Communication Circuits Design

Academic year 2018/2019 – Semester 2 – Week 2

Lecture 2.5: Antennas in a circuit

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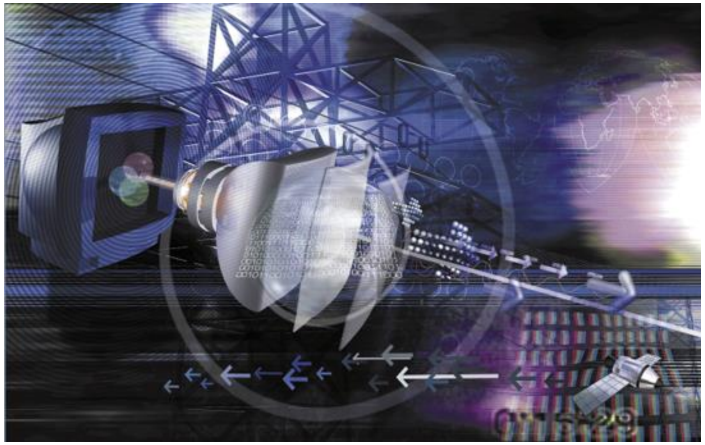
Outline



- **Antenna: what are they?**
- **Near and far field radiation**
- **Parameters to describe antennas (radiation pattern, gain)**
- **Antennas in a communication system (Friis equation, antenna impedance & efficiency)**

References:

- *J. Beasley, G. Miller, "Modern Electronic Communication", Pearson, 9th ed. – Page 610 and following on antennas*
- *C. Balanis, "Antenna theory: analysis and design", Wiley* (this is an excellent book but for the level of details of this course you do not need it!)

Antennas

A ***circuit element*** providing a **transition** from a guided wave on a transmission line (a cable for example) to a free space wave, or vice versa a way to receive and collect EM energy and couple this into a transmission line. Antennas are obviously fundamental for wireless communication systems.

The key point is that the antenna has to be **efficient** in “translating” EM power from the circuit/transmission lines to free space, and vice-versa, to avoid losses (waste of power) and reflection (back into the circuit).

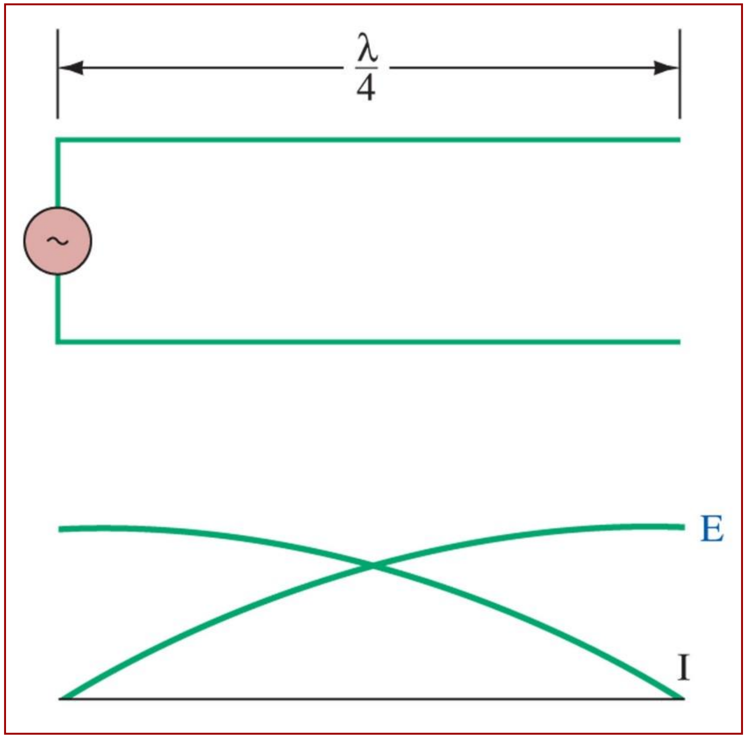
The physical mechanism is described by Maxwell’s equations in the transmission line and in the free space, but we will not study this in detail in this course.

One key property we note though is the **<u>reciprocity</u>**, i.e. the behaviour and properties of the antenna are the same in transmission and reception operations, i.e. for exchange of EM power from circuit to free space and vice versa.

Half-wave dipoles

What if we forget about the antenna and just use an open transmission line (for example an RF cable but open).

Imagine to use a ***quarter wavelength line long λ/4*** and leave it open. As the line is open, the impedance at the end is infinite which implies maximum (infinite) voltage and therefore electric field E and minimum (zero) current. Vice versa, the impedance at the feeding point is very close to zero (it is the ratio E/I).



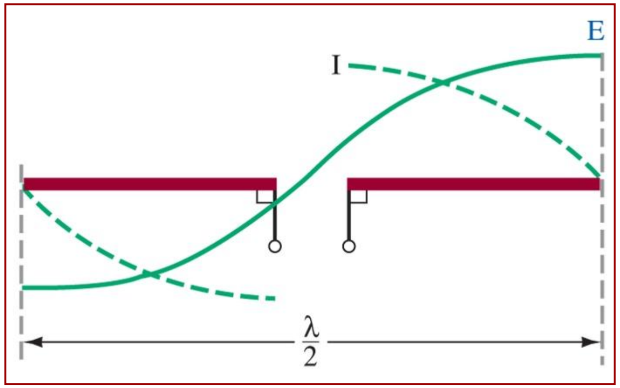
This is not a great antenna because the signal applied from a generator for example will be reflected back into the circuit with minimal or no transmission (it can be shown analysing the magnetic fields on each wire close to each other).

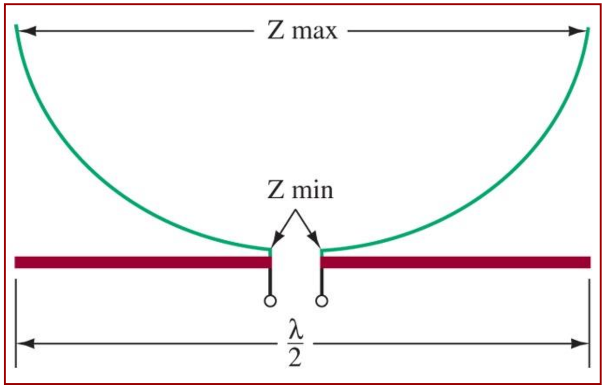
What happens now if we bend out the two conductors (wires) of this structure?

Half-wave dipoles

In this case we obtain the so called half-wave dipole antenna or ***λ/2 dipole***

This has still maximum voltage and electric field at the end, and current which is maximum at the centre of the antenna and minimum at the end. The impedance is generically low at the feed and maximum at the end of the antenna; the exact values depend on how the antenna is designed.





The main point to remember here is that going from the λ/4 to λ/2 structure enabled to get a <u>finite input impedance in the antenna</u>, hence the antenna can accept EM power from the circuit to radiate it into the space.

Near and far field

Now, part of the EM field generated by an antenna will collapse back into the antenna itself as an induced current – this is called the **induction or near field**. Part of the EM field will not be captured back by the antenna but radiated out into the space – this is called the **radiation or far field**.

You can grasp that physical distance is a key parameter here: near the antenna there is more induction field and less and less moving away.

There exist several relationships to describe the boundaries between these two regions of the antenna. Three are reported below where $\mathbf{R_{eff}}$ is the far-field distance of the antenna, **D** is the dimension of the antenna, and **λ** is the wavelength

(a) $R_{ff} = 1.6\lambda$: $\quad \frac{D}{\lambda} < 0.32$

(b) $R_{ff} = 5D$: $\quad 0.32 < \frac{D}{\lambda} < 2.5$

(c) $R_{ff} = \frac{2D^2}{\lambda}$: $\quad \geq 2.5\lambda$

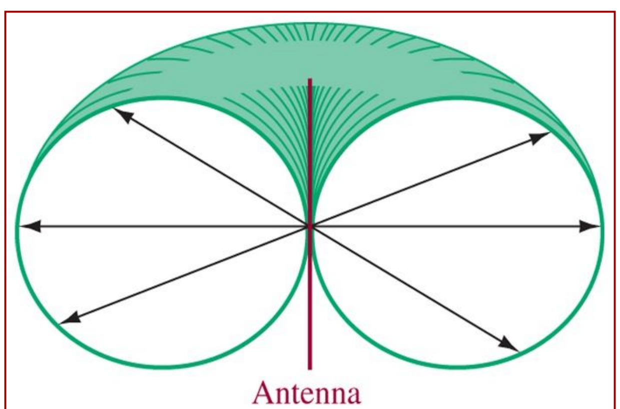
Key point is the dominant size of the antenna **D** with respect to the wavelength used **λ** to select one or another formula

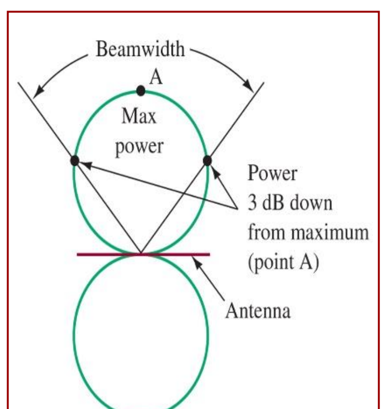
Radiation Pattern

The **radiation pattern** of an antenna describes the strength of its radiation field in the 3D space surrounding the antenna (can be described as a 3D plot or as 2D cuts of the 3D plot).

An ***isotropic source*** is an ideal antenna radiating equally in all directions, so the radiation pattern is a sphere (or a circle if cut on a 2D plot). We call this an omnidirectional radiation pattern.

A real antenna will have a ***directional radiation pattern***. The λ/2 dipole will have a sort of "doughnut" shape in 3D with the 2D cut also shown below. Essentially max power is radiated radially, 90 degrees from the antenna dominant axis, and (ideally) no power off the top/bottom ends. The **3dB beamwidth** of the antenna is the angular distance between the half-power points on its radiation pattern.





Question: in which direction will the antenna receive max power instead?

Antenna gain

The **gain** of an antenna is the amount of EM power radiated/received in a certain direction with respect to a reference antenna or to the ideal isotropic radiator. This is typically expressed in [*dBi]*.

Note two points: the gain depends on the spatial direction (higher/lower depending on the direction) AND it is different from an amplifier gain for example -> the amplifier increases the output power with respect to the input (taking it from its DC feed); the antenna cannot increase the power fed into it, but only distribute it in specific directions of space (if the gain is higher in some directions, must be lower in others).

The consequence of this is that, if you want *very high gain, your antenna becomes highly directional* (essentially you maximise the power radiated towards a specific direction); this can create problems of coverage for communication systems.

A half-wavelength dipole has a max gain of ~2.15 dBi. Many antennas can have max gains in the order of several dBi or 10-20 of dBi.

Friis equation

Why is antenna gain important? Because it is related to *how much power can be transmitted/received by a communication system*.

In free space, this can be modelled by **Friis equation** which considers the power exchanged between two separate antennas. The derivation and the details go beyond this course, but we report it here (its simplest version)

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

P_r and P_t are the received and transmitted power, G_t and G_r the gains of the transmitter and receiver antenna, λ is the wavelength, and R is the distance between the two antennas.

Key points:

- Numbers can be either in linear scale or dB but do not mix them!
- The distance reduces the received power by a quadratic factor, not just linear!
- The wavelength of the transmission (or the frequency) matter: with all parameters the same, working at higher frequency OR shorter wavelengths reduces the received power!

Radiation resistance

So far we have seen that an antenna has the aim to irradiate/receive power. From a circuit perspective the antenna can be modelled by an impedance Z.

A part of its real, resistive part, is the ***radiation resistance*** $\mathbf{R_r}$ which takes into account the power radiated by the antenna into the space **P**. It can be demonstrated that there is a relationship between these quantities and the current flowing into the antenna -> $\boldsymbol{R_r = {}^{P}/_{I^2}}$ Here I is the effective RMS value of the antenna current at the feed point.

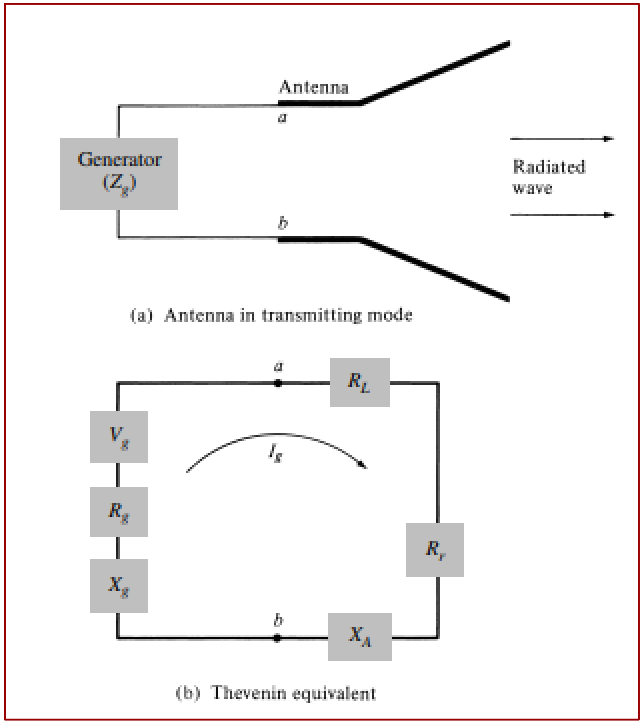
Note that not all power absorbed by the antenna is radiated; some is lost in the antenna conductor, imperfect dielectrics, eddy currents on metallic objects within the inductive field of the antenna for example. These losses can be represented by a resistive element, ***loss resistance*** $\mathbf{R_d}$ so that the total antenna resistance sums R_r and R_d.

The ***antenna efficiency*** **η** can be therefore expressed as below

$$\eta = \frac{Pradiated}{Pabsorbed} = \frac{R_r}{R_r + R_d} = \frac{R_r}{R_{tot}}$$

Antenna in a circuit

The real part of the antenna impedance models, represents the radiated power, but the antenna impedance is generally complex – there is a real part R_{tot} (which we have seen models both radiation and losses) and an imaginary part X_a that models power storage and/or reflections back to the circuit.



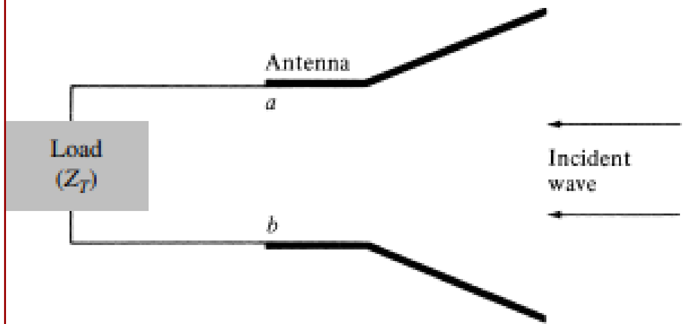
So **at the transmitter side** the antenna connected to a generator can be modelled by the Thevenin equivalent shown. The generator has its own impedance Z_g and the antenna its own impedance Z_a

We have already discussed talking of matching networks that maximum power transfer is obtained when $\mathbf{Z_a^* = Z_g}$ conjugate matching.

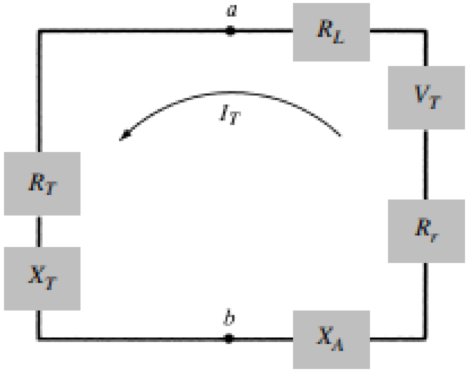
Also, as discussed, a matching network can be used to achieve good quality matching.

Antenna in a circuit

This is also true **at the receiver side**, where the antenna will be modelled by its impedance and the load by its (complex) impedance – the reception of waves and their conversion into voltages/currents will be model by a generator (indicated by V_T in the picture)



(a) Antenna in receiving mode



(b) Thevenin equivalent

Conjugate matching condition is still valid, and so is the possibility of adding a matching network to achieve good matching

Summary

In these slides we have seen some basic concepts about antennas:

- What they are in simple terms and how reciprocity helps characterise them in transmission and reception
- Simple example of half-wave dipoles
- The distinction between near and far field
- Some metrics: radiation pattern, beam-width, gain, radiation resistance, impedance, efficiency
- The importance of gain in the Friis equation
- How an antenna can be represented in a circuit by Za and the relevance for matching this to other circuits components.

Test your understanding

Example 1

Determine the distance from a λ/2 dipole to the boundary of the far field region if the λ/2 dipole is used in a 150-MHz communications system.

Solution: >5m – Tip: you need to find the parameter D/λ and then choose the correct far-field boundary equation

Example 2

Determine the distance from a parabolic reflector with diameter (D) = 4.5 m to the boundary of the far-field region if the parabolic reflector is used for Ku-band transmission of a 12-GHz signal.

Solution: >1.62km – Tip: as above, the parameter D/λ matters.

Example 3

Two λ/2 dipoles are separated by 50 km. They are "aligned" for optimum reception. The transmitter feeds its antenna with 10 W at 144 MHz. Calculate the power received.

Solution: ~0.296 nW – Tips: as it is a "power budget" you need Friis equation. As all numbers are in linear scale, you need the gain of the dipole to be converted in linear scale from 2.15 dB.

Note that the resulting power looks tiny but converted into voltage on a matched 73Ω resistor, it is still good for modern receivers ($V = \sqrt{PR}$)

Test your understanding

Example 4 → *An antenna with 70% efficiency and power losses represented by a 30Ω resistor is the terminal end of a transmitter circuit, fed by a generator. Calculate the required impedance of the feeding source to achieve conjugate matching if the reactive part of the antenna impedance is +25Ω.*

Tips: use the efficiency to find the radiation resistance and the total antenna impedance, then use conjugate matching.

Solution is Zs=100-j25 Ω

Example 5 -> *A patch antenna has max gain in its radiation pattern equal to 5 dBi and a horn antenna has max gain of 15 dBi, and a dish reflector has max gain of 22 dBi.*
Which one would you choose to maximise the transmitted power?
Which one would you choose to maximise coverage (beam-width)?
Which one would you choose to maximise efficiency?