RFID Systems: Power exchange and tags

How much power needs to be sent to the tag.

How much power needs to be scattered back.

How the tag modulates what it scatters back.

Link budgets, and how energy propagates.

Start reading Chapter 4 in the text.

Backscattering

How is it possible that energy from the reader can be reflected back? For backscattering to work, we exploit the physics of antennas.

Recall from previous lectures how antennas work.

- They work by generating voltages that can be seen at a distance.
- If the antenna is structurally large WRT λ, the voltages generated are big. We can use radiative coupling.
- If the structure is small WRT λ, energy is transferred using a magnetic field and we use inductive coupling.

- But, in either case AC current has to flow in the antenna! No AC current, no radiation.

- The same thing is true on the receiving side, ie the tag.

We are going to talk about tags next.

Backscattering

In radio, antennas follow a *principle of reciprocity*.

- If a transmitting antenna can effectively radiate power on frequency *f*, then it can also effectively receive power on *f*.
- If I set up proper voltages and currents along a receiving antenna at *f* (doesn't matter how I do it), it will radiate again at *f*. In the RFID case, that is *backscattering*.
- I can control if my receiving antenna backscatters or not by doing something to the voltages or currents on the antenna.
- One way is to use a switch to interrupt the AC current. That makes sense because no AC then no radiation.

Backscattering and antenna current

[See figure 3.14 in the text book.]

Backscattering and antenna current

A field effect transistor makes a good switch for this. You can start to see how you might be able to make a simple tag simulator out of a MSP-430 or other microcontroller.

[See figure 3.15 in the text book.]

Tags and coding

It seems like backscattering by switching could allow us to generate OOK signals. But, how should it be coded? Should we just use PIE?

- Recall that a coding scheme like PIE was a reasonable thing for a *reader* to do.
- It allowed power to be sent to the tag regardless of the data.
- It also had a small degree of robustness. You can tell where the bits are more reliably than other forms of coding.

- But, PIE may not be a good way to code the *tag*.
- The tag does not need to send energy to power anything.
- Instead, data integrity is a problem. The amount of energy that is backscattered from the tag isn't very much.
- To make it worse, the RFID system is probably operating at a "license free" radio frequency. It has to compete with other things that radiate or backscatter and use the same frequency.

Interference

Also, the tag isn't the only thing that can reflect a signal. There can also be other things that generate RF in the same frequency range.

[See figure 3.16 in the text book.]

This is shown for radiative coupling, but even inductively coupled systems can be subject to similar interference.

Tag coding

- To account for this we need to look for signal *state changes* from the tag, not signal highs and lows.

We need to know:

- When a bit begins and ends.
- If it is a logic 1 or 0 based on signal change.

- Signal change is useful, because no matter how all the interfering signals combine, a change can usually be detected.

Tag FM0 coding

[See figure 3.18 in the text book.]

- FM0 tag coding uses level changes to code symbols.
- It is similar to PIE in that logic 1’s and 0’s have different *duty cycles*.
- Note that the waveform on the right shows a string of six 1’s, not three.
- Logic 1’s are now the same length as a logic 0.
- However, note how the state changes between consecutive 1’s. They flip over.
- Logic 0’s can do the same thing. Imagine what the sequence 1,0,1,0,1,0 would look like coded as FM0.

Tag coding, bandwidth and sidebands

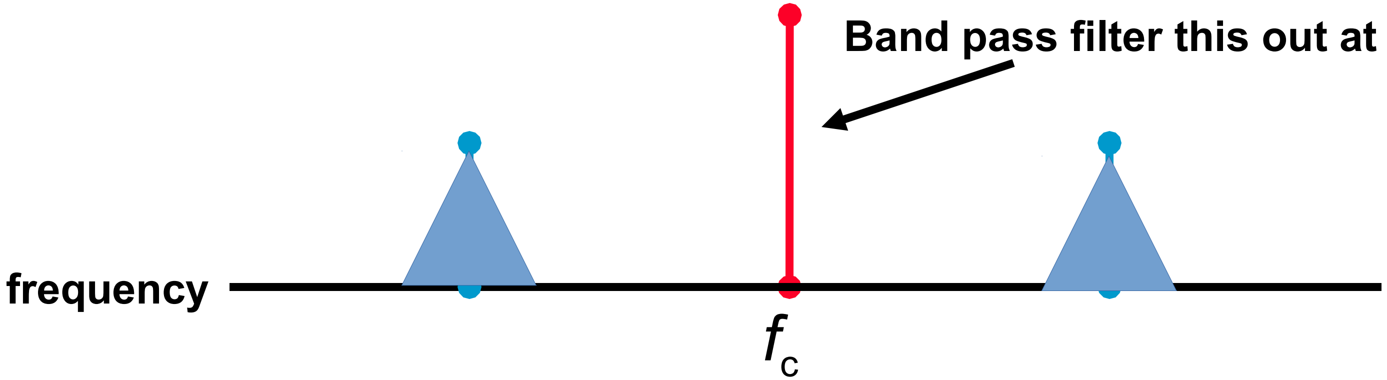
- By switching and causing encoded backscattering, the tag is modulating the carrier sent by the reader.
- Just like reader generated modulation, this will result in sidebands.
- As the data rate increases, the sidebands move further away from the carrier.

- This increases the bandwidth of the backscattered signal. That can be bad from a spectrum use viewpoint.

- It also can be good! By moving the sidebands well away from the carrier, the carrier doesn't interfere.
- Also the reflected carrier from other objects interferes less.

Tag modulation and sidebands

[See figure 3.20 in the text book.]



Tag demodulation

We've talked about modulation at the reader and the tag. What about demodulation, esp at the tag? Remember that the tag has to be simple.

[See figure 3.19 in the text book.]

This tag example uses a simple method called envelope detection.
It is just a diode and a low pass filter.

Link Budgets

- Link Budgets are a way to express the amount of power that needs to be sent between two communicators for them to work successfully.

- In passive RFID, the tag needs power to run.
- There also needs to be enough extra power sent so that the tag can understand commands from the reader.
- The tag also has to backscatter enough power so that the reader can understand what the tag is saying.
- So we have both a *forward* and *reverse* link. They are not symmetric.

- How much power is enough? Do you have the “budget” to do it??

Forward link

We will first look at the link going forward, ie from the reader to the tag. How much power can a reader give? You could build a really big reader.

Practical RFID readers are bounded by:

- Cost: The higher the power, the higher the cost.
- Regulation: Although ISM bands are license free, governments limit what can be done in them so everyone can benefit.
  - Ie, in the 902-918 Mhz ISM band, 1 watt is the limit you can radiate.
  - The low cost readers we have in the lab running in the 13.56 Mhz band can radiate 0.125 watts.

- Performance/Watt/Euro is important! If you are building a reader, you always want to optimize this for a set of customer needs.

- For the lecture, we will assume that we have 1 watt to spend. That's 30dBm.

Link budgets and Path Loss

Power from a source will be lost just as the energy propagates.
It depends on:

- The distance the energy has to travel.
- What the energy has to travel though, ie air, water, metal.

- We will assume for now that energy is traveling though clean, dry air.
- Also, that there are no objects in the way to obstruct the energy in any way, such as bending, reflecting, or attenuating.

- We need now a model for how the energy gets into this space. We need a model of how the energy radiates from antennas.
- A very useful model to start with, and compare other designs to is an *isotropic* radiator.

Isotropic antennas

- In radio, antenna designs are often compared to an imaginary ideal antenna that radiates power equally in all directions.
- The relative measure dBi is *decibels isotropic*, or the amount of power gain/loss an antenna is capable of relative to an ideal isotropic radiator.
- In an ideal isotropic antenna, we can imagine the power being equally distributed over a spherical area, which is just $4\pi r^2$.
- As r gets bigger, the amount of distributed power per unit area is less. It gets less by the square of the distance.
- Let's pretend we have a reader with such an antenna. For this discussion, the system will be radiative.

Isotropic antenna radiation

[See figure 3.21 in the text book.]

The tag's antenna is not isotropic. It lies in the field of the reader's isotropic distribution, and sees an *effective aperture* into it.

Effective aperture, A_e

- The effective aperture the tag antenna sees is a function of how much spherical area representing power distribution from the reader hits it. The tag antenna also is just an area.
- The amount of power that is then available to the tag is just a function of the ratio of the areas.:

$$P_{\mathrm{rx}}(\mathrm{tag}) = P_{\mathrm{tx}} \frac{\mathrm{Ae}}{4\pi r^2}$$

- So, what is Ae? It's reasonable to imagine that it is some function of the tag antenna's area.
- To know that, we need a reasonable model of the tag antenna.

Tag antenna model

The tag antenna is not isotropic, but it is physically large with respect to λ.

- Many tags using radiative coupling will use antennas made from carefully chosen lengths of conductor such as wire or PCB trace.
- The physical length of such an antenna is typically about $\lambda/2$.
- They are often called halfwave dipole antennas. They have lots of advantages. Cheap, easy to make, resonant and more.
- They can have different shapes. They don't have to be straight.
- One simple model is just a square of $\lambda/2$ length on a side.

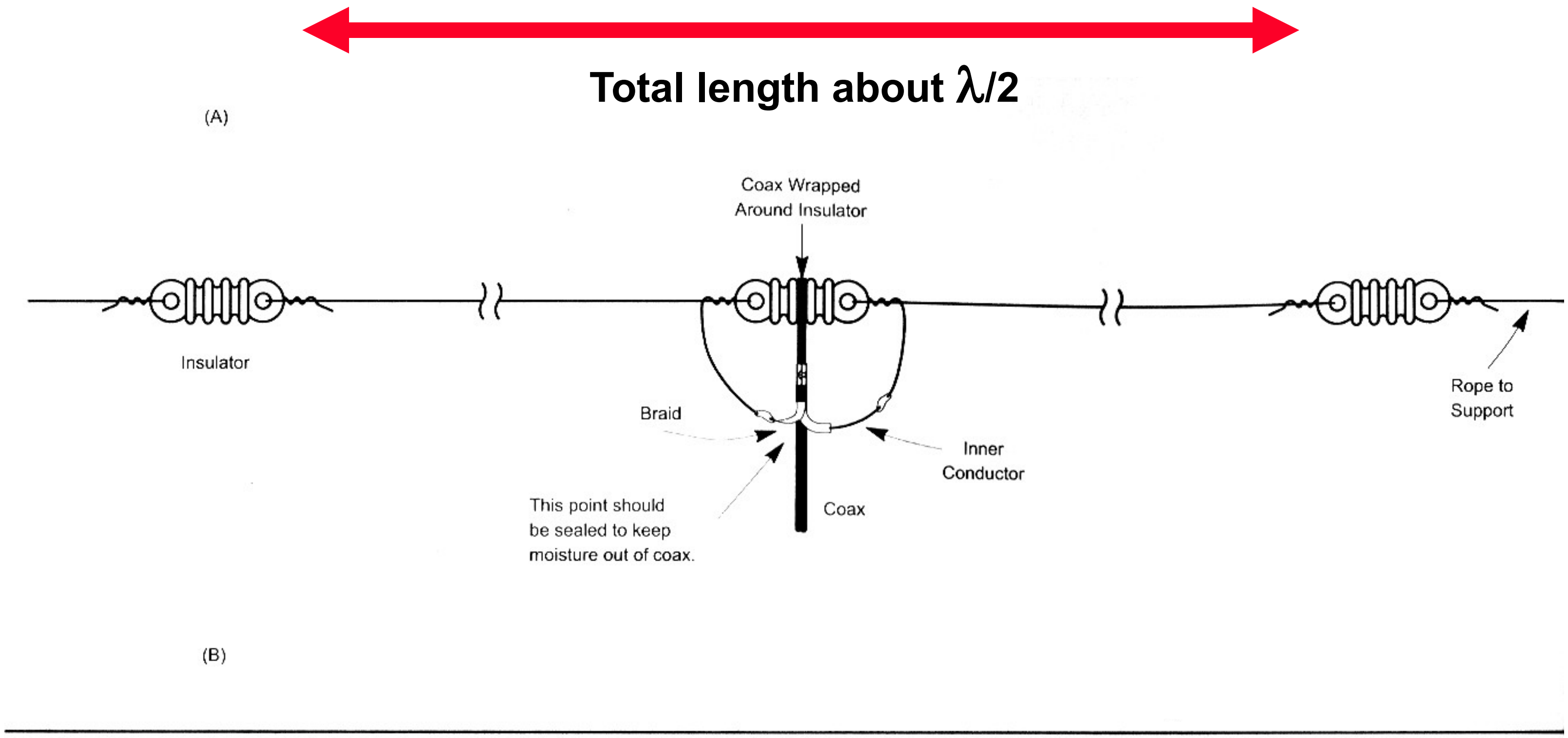
- This is probably too simplistic, as tag antennas often have a high aspect ratio. They are much longer than they are wide.
- The book suggests a good approximation for a dipole:

$$Ae = \frac{\lambda^2}{4\pi}$$

Classic half wave dipole

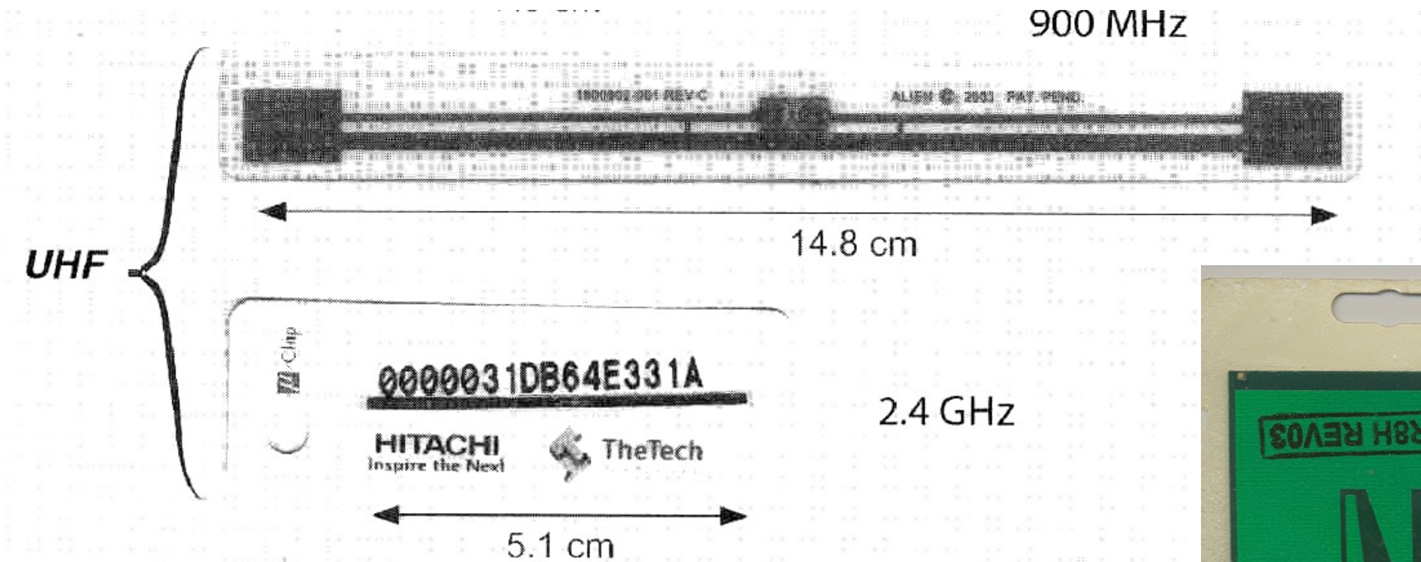
Total length about $\lambda/2$

(A)



(B)

900 Mhz and 2.4 Ghz dipole tag antennas



Ae at 915 Mhz is about **<u>86</u>** cm^2.

Path loss scaling

This example is from the book and assumes 915 Mhz

We now have what we need to come up with a model of path loss. A sphere of 1 meter radius has an area of 126000 cm2. So, for 1 watt of transmitted reader power, the path loss at one meter is:

$$P_{rx} = P_{tx} \frac{Ae}{4\pi r^2} = \frac{1*86}{126000} = 0.682\,\mathrm{mW} \approx 0.7\,\mathrm{mW} \quad \text{and :}$$

$$10\log\left(\frac{1000\,\mathrm{mW}}{0.7\,\mathrm{mW}}\right) = 31.55\,\mathrm{dB} \approx 32\,\mathrm{dB}\ \text{path loss per meter at 915 Mhz}$$

Because we know that the isotropic spherical area scales with the square of the radius, it is easy to scale this for any distance you want. For example, for r=10 meters, you just add to the path loss:

$$10\log\left(\frac{10\mathrm{m}^2}{1\mathrm{m}^2}\right) = 20\,\mathrm{dB}\ \text{ or total path loss} = 52\mathrm{dB}$$

Tag power requirements

To finish the forward link budget, we need to know the tag power needs.

- Tags vary in power needs. The trend is lower power and cost.
- Typical tag circuits use a few microwatts. Lets say 30 μW for example.
- The efficiency of converting RF energy at some *f* into DC for the tag is not very good. Maybe 33%. That means we need 100 μW or -10dBm.

- To find our link budget, we start with 1 watt (30 dBm) from the reader, and for the tag to work we have to end up with at least -10 dBm.
- So, our forward link budget is 30 – (-10) = 40 dBm.

- All we need now is the maximum distance at which we get a path loss of no more than 40 dBm.
- Note also that this is just the *forward* link. It's the amount of power we need to run the tag. We will need more than this total to hear the tag.

Maximum forward link budget distance

To find this for our assumed 1W reader, isotropic antenna and tag Ae, the easy way is to just scale our known 1 meter path loss.

- For our system, we computed the path loss at 1 meter to the tag to be 32 dB.

- We have a forward link budget of 40 dB, so we need to scale our 1 meter to account for an extra 40-32=8dB of path loss.

$$10\log\left(\frac{d^2}{1m^2}\right) = 8\text{ dB} \quad \text{or}$$

$$d^2 = 10^{0.8} \quad \text{or} \quad d = 2.5\text{ meters}$$

- For our system, the maximum distance we can have and still <u>power</u> the tag is under 3 meters.

Graph of our forward link budget

[See figure 3.22 in the text book.]

Reverse link budget

This is the budget for the tag talking back to the reader. How much power can the tag scatter back, and how much power does the reader need.

- The amount of power a tag can backscatter is very tag dependent. Tag antenna geometry plays a big part.
- As an example, let's assume that the tag can backscatter 1/3 as much power as hits the tag. In terms of dB, that's just 10*log(1/3) = -5dB loss. That's called "*modulation efficiency*".
- There will also be path loss in the reverse direction. In our example, we know it is over 3 meters which gives us a path loss of 40dB.
- Therefore, our total reverse link budget is 40dB –(-5dB) = 45dB.

Power at the receiver

- What is the power the receiver finally sees? Just add up the forward and reverse link budgets and subtract from the original power (1 watt or 30 dBm):

30 dBm – (40 dBm + 45 dBm) = -55 dBm

- Is it enough for the receiver to work?

- Receiver sensitivity is also very implementation dependant.
- However, receiver technology is good. It is possible to make very sensitive, inexpensive receivers.
- A realistic number for receiver sensitivity can be as low as 0.03 nW of signal at a reasonable SNR. That's -75 dBm

This system is *forward link limited*

From all this, we can see that the receiver has plenty of received signal to work. But we can't increase the tag distance and still be able to supply it with power.

[See figure 3.23 in the text book.]

Other points about path loss

- Remember the idea of antenna reciprocity. Things are symmetrical.
- The forward path loss is an inverse quadratic function of distance.
- That means so is the reverse path. Thus, the round trip loss is a inverse fourth power of the distance, or:

$$P_{rx, receiver} \approx \frac{1}{d^4}$$

- Increase your distance by X, then you have to increase your power by X^4 for the same received power.
- This holds for any radiative antenna architecture.
- RFID tags are getting lower power and more efficient. Some day the system may not be forward link limited.

Antenna gain and the art of antenna design

The isotropic antenna is a nice concept and handy model, but a bad realization.

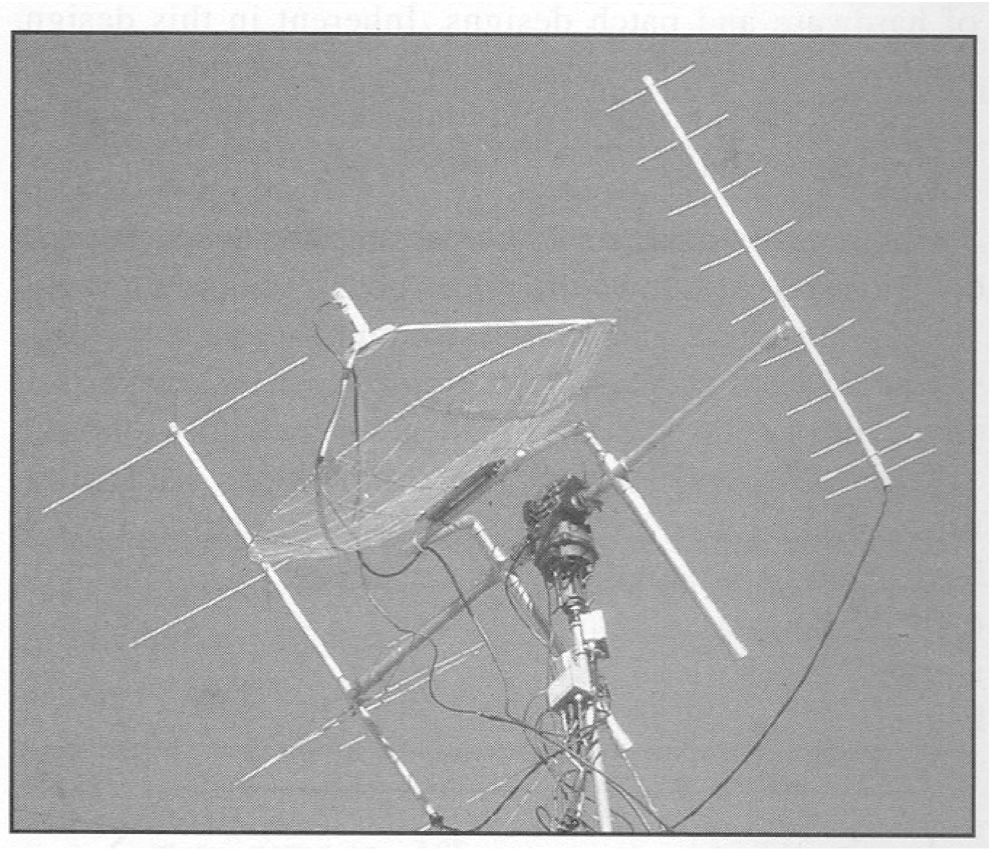
- A perfectly isotropic antenna is not possible to build
- Even if you could, it is not at all ideal. It reads everywhere, and you probably don’t want that.

Power going where there are no tags is wasted power.

- It doesn’t help your application.
- It may interfere with someone else’s system and application.

We’d rather be able to focus the power where we want it.

Directional Antennas



- Some maybe look familiar
- 3 are shown in this picture. Two *yagi*s and one *parabolic dish*.

Directional antennas

Antennas that do this are called *directional* antennas. All antennas have directional properties. The design challenge is to get the right ones.

- Directional antennas focus most of the radiated energy into one or more sections of the isotropic sphere. For RFID it is usually just one section or one *beam*.

- The area of a *unit* sphere is just 4π. it represents a solid angle of 4π steradians.
- If all the radiated energy is concentrated into a single beam with a solid angle area smaller than 4π, then we can say the antenna provides *gain* over the isotropic model.

$$G = \frac{4\pi}{\Omega}$$

This is the beam solid angle in steradians

Directional antennas

Note that this “gain” is just relative to the isotropic case. You still have the same amount of transmit power.

3 dB is where the power is down by a factor of 2.

[See figure 3.26 in the text book.]

There is 100 times less power behind this antenna than in front of it!

This is a typical chart of antenna beam pattern provided by a manufacturer.

Might look something like this in 3D

[See figure 3.25 in the text book.]

[See figure 3.26 in the text book.]

Expressing antenna gain

In our discussion here, antenna "gain" is just relative to the isotropic case.

- That just means that the gain you see is just the amount of energy you see from the directional antenna compared with an isotropic one:

$$Gain \text{ in dBi} = 10 \log \frac{\text{power seen from the directiona l antenna}}{\text{power seen from an isotropic antenna}}$$

- Note the units: dBi, where 'I' stands for isotropic.
- This works if the only difference in measurement parameters is to replace the directional antenna with an isotropic one.
- The gain you see depends on where you stand and measure.
- Gain for an antenna is usually expressed as the maximum gain you can see.

Effective Isotropic Radiated Power (EIRP)

- Another way of describing antenna gain is that it is equal to the extra amount of power you would need to put into the isotropic antenna in order to see the *same* amount of received energy as the directional antenna can give.
- In other words, if I see power P from the directional antenna, and then replace the antenna with an isotropic one, how much extra power do I need to transmit to see P again.
- This is expressed as:

$$\mathrm{EIRP} = P_{tx}\ (\mathrm{dBm}) + G_{tx}\ (\mathrm{dBi}) \quad \text{where } G_{tx} \text{ is the antenna gain}$$

- EIRP is an important parameter. It is how you reconcile transmit power and transmit antenna gain in order to express in 1 number what power is going towards the tag.
- It is also used a lot in government regulations. They don't care how you get the power density, as long as it isn't too much.

Graphical view of EIRP

[See figure 3.28 in the text book.]

You can reference other antennas as well, such as a dipole.

Graphical view of a $\lambda/2$ dipole's radiation pattern

A $\lambda/2$ dipole is not isotropic, and it has some gain over an isotropic antenna.

[See figure 3.27 in the text book.]

A directional antenna referenced to a dipole has gain in terms of dBd. Equivalent Radiated Power (ERP) is like EIRP except with respect to something like a dipole. It could be other antennas. We will use EIRP.

Antenna gain and the forward link budget

By directionally concentrating transmitted energy, using an antenna with gain should increase our forward link budget and result in more range.

- Suppose our directional antenna gives us 6dBi of gain.
- To find our link budget, we start with 1 watt (30 dBm) from the reader and compute our EIRP which allows us to include our antenna gain. That's no problem at all:

$$\mathrm{EIRP} = 30\,\mathrm{dBm} + 6\,\mathrm{dBi} = 36\,\mathrm{dB}$$

- Recall for the tag to work we have to end up with at least -10 dBm.
- So, our forward link budget is 36 – (-10) = 46 dBm.

- We now compute the maximum distance at which we get a path loss of 46 dBm.

Forward link budget with gain

Recall that for our assumed 1W reader, isotropic antenna and tag Ae, the easy way is to just scale our known 1 meter path loss.

- For our system and tag Ae, we computed the path loss at 1 meter to the tag to be 32 dB.
- We have a forward link budget of 46 dB, so we need to scale our 1 meter to account for an extra 46-32=14dB of path loss.

$$10 \log\left(\frac{d^2}{1m^2}\right) = 14 \text{ dB} \quad \text{or}$$

$$d^2 = 10^{1.4} \quad \text{or} \quad d = 5 \text{ meters}$$

- Recall that for the isotropic case, the range was about 2.5 meters. We have effectively doubled our range.

Graphical representation of new link budget

[See figure 3.29 in the text book.]

Antenna gain and reverse link budget

Antenna gain also benefits the reverse link budget. It does it in 2 ways. The first is because the tag's antenna gain increases the tag's Ae.

- Remember we developed an expression for effective aperture (Ae) for the isotropic case.
- The effect of having antenna gain at the tag is to increase the effective aperture by the amount of the gain.
- This makes sense, as you are concentrating 'G' amount more energy into the RFID tag's antenna. Ae just becomes:

$$Ae = \mathrm{G}\left(\frac{\lambda^2}{4\pi}\right)$$

Also, the gain is a normal multiplier here. Ae is not expressed in dB.

Antenna gain and reverse link budget

- The second way antenna gain affects reverse link budget is when the RFID reader receives the backscattered power from the tag.
- This is because a directional antenna will also have gain when used to *receive*.
- For example, if the same antenna is used to transmit and receive, you get the same amount of gain receiving as you do transmitting.
- Because the tag is backscattering what you send, you get an advantage from antenna gain both when sending (more power hitting the tag) and receiving (receive gain focuses power into the antenna).
- We now can use this to extend our equation for both tag power and expected receive power.

Receive power, gain and path loss

- To do this, recall our equation for received power (received power at the RFID tag) for the isotropic case:

$$P_{\mathrm{rx}} = P_{\mathrm{tx}} \frac{\mathrm{Ae}}{4\pi\, r^2}$$

- Now, your transmit antenna has gain, so we take it into account:

$$P_{\mathrm{rx}} = P_{\mathrm{tx}}\, G_{\mathrm{tx}} \frac{\mathrm{Ae}}{4\pi\, r^2}$$

- Substitute the expression for Ae into this equation:

$$P_{\mathrm{rx}} = P_{\mathrm{tx}}\, G_{\mathrm{tx}} \left(G_{rx} \frac{\lambda^2}{4\pi} \right) \frac{1}{4\pi\, r^2} = P_{\mathrm{tx}}\, G_{\mathrm{tx}} G_{rx} \left(\frac{\lambda}{4\pi\, r} \right)^2$$

Friis equation

- This resulting expression is called Friis Equation:

$$P_{\mathrm{rx}} = P_{\mathrm{tx}}\, G_{\mathrm{tx}} G_{rx} \left(\frac{\lambda}{4\pi r} \right)^2$$

- Note the double effect of antenna gain in the form of transmit and receive gain.
- G_{tx} is the gain of the transmitting antenna. Usually that is the reader's antenna.
- G_{rx} is the gain of the receiving antenna, for example the tag.
- Note that this is a general expression for power received by an antenna from a transmitting source. Next we see how it is useful in RFID systems.

Reverse link budget with gain

Recall our reverse link budget for the isotropic case:

- We decided that the tag can backscatter 1/3 as much power as it takes to run the tag. In terms of dB, that's 10*log(1/3) = -5dB
- We knew our path loss over about 3 meters (our forward link limited distance) which gave us a path loss of 40dB.
- So the isotropic reverse link budget was 40dB –(-5dB) = 45dB.
- But now we have gain due to the directional antenna on the reverse link. According to the Friis equation, our received power is simply increased by the receiver antenna gain. 6dBi in our case.
- Reverse link budget is now 40dB –(-5dB) + 6dB = 51dB

In the graphical case

[See figure 3.30 in the text book.]

A couple more things about the Friis equation

- We know that tags have gain. A dipole like antenna has a gain of about 2dBi.
- You can use the Friis equation to determine the amount of power a tag receives that it can use.

$$P_{\mathrm{tx(tag)}} = P_{\mathrm{tx(reader)}}\, G_{\mathrm{tx(reader)}} G_{rx\mathrm{(tag)}} \left(\frac{\lambda}{4\pi r}\right)^2 T_b$$

- The T_b takes into account the amount of energy lost to the tag due to *modulation efficiency*. $T_b \approx 1 - (\text{modulation efficiency})$
- The above equation is a generalization.
- See equation 3.21 in the book for determining the power that arrives back at the reader.

You can also solve for link limited <u>*R*</u>ange

You can re-arrange the Friis equation to get these convenient equations. You can also introduce a term for the power needs of the IC in the tag.

- If you know the minimum power the tag needs to operate, you can get the forward link limited range from:

$$R_{forward} = \left(\frac{\lambda}{4\pi}\right)\sqrt{\frac{P_{tx} G_{reader} G_{tag}}{P_{\min,tag}}}$$

- If you know the minimum power the reader needs to demodulate the tag, you can get the reverse link limited range from:

$$R_{reverse} = \left(\frac{\lambda}{4\pi}\right)\sqrt[4]{\frac{P_{tx,reader} G^2{}_{reader} G^2{}_{tag} T_b}{P_{\min,reader}}}$$

- Everything is squared, and there is the root-4 term because you lose power as the square of the distance *to the tag*, and again *back to the reader*.

Antenna polarization

Remember we mentioned that tag orientation makes a difference.

- For example, if it isn't lined up in a way that maximizes effective aperture.
- For example, what happens if the tag dipole antenna is pointing to the reader antenna with its ends (it is not broadside).

[See figure 3.21 in the text book.]

For example, the end of the antenna points directly at the reader antenna

This is intuitively not optimal. The tag dipole has no gain in that direction. But, there is one other way to look at antenna orientation.

Antenna polarization

- Remember how antennas work. You need to set up a potential difference across the *structure* of the antenna.
- What if the antenna is aligned wrong with respect to the voltage potentials?

[See figure 3.33 in the text book.]

Antenna polarization

The electric field of the electromagnetic energy can be oriented horizontally or vertically. In other words, it is polarized in a vertical or horizontal direction.

- If the reader's antenna polarization matches the orientation of the tag, then everything works as we have been predicting.
- If the reader's antenna polarization is 90 degrees rotated from the orientation of the tag, then nothing works (cos(90)=0).
- We can express this orientation as a function of the effective aperture:

$$Ae = \frac{(\lambda \cos(\phi_{pol}))^2}{4\pi}$$

- Where ϕ is the antenna polarization angle with respect to the tag.
- We can use this value of Ae in the Friis Equation.

Friis equation and polarization

- Recall that:

$$P_{\mathrm{rx}} = P_{\mathrm{tx}}\, G_{\mathrm{tx}} \frac{\mathrm{Ae}}{4\pi\, r^2}$$

- Substitute the new expression for Ae into this equation:

$$P_{\mathrm{rx}} = P_{\mathrm{tx}}\, G_{\mathrm{tx}} \left(G_{rx} \frac{(\lambda \cos(\phi_{pol}))^2}{4\pi} \right) \frac{1}{4\pi\, r^2}$$

$$= P_{\mathrm{tx}}\, G_{\mathrm{tx}} G_{rx} \left(\frac{\lambda}{4\pi\, r} \right)^2 \cos^2(\phi_{pol})$$

Real antennas and polarization

We can't control the orientation of the tag, so at times we may not be able to read it. There are two things we can do to minimize this problem.

1. We can use a reader antenna that is *circularly polarized*.

[See figure 3.31 in the text book.]

[See figure 3.32 in the text book.]

Real antennas and polarization

2. We can use multiple tag antennas. For example, here are two bent dipole antennas. These are on an 802.11b wireless LAN card, but it has the same orientation problems RFID has.