can anyone use it?
6. Efficiency
   - Doing all of this at the lowest power
   - Flexibility, for example can the radio be used with multiple RFID protocols.

There are others, but for RFID these are most important. The whole point of radio is to modulate radio energy so that it contains information, and be able to transmit it and receive it for the benefit of a user.

One way to look at all this:

Radios, in general, only have 2 kinds of things inside to make them work:

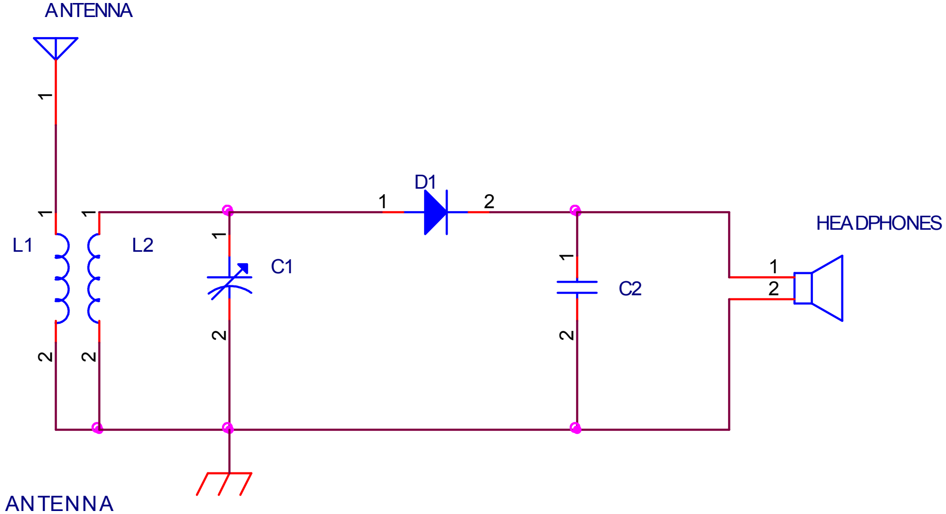
1. Amplifiers : They create or magnify the signals you want.

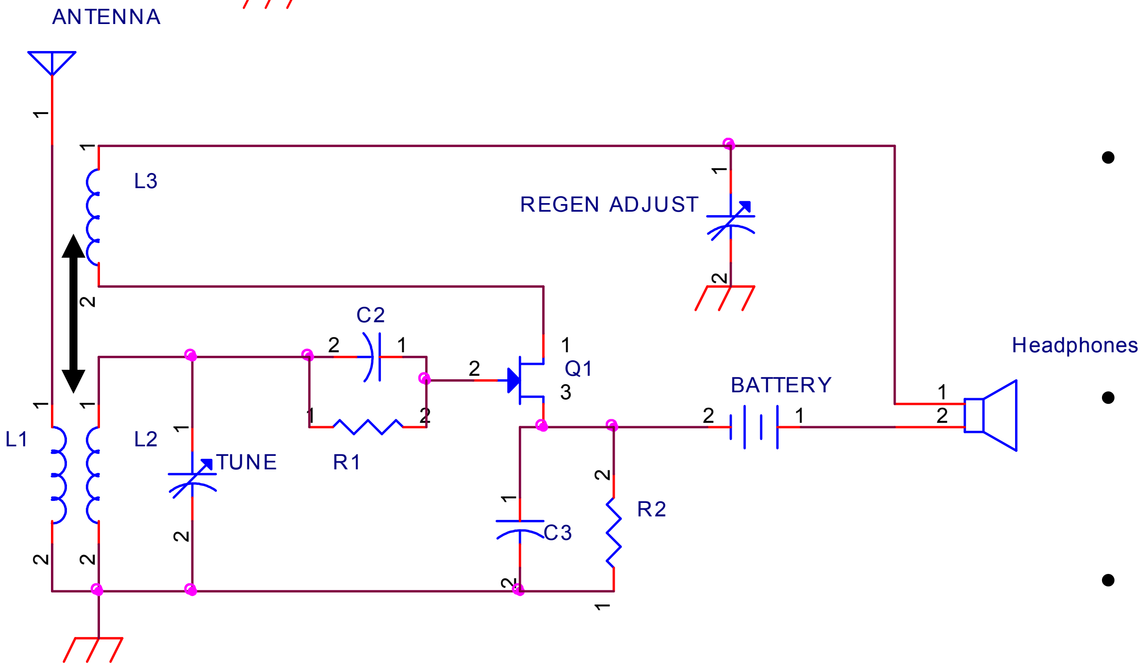
2. Filters : They remove the signals you don’t want.

That’s really all there is.

Here are some illustrative examples that show these parameters as an evolutionary path toward radios we have today.

Getting the signal you want



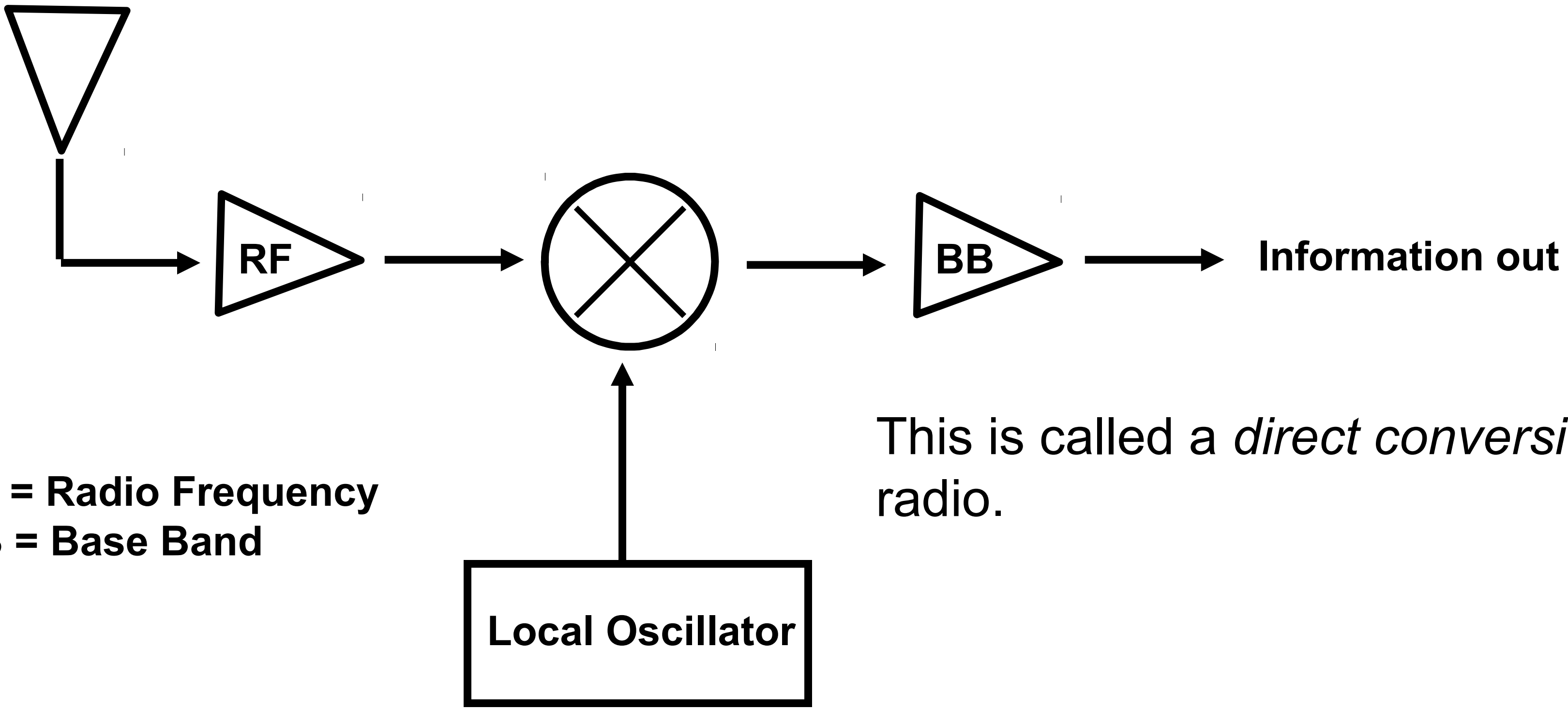


- Our crystal radio works, but has terrible **sensitivity**. The signal must be very strong to pass D1.
- The **selectivity** is also bad. You can hear many stations at the same time.

- Adding amplification and providing a positive, in phase feedback path greatly improves sensitivity *and* selectivity.
- These were invented in 1917. They were called *regenerative* receivers.
- They aren't very **stable.**

Direct conversion

The regenerative design was cheap but hard to adjust, and so was complex to use. It could also be unstable. The next step was to keep the amplifier, but add a local oscillator and a mixer. Something like this:



This is called a *direct conversion* radio.

RF = Radio Frequency
BB = Base Band

Local oscillators and mixers

- A local oscillator is just a radio signal source of a known frequency.
- It outputs a sinusoid at some frequency *f*.
- They can output a fixed or adjustable *f*.

- A mixer is a non-linear device that in effect multiplies two signals in the time domain. We already know some of how it works.
- Recall what a carrier looks like after it has been modulated:

[See figure 3.5 in the text book.]

Mixing and direct conversion

- Remember that the sidebands were due to the effect of modulating a carrier (ω_c) with some information signal (ω_m). (See chapter 3).

$$V(\tau) = \cos(\omega_{\mathrm{m}}\tau)\cos(\omega_{\mathrm{c}}\tau)$$

$$= \frac{1}{2}\left[\cos([\omega_{\mathrm{c}} + \omega_m]\tau) + \cos([\omega_{\mathrm{c}} - \omega_m]\tau)\right]$$

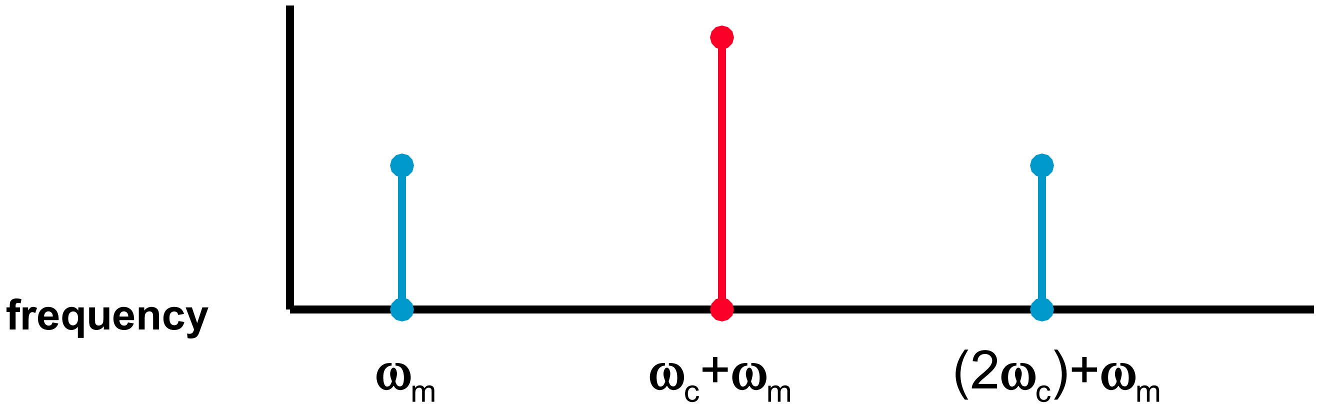
- The sidebands are located in the frequency domain at (ω_c+ ω_m) and at (ω_c- ω_m).
- Let's assume we want to receive the "*upper*" sideband (ω_c+ ω_m).
- Now, suppose we have a local oscillator where $2\pi f = \omega_c$. Suppose we use this to perform "modulation" (mixing) again on (ω_c+ ω_m).

$$V(\tau) = \cos(\omega_{\mathrm{c}}\tau)\left(\cos([\omega_{\mathrm{c}} + \omega_m]\tau)\right)$$

$$= \frac{1}{2}\left[\cos([(2\omega_{\mathrm{c}}) + \omega_m]\tau) + \cos(\omega_m\,\tau)\right]$$

Mixing and direct conversion

- Note that you get two output frequencies from this:
- $(2\omega_c)+\omega_m$ and just ω_m output
- ω_m is exactly the information that modulated the original carrier!



- The other term, $(2\omega_c)+\omega_m$ is at a relatively high frequency with respect to the carrier and the local oscillator. The receiver should have no trouble not receiving (rejecting) this frequency.

- Remember also that for this RFID case, modulating *is* mixing.

Problems with early direct conversion

A big problem was stability of the local oscillator (LO).

- Suppose f_c is 100 Mhz, and f_m is 1 Khz. You want to receive the 1 Khz information. The upper sideband is at 100.001 Mhz.
- In this case, the LO needs to also be 100 Mhz because 100.001 – 100 = 0.001Mhz = 1Khz.
- Now suppose the LO has drifted to a higher frequency. Let's say it only drifts by 0.1%, so now the LO is at 100.1 Mhz.
- To receive the 1 Khz information, (f_c + f_m) would need to be at a frequency of (0.001 Mhz + 100.1 Mhz) = 100.101.
- That means you are trying to receive at a frequency of 100.101 Mhz instead of 100.001 Mhz. You are 100 Khz off frequency.

- And that's with 0.1% LO accuracy!

Problems with early direct conversion

Another problem is with *images*.

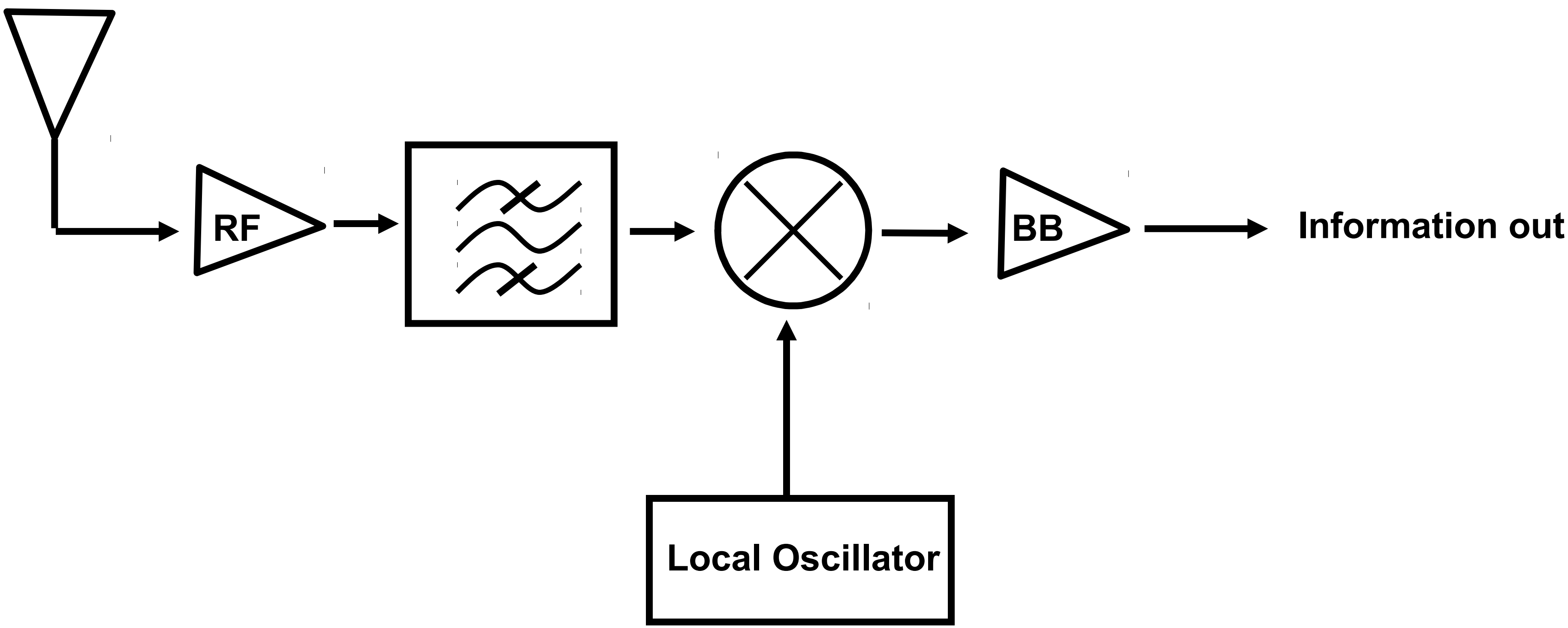
- Let’s imagine the LO is perfect, and has no drift. It is perfectly accurate.
- But remember that mixing gives both the *sum* and *difference* of the 2 frequencies being mixed.
- We know about the one at 100.001 Mhz, but…
- What about the one at 99.999 Mhz? 100-99.999=0.001 or 1Khz.

- The frequency at 99.999 Mhz is called an *image*. It is so close to the upper sideband that filters and simple mixers can not reject it.

- However in RFID, both sidebands generated by the tag have the same data. So it doesn’t matter that they interfere.
- Images ARE a problem if an interferer (another radio) is transmitting on the image frequency. How do you fix that?

Filtering images

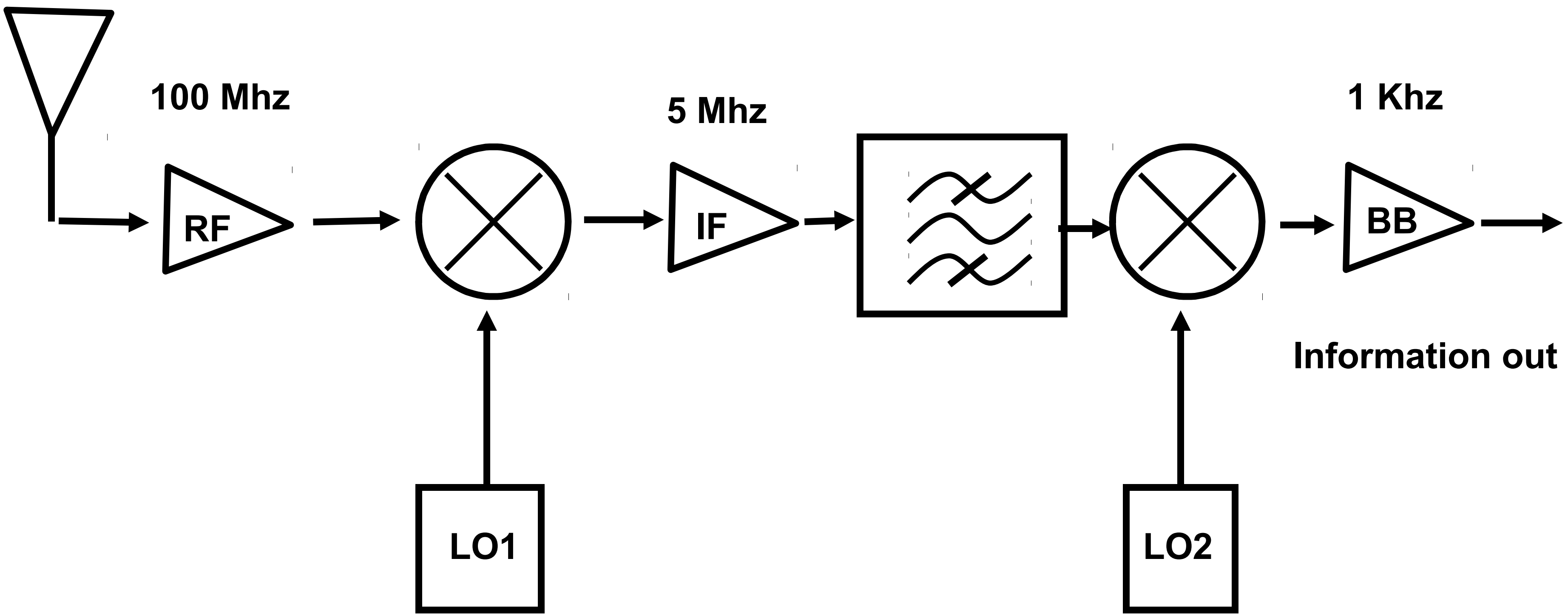
You could fix it by adding a *band pass* filter.



- If the BPF has a width of about 1 Khz, that works out to be about 0.001% of the 100 Mhz RF frequency.
- That's very hard to make at such a high center frequency!

Multiple conversion

Problems with images get less severe by doing *multiple conversion*. For example, lets say we still have a received signal at 100 Mhz.



RF = Radio Frequency
IF = Intermediate Frequency
BB = Base Band

Image filtering at a low IF

- With a low frequency IF stage, filtering out the image is much easier.
- With a BPF width of 1 Khz, and an IF of only 5 Mhz, the width of the filter is now 0.02% of the IF frequency.   It's greater than before.

- That is much easier to build. You can buy them commercially.

- If you add more IF stages and go even lower, the filters get very economical to build. Selectivity with multi IF receivers can be very good.

- Multi-conversion receivers for consumer electronics (like your stereo) are very common. They have good performance.

- But, those extra IF stages cost extra money.

Direct vs multi conversion

In this example, the multi-conversion receiver has one IF stage.

[See figure 4.2 in the text book.]

Multi-conversion receivers are sometimes called superheterodyne receivers.
Direct conversion receivers are sometimes called zero conversion receivers.

Most inexpensive RFID readers are direct conversion

[See figure 4.4 in the text book.]

The reasons for direct conversion

Also, what about the local oscillator? Don't we still have a stability problem?

1. We could still have a problem with images, but maybe not so bad.
   - Our own image contains the same data as the sideband we want
   - An image from another radio could maybe be filtered out, or
   - We can move away from it by *frequency hopping*
   - Frequency hopping is allowed for UHF RFID in many countries (not EU)
2. For RFID, we have NO local oscillator stability problem.
   - This is because the transmit carrier oscillator and the receive local oscillator are *exactly the same circuit!*
   - Even if it drifts, it doesn't matter unless we drift out of the band
3. It's cheaper and lower power
   - Extra IF stages add cost
   - They also burn power
   - Fewer circuits to fail. More reliability

Taking radio architecture further

We now look at the list of “good radio” parameters to see how well the generic RFID radio works.

- Getting the signal you want:
  - Selectivity
  - Stability
  - Sensitivity and dynamic range (although we suspect this is OK)
- Quality of the information
  - Accuracy during modulation and de-modulation
  - Low noise and low distortion
- Good performance with respect to information speed
  - Adequate bandwidth

Also these

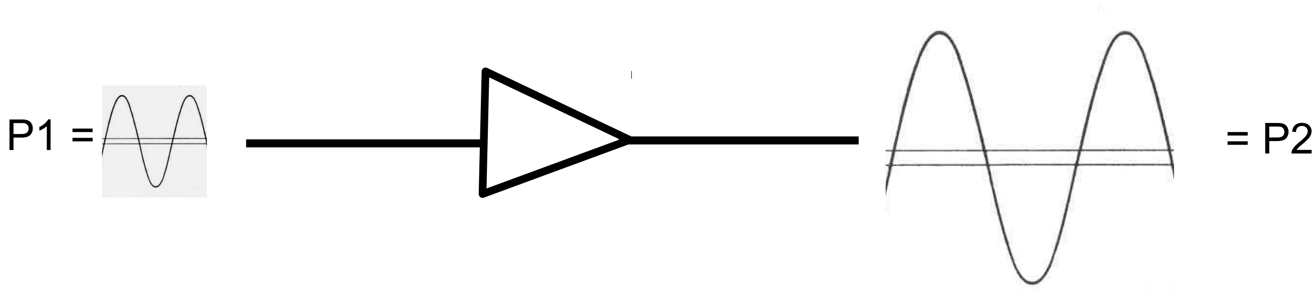
4. Cost
   - Can anyone afford it?
5. Complexity
   - Can anyone use it?
6. Efficiency
   - Doing all of this at the lowest power
   - Flexibility, for example can the radio be used with multiple RFID protocols. (This depends on the processing we an afford.)

Not too bad! The most important thing we need to look at is quality of the information. What still can pollute the data to make it un-usable.

We will look briefly at the red items to see what else in a RFID receiver architecture has influence on them. We start with distortion.

Amplifiers and distortion

- We all know what a “perfect” amplifier does. It takes a signal and makes it stronger, either with respect to voltage, current or power.



- A *perfect* amplifier is also perfectly linear
- Can have infinite gain and infinite bandwidth
- And has infinite output power capability

Amplifiers and distortion

Radios are full of amplifiers and unfortunately, real life amplifiers are far from perfect.

- For example, it is not possible to have infinite output power capability. Real amplifiers *saturate*.

[See figure 4.6 in the text book.]

- They don’t have any of the perfect attributes that were listed.
- The result of these imperfections is that signals going through them are *distorted*.

Distortion

One way to look at the effect of distortion is to consider what it means with respect to sinusoids.

- Consider a perfect sinusoid at a single frequency.
- Now, distort it so that it isn’t a perfect sinusoid any more.
- But, all periodic signals are made up of some sort of combination of sinusoids.
- This means that your distorted periodic waveform now has *amplitude* and *frequency* components in it that are different compared to when it was not distorted.
- These can have an impact on the operation of the RFID reader.

Characterizing distortion

- All amplifiers cause some degree of signal distortion.
- Suppose we have some input signal, Vin, and we want to amplify it. A perfect system would just give:

$$V_{out} = G_{amp} V_{in}$$

- But, a real amplifier distorts the signal. ANY non-linearity causes this.
- We can express this as a power series:

$$V_{out} = G_{amp} V_{in} + a_2 V_{in}{}^2 + a_3 V_{in}{}^3 + \ldots$$

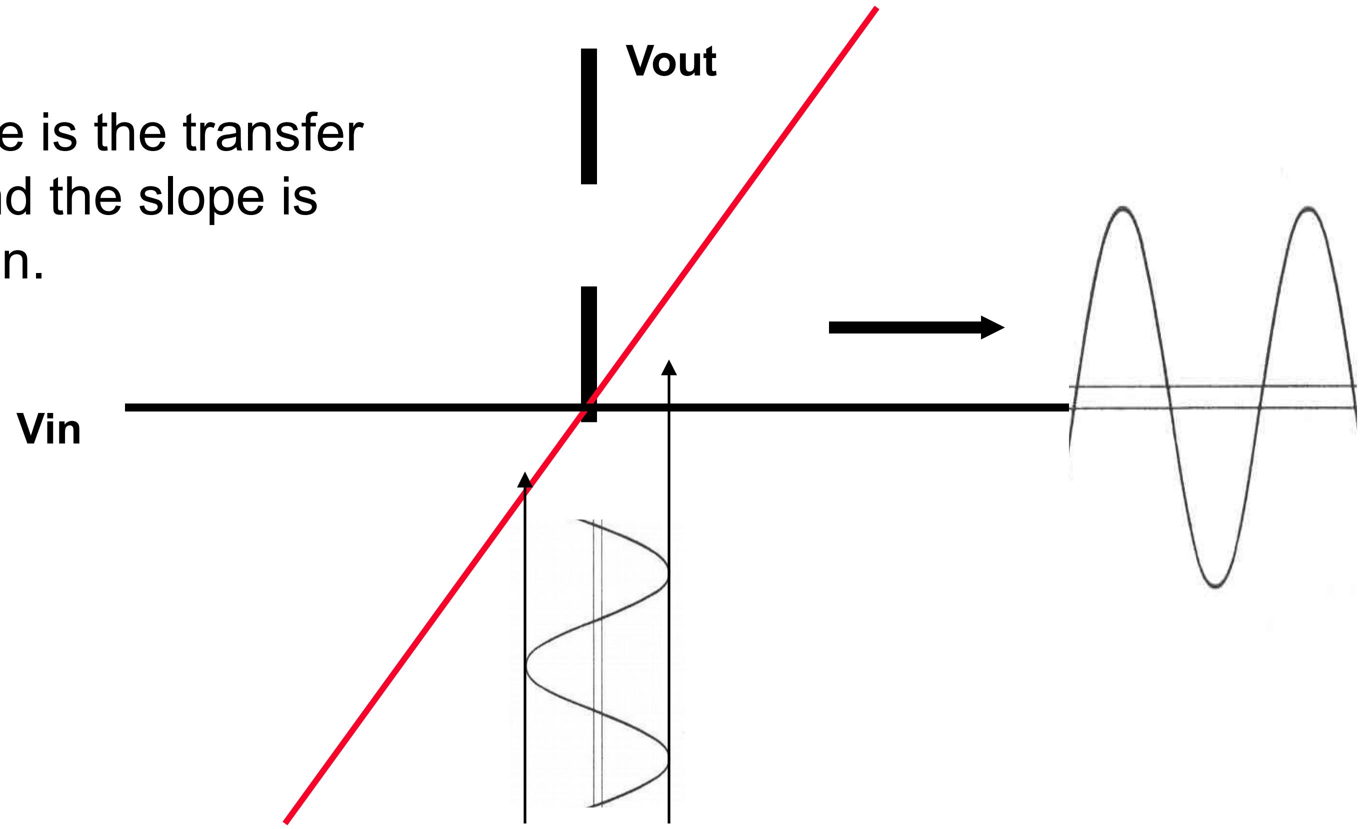
- The 'a' terms can be anything, but in a real circuit they should be small.
- In RFID radio design, 2^{nd} and 3^{rd} order distortion is often characterized. It is important to know what that means.

Second order distortion

What if the RFID reader has significant 2nd order (quadratic) distortion?

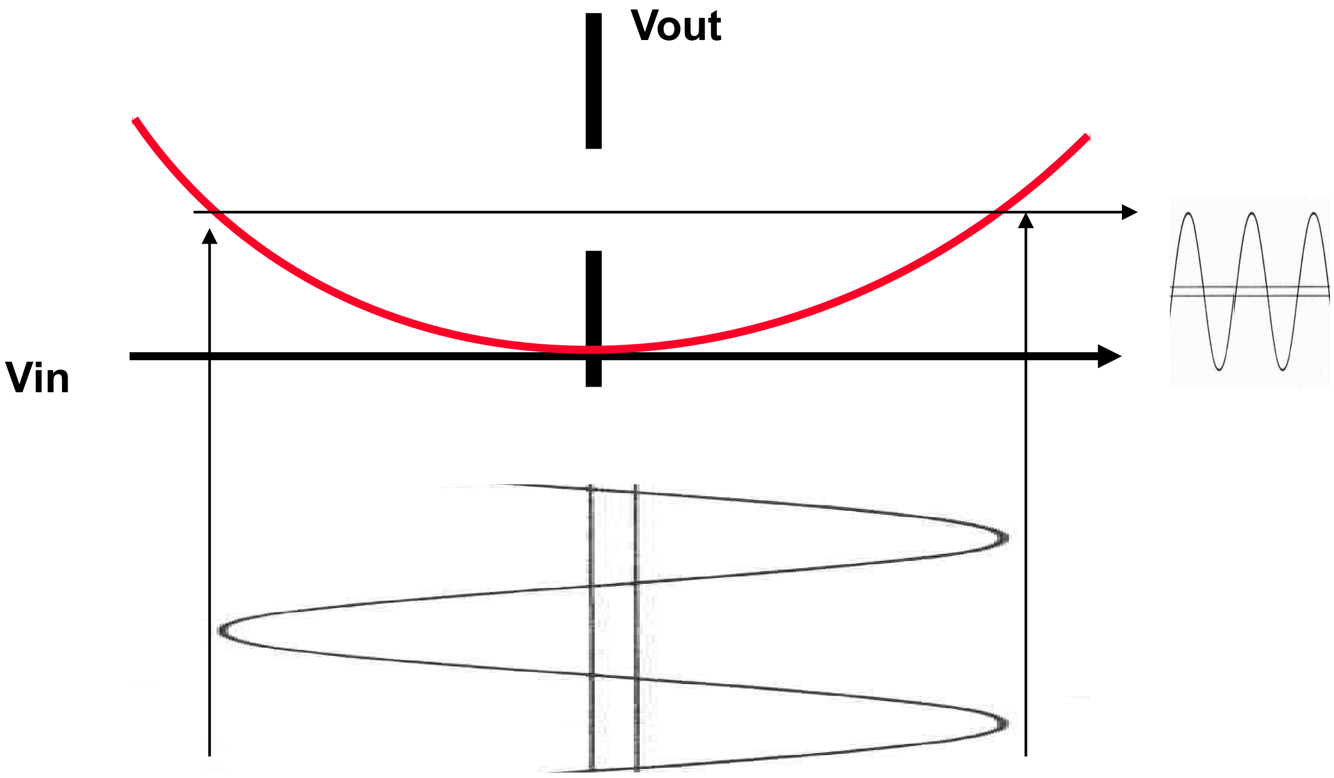
- A good way to look at it is graphically. For example, a *perfectly linear* amplifier will have a *transfer function* that looks like this:

The red line is the transfer function and the slope is just the gain.



Second order distortion

- But, a 2nd order, or quadratic transfer function will look like this:



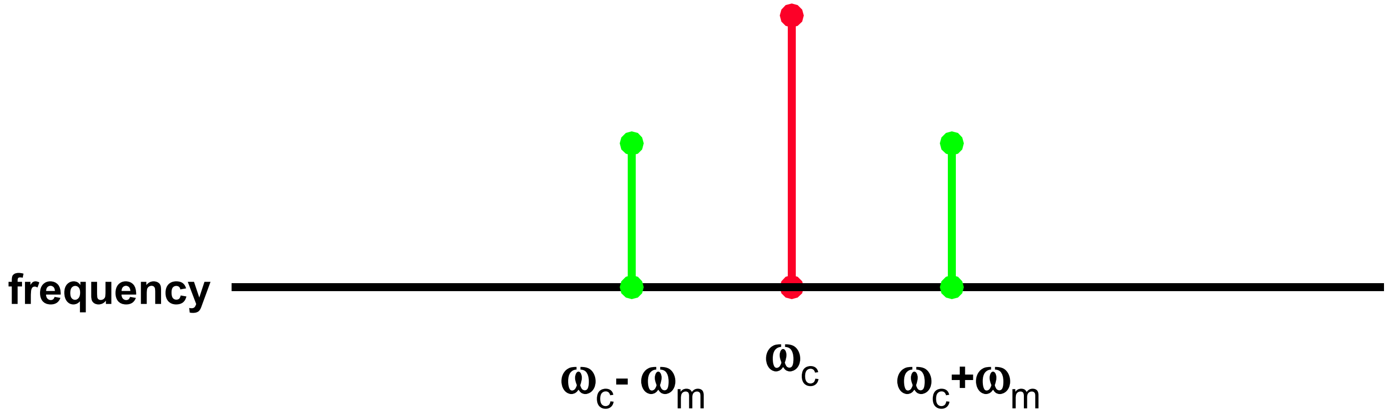
- The output of this is a new signal at twice the frequency!

Second order distortion

- To see the effect expressed in math, recall what a RFID reader sends out when it is communicating with a tag:

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

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



Second order distortion

Lets call the upper sideband ω_{hi} and the lower sideband ω_{lo}

- This means that the sidebands representing our modulated signal can be expressed as:

$$V(\text{mod}) = \text{v}_s \cos(\omega_{hi}\tau) + \text{v}_s \cos(\omega_{lo}\tau)$$

- Run it through an amplifier and include 2nd order distortion terms:

$$V(out) = \text{G}_v \text{v}_s[\cos(\omega_{hi}\tau) + \cos(\omega_{lo}\tau)] + \text{a}_2 \text{v}_s^{\ 2}[\cos(\omega_{hi}\tau) + \cos(\omega_{lo}\tau)]^2$$

- The linear term is no problem. The 2nd order term can be expanded using the trig identities in equation 4.9 in the textbook

Second order distortion

Expanding the 2nd order term gives:

$$\mathrm{a}_2 \mathrm{v}_\mathrm{s}^{2}[\cos(\omega_{\mathrm{hi}}\tau)+\cos(\omega_{\mathrm{lo}}\tau)]^2 =$$

$$a_2 v_s^{2}[1+\frac{1}{2}[\cos(2\omega_{hi}t)+\cos(2\omega_{lo}t)]+\cos([\omega_{hi}+\omega_{lo}]t)+\cos([\omega_{hi}-\omega_{lo}]t)]$$

Sure enough, the distortion gives us new signals.

[See figure 4.8 in the text book.]

Third order distortion

The analysis of the 3rd order (cubic) distortion products is similar, but the effects are more serious. Graphically, they look like:

[See figure 4.11 in the text book.]

Third order distortion

The math for 3rd order is similar to work through as the 2nd order case. See equations 4.11 and 4.12 in the text.

- The big problem is that among all the new frequencies that are generated, we now have ones at $2f_{lo}-f_{hi}$ and $2f_{hi}-f_{lo}$.
- Because f_{lo} and f_{hi} are so close to each other, these new frequencies can not be filtered out in any practical way.

[See figure 4.10 in the text book.]

Consequences of 3rd order distortion

Unlike 2nd order distortion, 3rd order distortion results in at least 2 problems.

1. Increased bandwidth when the RFID reader is transmitting.
   This can interfere with an adjacent RFID channel.

[See figure 4.14 in the text book.]

Consequences of 3rd order distortion

2. Interference while the RFID reader is trying to hear a tag. Note that the 3rd order distortion is generated inside the reader trying to hear the tag. The flo and fhi frequencies can come from another reader.

[See figure 4.15 in the text book.]

Distortion and the system design

Knowing these numbers for 2nd and 3rd order distortion are expressed by manufacturers in terms of *intercepts*. They help you evaluate readers.

- The idea of an intercept is that because 2nd or 3rd order output is amplified by a factor squared or cubed, eventually at some input power the distorted output will match, or intercept the linear output power.
- By telling you that one point, you can extrapolate backwards and know your distorted output power for any input power.
- You would like your linear output power to be many orders of magnitude above your distorted output, ie 30 dB or more.
- There are 4th and higher order distortion effects, but they only become important as the amplifier is operated at high gains with output near the saturation point.

Graphical example of 2^{nd} order intercept (OIP2)

For an input signal of -10 dBm the 2^{nd} Order Distortion is 15-(-25)=40 dB lower than the linear signal. Not bad!

[See figure 4.12 in the text book.]

Graphical example of 3rd order intercept (OIP3)

For the same -10dBm input the 3rd Order Distortion is 15-(-20)=35 dB lower from the linear signal. Not as good!

Unfortunately, 3rd order distortion output is closer to our desired linear output.

[See figure 4.13 in the text book.]

The bottom line is

The higher the 2nd and especially the 3rd order intercepts of the RFID reader, the better!

Quality of information, noise and amps

We noted that typical modern RFID readers have low input (thermal) noise.

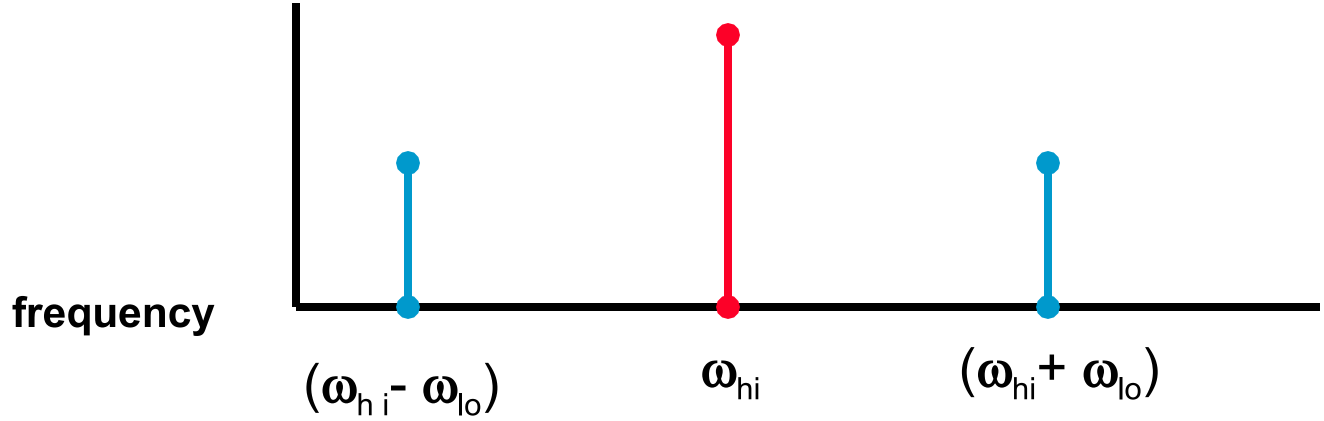
- Although all parts account for noise, it is very low in the RFID bands we are interested in.
- Signal to Noise ratios (SNR) are useful specification parameters. For two radios of equal performance, you want the one that can do it at a lower SNR.
- Typical parameters for amplifiers that affect the entire system are input SNR, output SNR and Noise Figure NF.
- The Noise Factor is just the ratio of input to output SNR
- In the long run, amplifier design is very good. More important is:

1. Trade off of noise performance and cost
2. Use really good antennas. Antenna gain goes a long way.
3. Be aware of the environment the system will be used in, for example obstacles, reflections, and interferers.

Quality of information and mixers

- Mixers are of interest because they are non-linear. Have to be.
- Recall that for us, mixing is related to modulation. In the ideal case the result of mixing gives the sum and difference of the signals being mixed.

$$V(\tau) = \cos(\omega_{\mathrm{lo}}\tau)\cos(\omega_{\mathrm{hi}}\tau)$$
$$= \frac{1}{2}\left[\cos([\omega_{\mathrm{hi}} + \omega_{lo}]\tau) + \cos([\omega_{\mathrm{hi}} - \omega_{lo}]\tau)\right]$$



Mixers and distortion

But this non-linear process produces a lot of distortion.

[See figure 4.19 in the text book.]

Mixers and distortion

- Note the sharp edges and other distortion in the output signal. We can try to filter it, but the output will not be perfect.

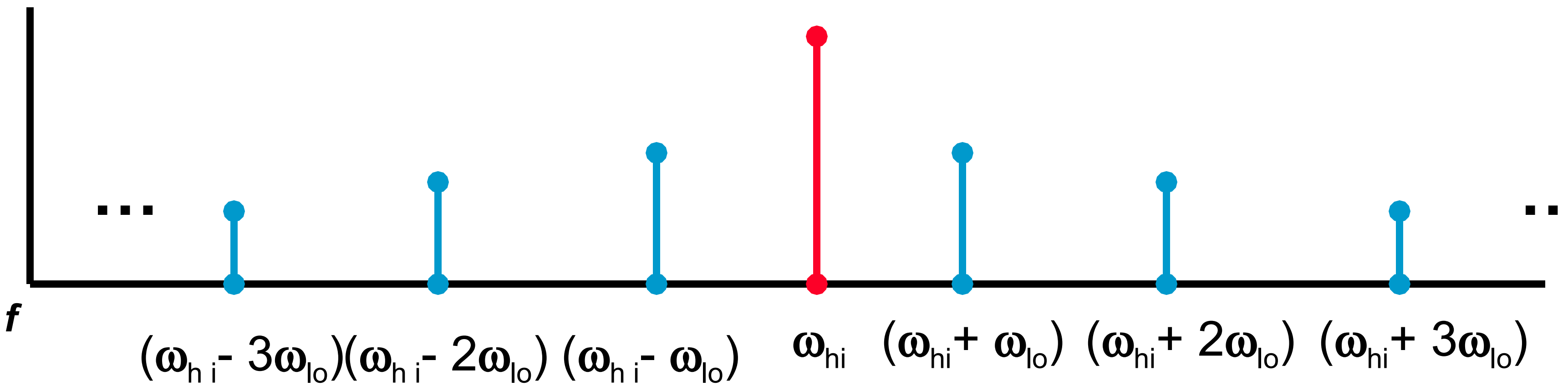
- Recall what we know about distortion.
- All periodic signals are made up of some sort of combination of sinusoids.
- The distorted periodic waveform now has amplitude and-or frequency components in it that are different compared to when it was not distorted.

- In fact there are a *lot* of frequencies in that mixer output.
- A real mixer will output all integer multiples of the input frequencies.

$$f_{out} = nf_{hi} \pm mf_{lo}$$

Mixers and spurious output

$$f_{out} = nf_{hi} \pm mf_{lo}$$



- These are called spurious output frequencies. They can feedback into your or another radio receiver and cause interference.
- Although unavoidable, good radios will have good filtering to give low numbers and levels of spurious outputs.

Precision and oscillators

All RFID readers have oscillators. They are used to create local oscillators that generate the carrier for transmitting and for receiving.

- Oscillators affect RFID system accuracy because they determine the frequencies you are operating on, both transmitting and receiving.

- They have to be *precise*, meaning they can't have a lot of variation in their properties. They have to be *stable*.
- If they aren't, you might be generating frequencies you don't want. An unstable oscillator does not product a perfect sinusoid output.
- That means distortion with respect to amplitude or frequency. Other frequencies are being generated.

- You could be operating out of the intended band, or causing interference to an adjacent channel.

Oscillators

[See figure 4.22 in the text book.] **This is a latch!**

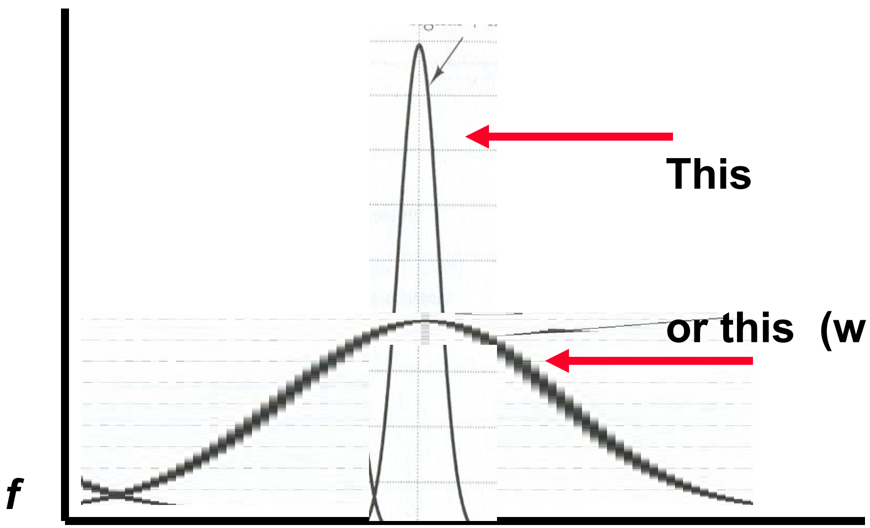
- An oscillator is made by exploiting positive feedback and resonance

[See figure 4.26 in the text book.]

Oscillators and stability

Oscillators built as shown in the previous slide are not stable enough for RFID reader use. The biggest reasons are:

- The quality factor or Q of the circuit. This is reflected in the shape of the resonant response of the LC circuit.



$$Q = \frac{1}{R}\sqrt{\frac{L}{C}}$$

- Another factor is temperature effects on the LC circuit, for example on the capacitor.

Oscillators and stability

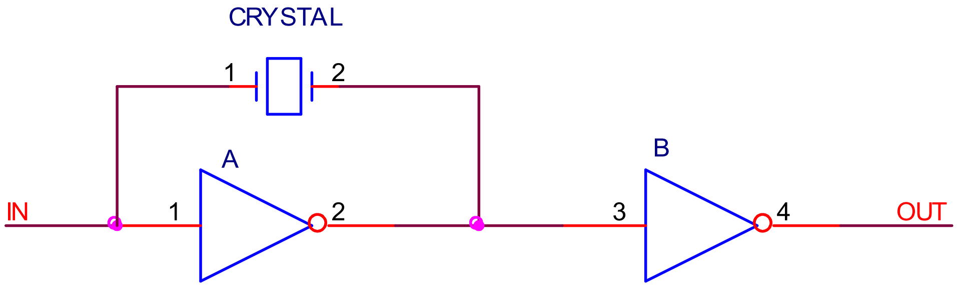
- LC based oscillators are not precise in the way they operate. The frequency changes, or jitters.
- The occurrence of the frequencies making up the jitter is a function of how close the frequency is to the calculated resonant frequency and on the Q of the resonant circuit: (Equation 4.23)

$$\left\langle v_n^{\,2}(\omega)\right\rangle = 4kTR\left(\frac{\omega_c}{2Q\left[\omega_c-\omega\right]}\right)^2 \left[\mathrm{BW}\right]$$

- "BW" is the frequency spectrum over which we observe the noise voltage.
- LC networks have Qs ranging from almost nothing to a few hundred.
- The point here is, in oscillators, if you want high stability, then you need a high Q in the resonant circuit.

Crystal oscillators

- Using a quartz crystal instead of a LC network greatly improves stability because the Q of a crystal is much higher. Over 10^6.



- But, the crystal is fixed at 1 frequency. What if we need a tunable oscillator, for example if we have UHF RFID with channels?

Tunable stable oscillators

We can still use a crystal and have high Q by building a frequency synthesizer based on a Phase Locked Loop.

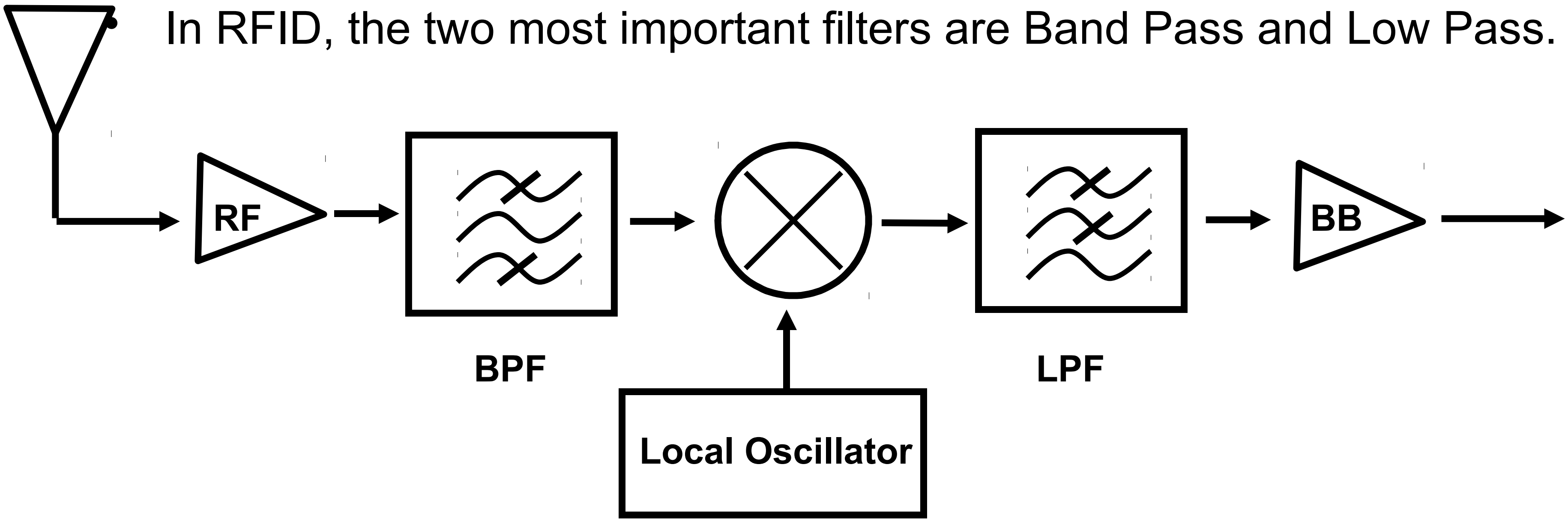
[See figure 4.30 in the text book.]

- A voltage controlled oscillator is precisely controlled by a crystal oscillator and by matching the frequency of the oscillator with the VCO / N.
- In this circuit we change frequency by changing N.

Quality of information and Filters

We have talked about unwanted signals, such as images and spurious frequencies. How do you get rid of them?

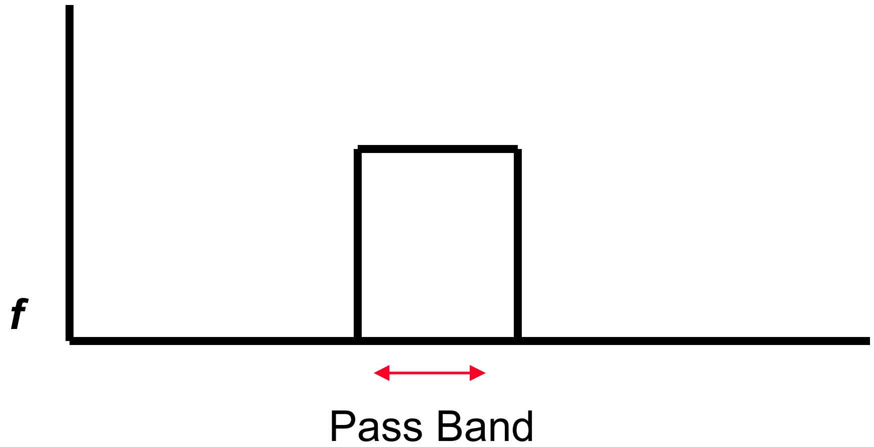
- We've noted that you have to either live with the interference, or you can filter them out, if that is possible.
- In RFID, the two most important filters are Band Pass and Low Pass.



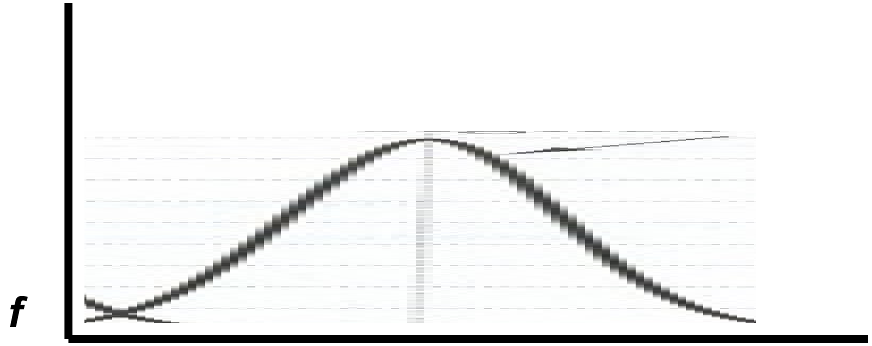
- Band Pass Filters (BPF) are interesting for us to look at further, as they have connections to things we have looked at already.

Band pass filters

- A Band Pass Filter passes a range or *band* of frequencies.
- If we could make a perfect BPF, it would look something like this:



- But in reality, they have a non-ideal response, more like:



Band pass filters

This looks familiar. It looks like the response of a resonant circuit. This makes sense because a BPF is made from resonant circuits!

- A simple BPF can be made from just a LC circuit. The shape of the edges are highly dependant on the Q of the LC circuit.

[See figure 4.33 in the text book.]

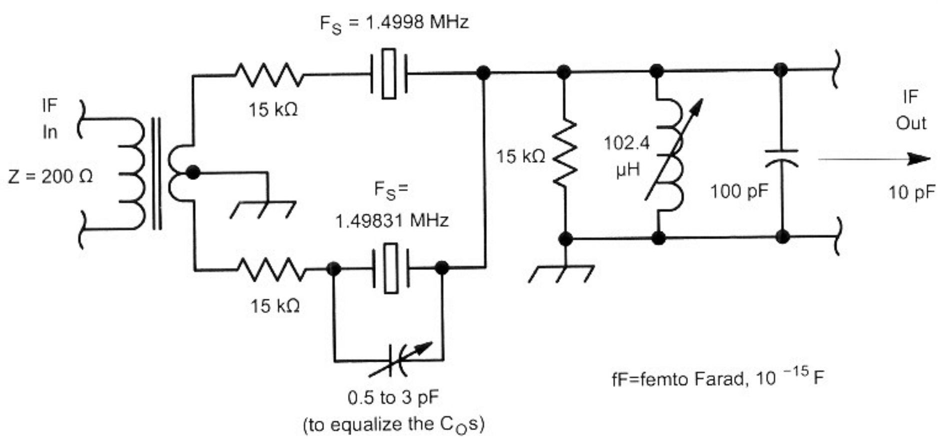
- Recall how Q is calculated, and its relationship to L, C and the bandwidth of the filter. *fo* is the resonant frequency.

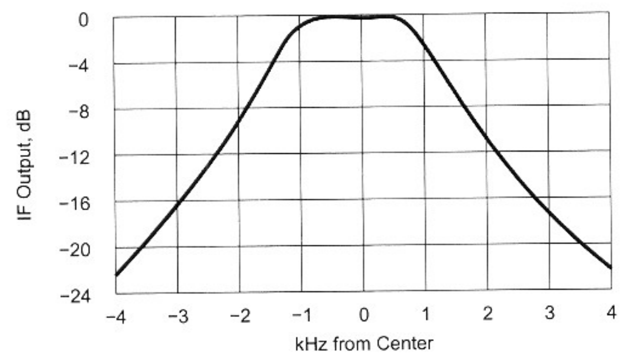
Q of LC circuits.

- We know that: $$Q = \frac{1}{R}\sqrt{\frac{L}{C}}$$
- Although the math says that we can create a LC circuit with as high a Q as we want, LC circuits practical for RFID readers only have Qs under 100.
- They work fine to filter out unwanted frequencies far from the RFID's carrier frequency, such as interference due to 2nd order distortion.
- But, they don't help for interference that is close to our wanted frequencies, such as that due to 3rd order distortion.
- In cases of spurious interference, a lot of it might be filtered out by using a better BPF. One with higher Q, so not made from LC circuits.

Better BPFs

- Recall that when we talked about oscillators, we needed higher Qs to get good stability. We got it by using a quartz crystal.
- They have Qs in the thousands, and can be used to make BPFs.





- Making crystal filters with very high center frequencies is difficult and expensive.
- 13.56 Mhz would be OK, but 900 Mhz is much harder. Not really practical for UHF single conversion RFID readers.

SAW band pass filters

Surface acoustic wave BPFs exploit properties similar to those of quartz crystals. They exploit resonant mechanical vibration to make acoustic waves. These are practical for very high frequencies.

[See figure 4.34 in the text book.]

This is practical to do because the RF energy is converted to an acoustic wave that travels 4 orders of magnitude slower than RF in air. That means a λ that is 4 orders of magnitude longer. The electrodes are practical to make.

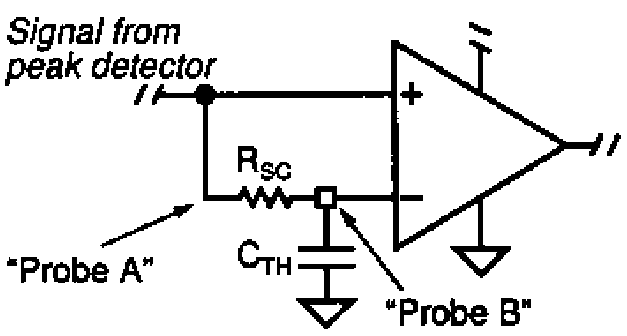
SAW BPF typical response

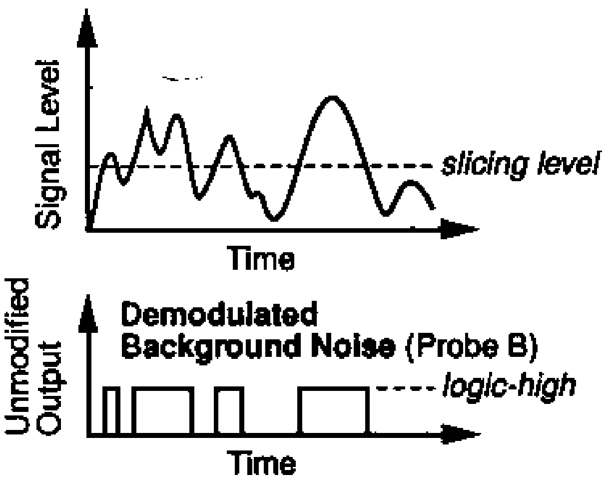
[See figure 4.35 in the text book.]

- Note the broad width. Many Mhz.
- Qs are only in the hundreds, so it may be hard to make the band pass characteristics much narrower.

Analog and Digital conversion

- In *simple* RFID, these are very easy single bit processes.
- Transmitting is just activating a switch to effect modulation.
- Receiving is just a process of *thresholding,* or *zero crossing*.
- In the simple circuit below, the LPF at probe B just computes a received signal average.
- If we are above the average, it's logic high. Below, it's logic low.





Analog and Digital conversion for advanced functions

- RFID can be used for more than just reading information from tags.
- You can use properties of the reflected signals to sense things.
- For example, timing the backscattered reflections can give you location. RFID can be great for this because timing problems are reduced.
- You may be able to do this also by looking at signal strength (not reliable at all).
- You can also tell how fast a tag is moving by looking at signal phase shifts (Doppler shift).
- To do these things, you need more resolution when digitizing the received signal. One bit is definitely not enough.
- You also need to pay attention to the sample rate.
- You can get phase information from the signal by using an I-Q demodulator.

Doppler shift and tags (just for fun)

Phase changes, along with amplitude, is often used to modulate carriers.
It is a polar to rectangular co-ordinate mapping.

[See figure 4.51 in the text book.]

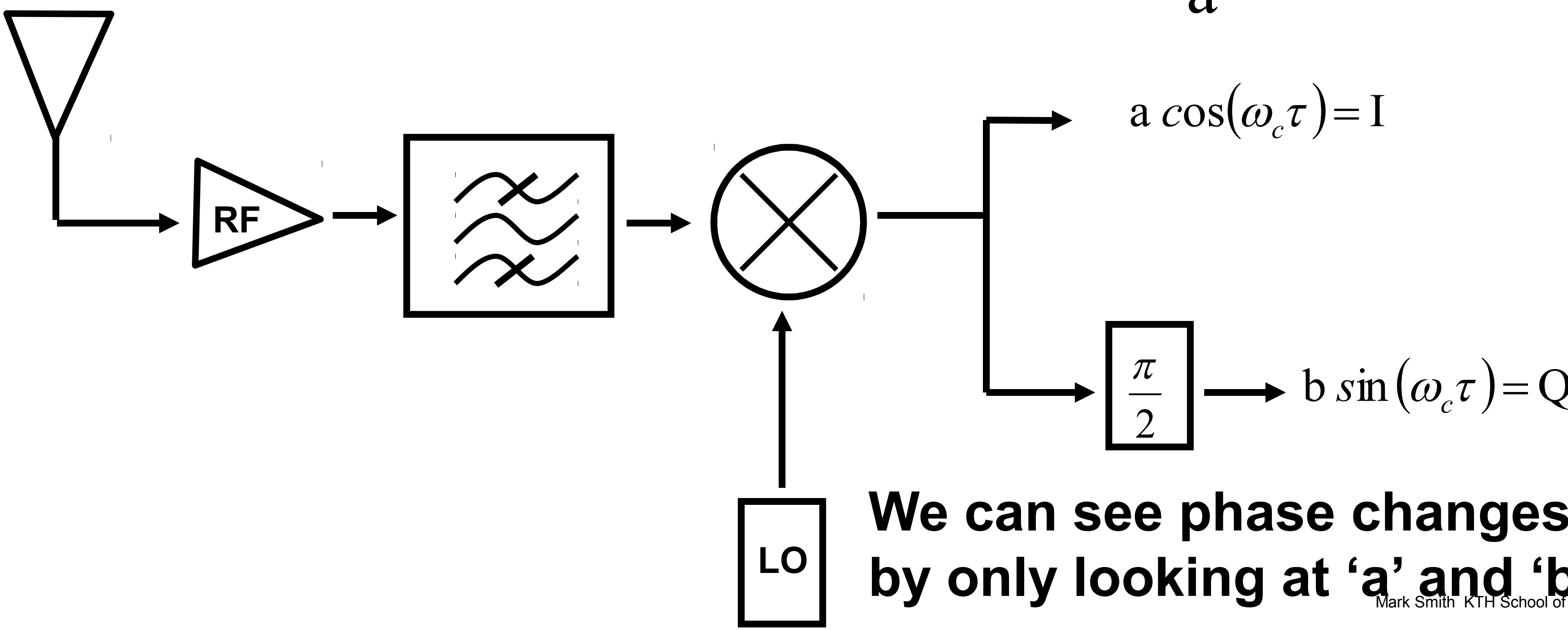
In a RFID receiver, what we want to do is determine the phase shift ϕ.

Doppler shift and tags

This is straight forward to do. Recall from an earlier lecture:

$$c\cos(\omega_c\tau+\phi)=a\cos(\omega_c\tau)+b\sin(\omega_c\tau)$$

$$\text{where}\quad c=\sqrt{a^2+b^2}\quad\text{and}\ \phi=\arctan\frac{b}{a}$$



We can see phase changes by only looking at ‘a’ and ‘b’.

Radio architecture summary (for now)

Radios can be bad, excellent, or something in between. But when you really look at it, radios are mostly a collection of just two things:

1. Amplifiers
- They might be linear
- They might be non-linear (mixers)
- They might be un-stable (oscillators)

2. Filters
- Maybe low pass
- Maybe band pass