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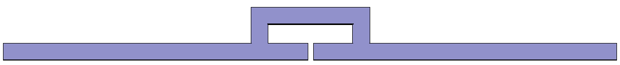
Microwave Measurements with Network Analyzer – Design of RFID Antenna



In the Course

Advanced Equipment in Solid State Electronics

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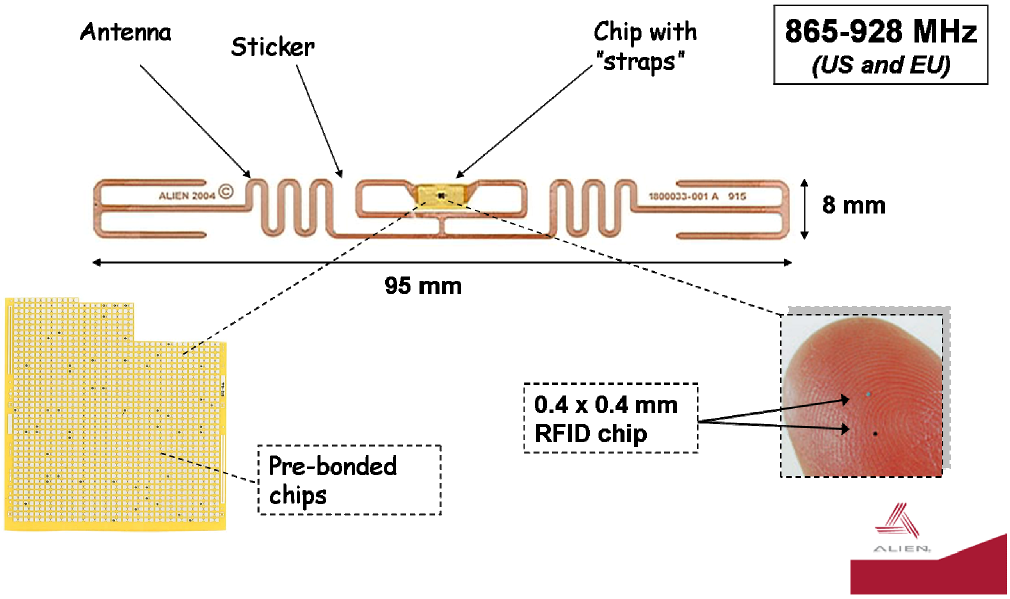
In this laboratory work you will show your classmates that you can get the best resonance on an RFID antenna and thereby read it at the longest distance
Answers to the assignment are written on a separate document. Handwritten is ok while computer written gives an extra point.

About RFID

RFID stands for Radio Frequency IDentification and is a collection of technologies for wireless identification with aid of radio waves where the identification unit, referred to a tag, reflects an answer back to an RFID reader. That is, the tag does not retransmit actively!

RFID technology is often compared to barcodes where a light signal is transmitted towards a label that with its specially line pattern reflects back an interference pattern that corresponds to a number that in turn can be matched to for example the price of an item in a grocery store.

RFID works in a similar manner with the difference that it utilizes radio waves instead of light waves. While the most advanced and most expensive tags can store several Kbytes and can be read at tens of meters, the absolutely simplest kind of RFID tags are the ones that are used for theft protection in stores. These most simple tags are called one-bit tags which means that they only have two modes; on or off. A typical RFID tag is shown in the figure below. It belongs to the most common standard, commonly referred to as *Gen-2*, and can be read at up to 10 meters and stores a 96 serial number.



RFID-tag from Alien Technology designed for the UHF band at 850-950 MHz. The tag comprises of an RFID chip of size about 0.4 x 0.4 x 0.2 mm and an antenna of length about just under one wavelength.

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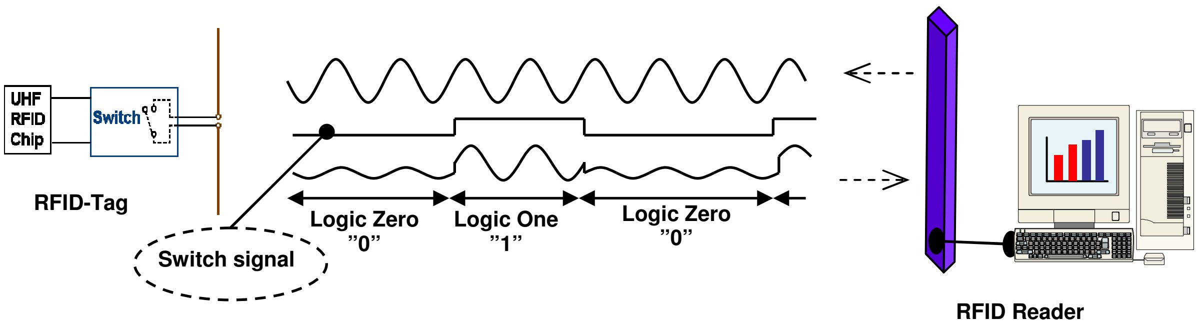
A passive tag (the most common) has no internal energy source in form of for example a traditional battery but instead harvest energy to operate its electronics by absorbing energy from the radio wave that the RFID reader transmits to the tag.

The antenna is the tags largest part and its general size depends on the frequency band that the tag operates on. A bit generalized, one can say that a lower frequency gives a longer maximum reading distance but necessitates a larger antenna.

The informative communication takes place by letting a radio signal that an *RFID reader* transmits toward an RFID tag *reflect* back. That is, the RFID tag itself doesn't comprise its own radio transmitter. In principal this works with by letting a switch be open or closed over the tag antenna terminals according to a digital number sequence, namely the tag's ID. The tag's antenna can therefore be seen as a *radar object* that dynamically changes its radar area in accordance to the series of binary numbers that corresponds to the tags ID number. An open switch then gives a relatively small radar echo while a short circuited antenna produces a larger radar echo. In this way a large echo can for example correspond to a logical "1" and a small echo correspond to a logical "0".



Limited Reading Distance

When an RFID reader transmits a radio signal towards an RFID tag a voltage is induced over the tag's antenna input terminals. If this voltage is high enough, the tag's microprocessor starts running.

The problem is that air is not the best medium to transmit electrical energy through. In air, the energy density for radio waves also decreases inversely proportional to the square of the distance to the reader. Therefore there is always a point at some distance from the RFID reader when the tag is not readable anymore since the induced voltage is too low to drive the tag's electronics.

Question 1:
a) At what distance can you read a barcode? Guessing is ok but give it a thought, what is for example the longest distance you yourself have ever seen a barcode been read at?

b) Can you mention a few things that you see as limitations and disadvantages with barcodes? Write at least two things.

Frequencies, wavelengths and the antenna's size

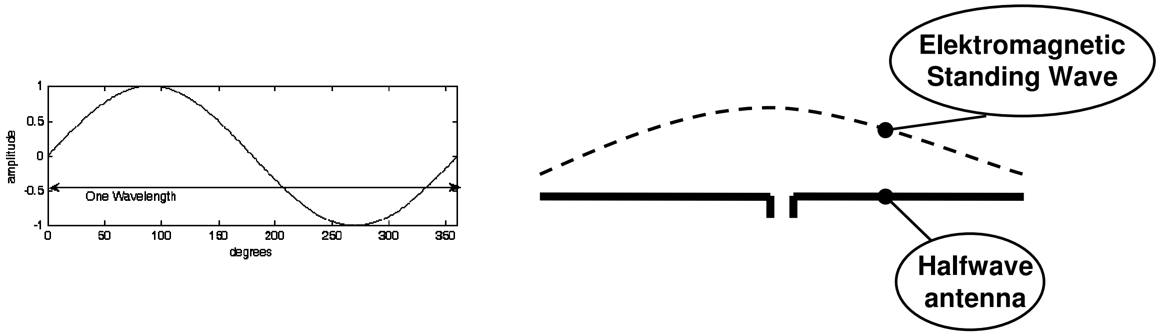
The most common RFID frequency for RFID in Europe today is around 866-869 MHz. Each frequency, *f*, has a wavelength, λ (Greek lambda), that is proportional to the radio waves propagation velocity, that in turn is the same as the speed of light, *c* = 300 000 000 meter/second = $3 \cdot 10^8$ m/s. The relation reads:

$$c = f \cdot \lambda \tag{1}$$

Question 2:
a) What wavelength corresponds to the frequency 867 MHz?

b) How long is consequently half a wavelength for 867 MHz?

An antenna often has a size of about half a wavelength in at least one dimension. The antenna then has *resonance* and the electrical current creates a *standing wave* on the antenna. This standing wave can be directly compared to the mechanical standing wave that a guitar string creates at its fundamental tone.



An antenna that together with its connected circuits has resonance has pure *resistive* so called *input impedance, Z*. Such antenna can therefore be seen as a common resistor.

An antenna that do *not* has resonance, besides a resistive part also has an imaginary part that is either capacitive (negative) or inductive (positive) in its input impedance, referred to as the *reactive* part. Such antenna can be seen as a resistor in series with or parallel to an inductance or a capacitor. The value is written just as with complex numbers, for example Z=30 +j130 Ω, where the letter *j* is used instead of *i* to not confuse with the notation of electrical current. An effective antenna together with a connected circuit has resonance, i.e. no reactive parts in its input impedance when they are put together!!

Wave propagation

Received power in any antenna can be calculated with *Friis Transmission formula*:

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi R)^2} \tag{2}$$

Where P_r is received power, P_t transmitted power, G_t and G_r respective antennas *gain*, i.e. the antennas' ability to concentrate energy in a certain direction, λ the wavelength and *R* the distance between transmitting and receiving antenna.

An ordinary dipole has gain of about 1.6. Regulations for maximum output power often considers the product of transmitted power times the antenna's gain. For European RFID this means that $P_t \cdot G_t$ can have a maximum of 2 W.

Equation (2) also shows that in order to double a specific reading distance, the reader output power must fourfold (try to understand this from (2)). On the other hand, an RFID tag could in principle be powered up very far away if he RFID reader antenna just has high enough output power. The highest allowed output power from RFID readers is however regulated by governmental authorities with 2 Watts maximum within the EU, 4 Watts in the US etc, which makes the tag readable in the order of meters from the RFID reader.

Question 3:
What is theoretically the maximum distance where an 867 MHz RFID tag can be read if the tag needs 0.5 mW to operate and normal half wave dipole antennas with Gain of 1.64 are used for both the RFID reader and RFID tag?

The RFID tag antenna's input impedance

When an antenna's input impedance only comprises a real part it is usually written as for example 75 Ω and when it is also comprises a complex part (both real and imaginary part) it is written as for example 75 + j100 Ω.

Impedances are often standardized to a certain value and within high frequency electronics 50 Ω is the absolutely most common, while 75 Ω is the most common for for example TV antennas.

Tag antennas for passive RFID chips are however an exception where the impedance most often is found in the area 30 + j130 Ω. This is because the antenna always has to be *impedance matched* to its connected circuit and passive RFID chips typically *do* not have 50 Ω input impedance.

Impedance matching, reflected power and maximum reading distance for RFID

Within high frequency electronics one often hears about the importance of *impedance matching*. In a perfect impedance matched coupling, ALL energy from one unit to another is transferred and with a non-perfect coupling some or none of the energy is transferred. The energy that is not transferred is reflected back from where it came from. Impedance matching is obtained when two connected units has impedances that is each other's *complex conjugate*, which means that their impedances should have the same total value on the real- and imaginary part but opposite sign on the imaginary part.

The common TV antenna for example has the impedance 75 Ω, that is pure real, with no imaginary part. It should therefore be matched to transmission lines or circuits having impedance 75 Ω. Mathematically correct one could instead say that the antenna has input impedance 75 + j0 Ω and should therefore be matched to 75 - j0 Ω. A transmission line for TV signals is therefore usually marked with 75 Ω, which is the transmission line's *characteristic impedance,* and the connection point at the TV is similarly commonly marked with 75 Ω.

If the transmission line that is connected an antenna with impedance Z_A=75 Ω instead has characteristic impedance Z_C=50 Ω some of the energy will be reflected back and the reflected signal's *relative* amplitude, Γ, is calculated as:

$$\Gamma = \frac{Z_A - Z_C^*}{Z_A + Z_C} \tag{3}$$

Which in this example gives a reflected signal with amplitude 0.20 times the amplitude of the original signal. The ”star” over Z_C in the numerator in (3) means that the complex conjugate should be used.

As power, P, is proportional to voltage, U, squared over a resistor, R, according to

$$P = \frac{U^2}{R} \tag{4}$$

, relative reflected power, $P_{Reflected}$, is proportional to relative reflected voltage squared:

$$P_{Reflected} = |\Gamma|^2 = \left| \frac{Z_A - Z_C^*}{Z_A + Z_C} \right|^2 \tag{5}$$

Note that it is the *absolute value* of the reflection coefficient that is squared in (5) leaving $P_{Reflected}$ as a real number (i.e. no imaginary parts). In the case with the TV antenna the indicators for absolute value however doesn’t matter since no terms contains complex numbers. For a 75 Ω TV antenna that is connected to a 50 Ω transmission line this means that 0.20^2=4.0 % of the antenna received power is reflected back into the air and the remaining 100 – 4.0 = 96 % continues to the transmission line. If the TV also has input impedance 75 Ω the same thing happens again, that is, the signal looses additional 4.0 % which gives a total loss of 7.8 % (try to understand why it is not 8.0 %...). A loss of 7.8 % means that 100 – 7.8 = 92.2 % of the power still reaches into the TV, in despite that a 50 Ω line is used instead of the correct 75 Ω lines.

Please go through the equations (3) to (4) and calculate your way through the example with the TV antenna before moving on to Question 4 below.

Question 4:
How large part of the received power in an RFID antenna is transferred to an attached RFID chip if the chip has input impedance Z_C = 20 - j130 Ω and the antenna has input impedance Z_A= 50 + j80 Ω?

Available power decreases with increased distance, R, to the RFID reader, proportional to $1 / R^2$. Maximum reading distance is therefore proportional to:

$$\sqrt{1 - |\Gamma|^2} \qquad 6)$$

If Z_A is the complex conjugate to Z_C, reflected power will thus be zero and the relative maximum reading distance becomes 1.0, that is, 100%.

Question 5:
How long does the relative reading distance become for the impedances given in Question 4? Remember that this is relative calculations and answer in percent!

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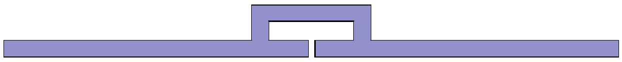
Your Antenna

You will manufacture your very own RFID antenna, assemble it with an RFID chip and try what distance from an RFID reader you can read it at.

The RFID chip has an input impedance with relatively large capacitive part, why your antenna's input impedance must have corresponding inductive part. This can for example be obtained through an ordinary dipole by adding an extra, inductive, loop over the antenna terminals, (loop = inductance with one turn), like for example the antenna depicted below.



You will manufacture your antenna by cutting it out from aluminum tape that you then stick on ordinary paper. Remember that most aluminum tapes are only conductive on one side so that if you make a bridge between two aluminum parts you need to double-fold it in the ends or put one of the parts upside down. You have total freedom to choose the shape of your antenna but it is recommended that you make an antenna that is in order of about ½ λ in at least one dimension and put the chip somehow symmetric.

When you have made a suitable antenna you simply put the RFID chip over the antenna input terminals with ordinary tape. Make sure it is the silver side of the chip that goes towards the aluminum. You can try your tag directly in front of the RFID reader and see what the maximum reading distance is. After that you will get help from a lab assistant to measure the input impedance of your antenna, with aid of a special instrument, a *Network Analyzer*. From the measured data you will get tips on how you can make small changes to your antenna structure and thereby achieve a longer reading distance.

Question 6:
Measure and write down both your antenna's and your RFID chip's input impedance at 867 MHz.

Question 7:

- Make a simple drawing of your antenna on a paper or in suitable computer program, with numbers indicating the dimensions.
- Make a table where you for each consecutive try fill in:
  - Measured maximum read distance
  - Measured input impedance
  - Calculated relative maximum reading distance
    - Put the data for measured impedances in equation (5)-(6).
  - For each new try, the table should also be filled in with:
    - Notes and/or drawing with measurements indicating what is changed at the antenna. Increased and/or decreased dimensions, added/removed parts etc.
    - A short motivation WHY this modification has been made. If you are writing for hand and the table cell is too small you can write on the backside of the paper!
- Try to all the time, with aid of the lab assistant, understand why the changes you make gives the results experience.
- Discuss with the lab assistant when you think the antenna is "good enough" and you should go on to the next task.

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Question 8:
Give a short comment for how reading distances calculated from measured impedances relates to measured reading distance with the RFID reader. Does theory and experiments agree?

Influence of the surrounding

An antenna is strongly influenced by nearby materials. An antenna in a cell phone for example must be able to operate in a human hand and near a human head.

To experience this influence you should therefore try to put your RFID tag on some different objects and see if and how the maximum read range changes.

Question 9:

a) Make a table and write down the maximum read distance when your tag is put against:

1. *A book*
2. *A metallic surface*
3. *A plastic bottle filled with water*
4. *I your own hand (without any air between the tag and your hand)*

5-? Other object(s) you tried on:

b) What conclusions can you make from the results in 9 a)?

Question 10 (Optional): If some of the object in Question 9 gave a non-working tag or an extremely short reading distance, how could you solve this? How far from the object do you have to hold the tag to make it work and what reading distance do you now have? Can you put a "spacer" between a "difficult object" and the tag? There are no definite answers to this question but feel free to try it and discuss with your classmates and the lab assistant.

Question 11, Home assignment:
Search the general literature, Internet etc. and find out what 'S-Parameters' means. In the answer you should include:
a) Short definition of S11
b) Short definition of S12
c) A formula of how one can calculate impedance, Z, from a measured S11.

Question 12, Home assignment:
Below Smith Chart indicates one frequency point on a specific antenna, not necessarily for RFID. If this Smith Chart is normalized to 50 Ω, what impedance does it indicate, and what S-parameter does it correspond to.

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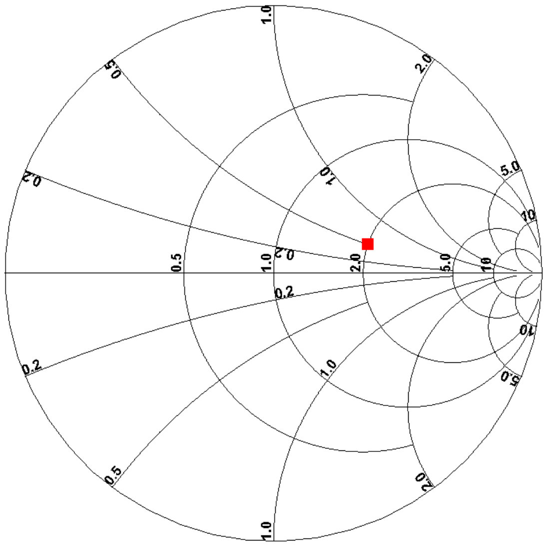

Lab reports can be written by hand or with computer, and can for example:

- Be handed in directly at the end of the lab
- Be put in Johan's mailbox on the 2nd floor in the S-building
- Be emailed, or scanned and emailed, to johan.siden@miun.se (Preferred)

Good Luck!

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