RADIO SYSTEMS – ETIN15

Lecture no: 2

Propagation mechanisms

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Contents

- Short on dB calculations
- Basics about antennas
- Propagation mechanisms
  - Free space propagation
  - Reflection and transmission
  - Propagation over ground plane
  - Diffraction
    - Screens
    - Wedges
    - Multiple screens
  - Scattering by rough surfaces
  - Waveguiding

DECIBEL

dB in general

When we convert a measure X into decibel scale, we always divide by a reference value X_{ref}:

$$\frac{X|_{non-dB}}{X_{ref}|_{non-dB}}$$

Independent of the dimension of X (and X_{ref}), this value is always dimension-less.

The corresponding dB value is calculated as:

$$X|_{dB} = 10\log\left(\frac{X|_{non-dB}}{X_{ref}|_{non-dB}}\right)$$

Power

We usually measure power in Watt [W] and milliWatt [mW]

The corresponding dB notations are dB and dBm

	Non-dB	dB
Watt:	$P\|_W$	$P\|_{dB} = 10\log\left(\frac{P\|_W}{1\|_W}\right) = 10\log\left(P\|_W\right)$
milliWatt:	$P\|_{mW}$	$P\|_{dBm} = 10\log\left(\frac{P\|_{mW}}{1\|_{mW}}\right) = 10\log\left(P\|_{mW}\right)$
RELATION:	$P\|_{dBm} = 10\log\left(\frac{P\|_W}{0.001\|_W}\right) = 10\log\left(P\|_W\right) + 30\|_{dB} = P\|_{dB} + 30\|_{dB}$	

Example: Power

Sensitivity level of GSM RX: 6.3×10^{-14} W = -132 dB or -102 dBm

Bluetooth TX: 10 mW = -20 dB or 10 dBm

GSM mobile TX: 1 W = 0 dB or 30 dBm

GSM base station TX: 40 W = 16 dB or 46 dBm

ERP – Effective Radiated Power

Vacuum cleaner: 1600 W = 32 dB or 62 dBm

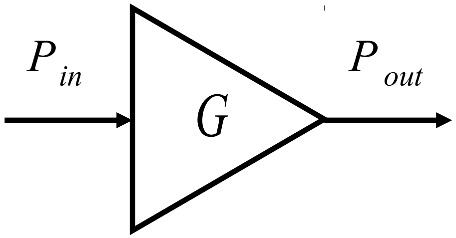
Car engine: 100 kW = 50 dB or 80 dBm

”Typical” TV transmitter: 1000 kW ERP = 60 dB or 90 dBm ERP

”Typical” Nuclear power plant : 1200 MW = 91 dB or 121 dBm

Amplification and attenuation

(Power) Amplification:

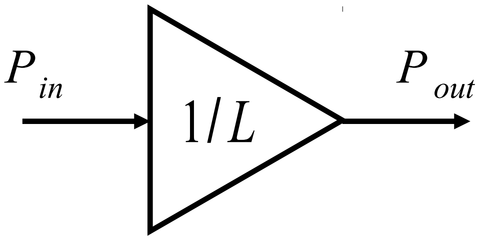


$$P_{out} = G P_{in} \Rightarrow G = \frac{P_{out}}{P_{in}}$$

The amplification is already dimension-less and can be converted directly to dB:

$$G|_{dB} = 10 \log_{10} G$$

(Power) Attenuation:



$$P_{out} = \frac{P_{in}}{L} \Rightarrow L = \frac{P_{in}}{P_{out}}$$

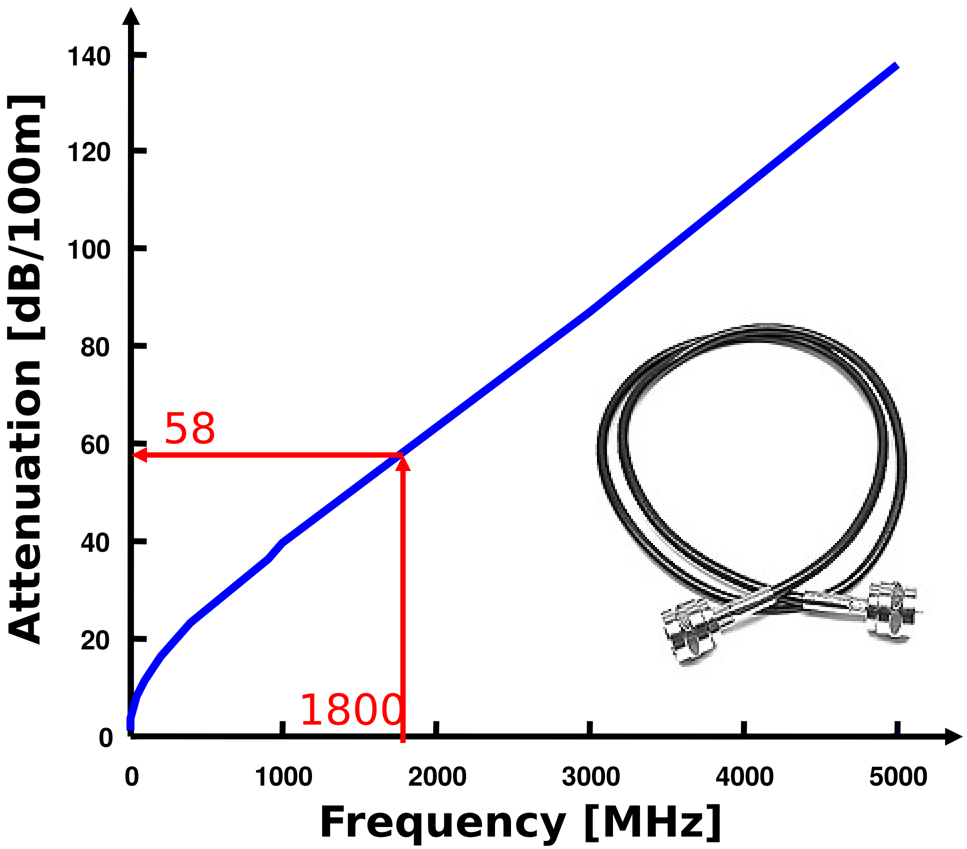
The attenuation is already dimension-less and can be converted directly to dB:

$$L|_{dB} = 10 \log_{10} L$$

Note: It doesn't matter if the power is in mW or W. Same result!

Example: Amplification and attenuation

High frequency cable RG59

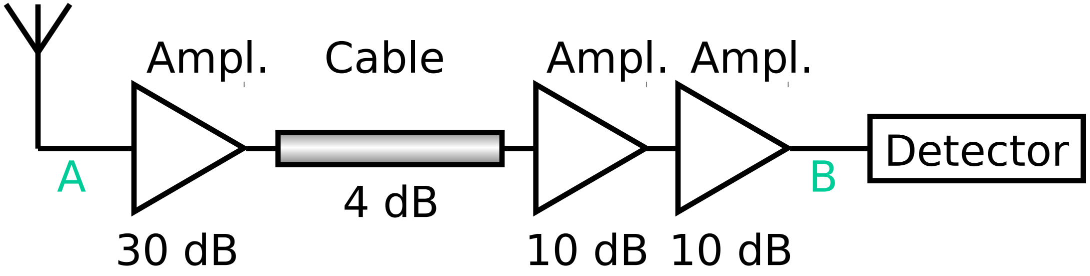


30 m of RG59 feeder cable for an 1800 MHz application has an attenuation:

$$G\big|_{dB} = 30 \underbrace{\frac{L\big|_{dB/100m}}{100}}_{dB/1\text{m}}$$

$$= 30 \frac{58}{100} = \underline{17.4}$$

Example: Amplification and attenuation



The total amplification of the (simplified) receiver chain (between A and B) is

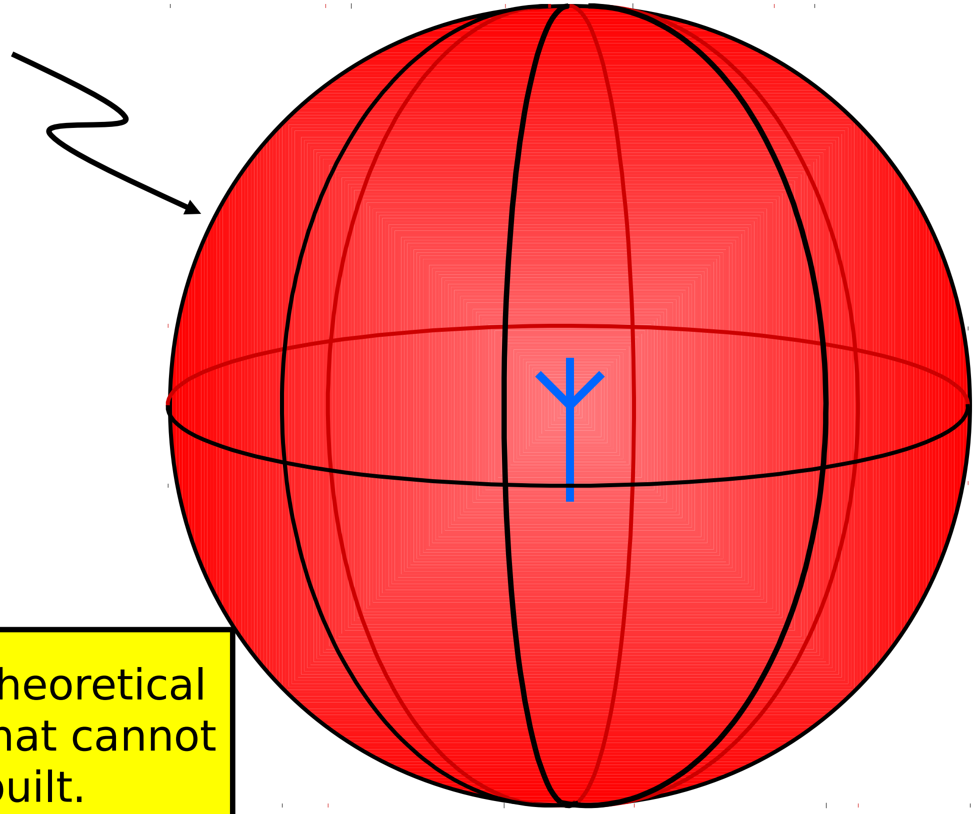
$$G_{A,B}\big|_{dB} = 30 - 4 + 10 + 10 = 46$$

ANTENNA BASICS

The isotropic antenna

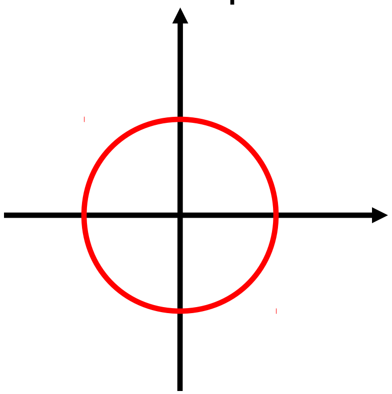
The **isotropic antenna** radiates equally in all directions

Radiation pattern is spherical

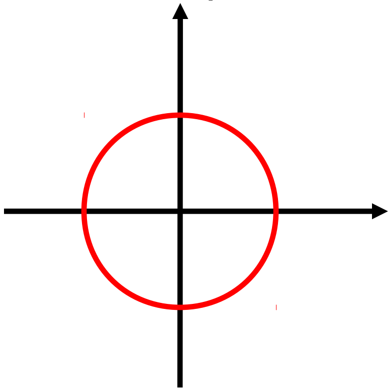


This is a theoretical antenna that cannot be built.

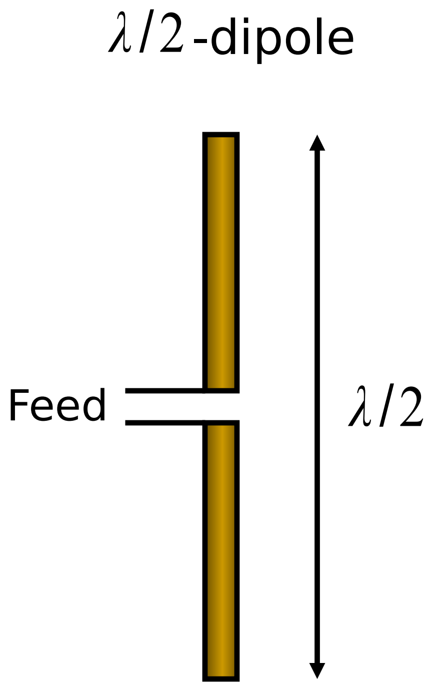
Elevation pattern



Azimuth pattern

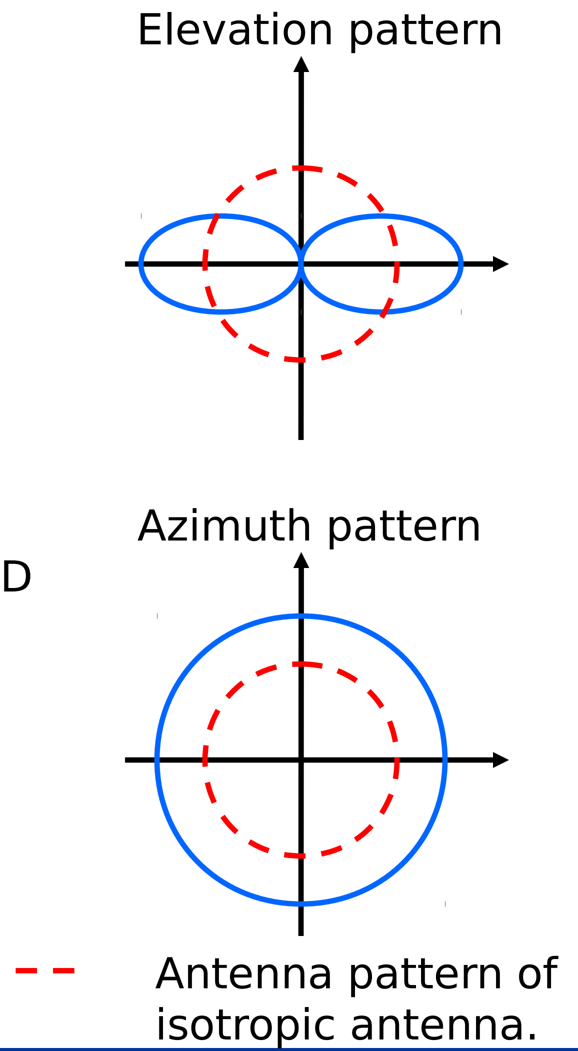


The dipole antenna



This antenna does not radiate straight up or down. Therefore, more energy is available in other directions.

THIS IS THE PRINCIPLE BEHIND WHAT IS CALLED ***ANTENNA GAIN***.

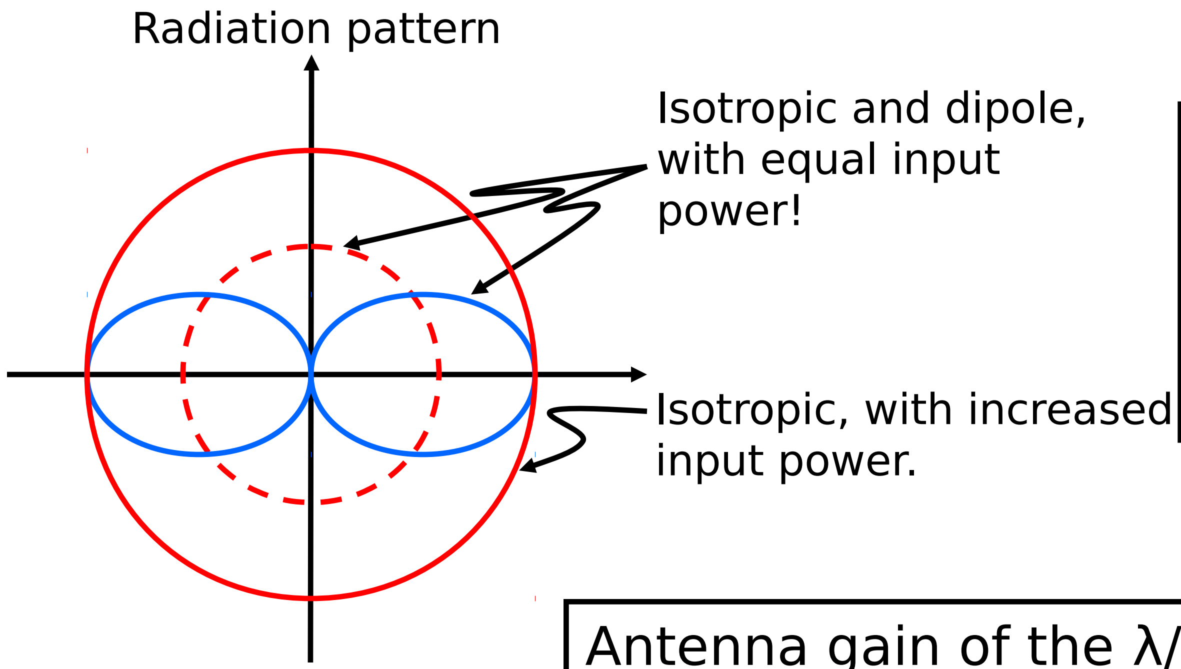


A dipole can be of any length, but the antenna patterns shown are only for the λ/2-dipole.

Antenna gain (principle)

Antenna gain is a relative measure.

We will use the isotropic antenna as the reference.

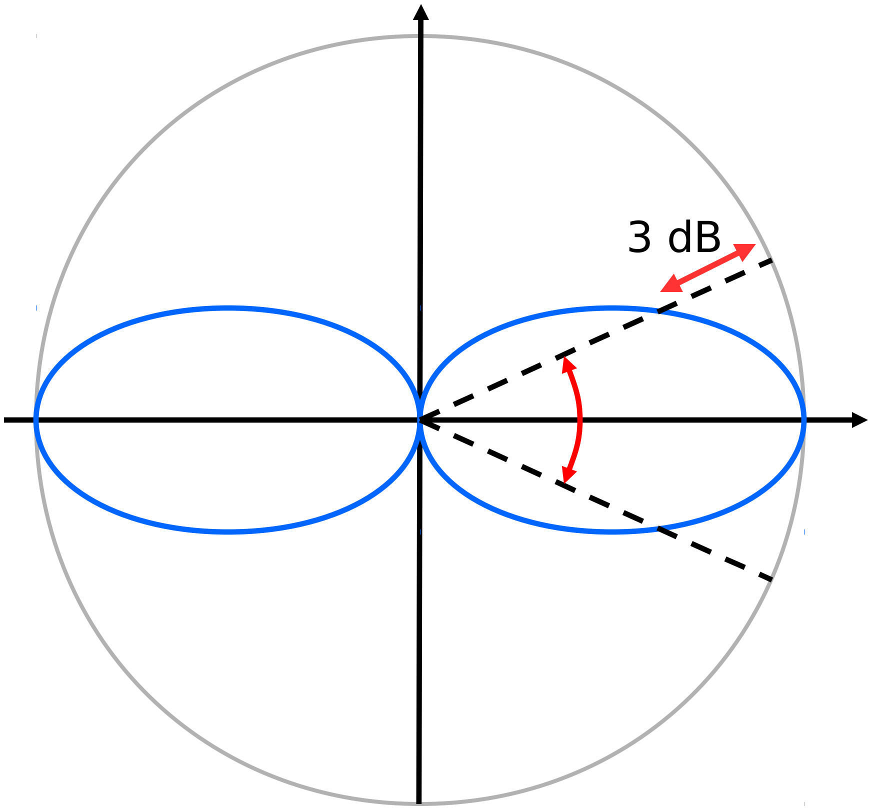


The increase of input power to the isotropic antenna, to obtain the same maximum radiation is called the **antenna gain**!

Antenna gain of the λ/2 dipole is **2.15 dB**.

Antenna beamwidth (principle)

Radiation pattern



The isotropic antenna has ”no” beamwidth. It radiates equally in all directions.

The **half-power beamwidth** is measured between points were the pattern as decreased by 3 dB.

Receiving antennas

In terms of gain and beamwidth, an antenna has the same properties when used as transmitting or receiving antenna.

A useful property of a receiving antenna is its ”**effective area**”, i.e. the area from which the antenna can ”absorb” the power from an incoming electromagnetic wave.

Effective area A_{RX} of an antenna is connected to its gain:

$$G_{RX} = \frac{A_{RX}}{A_{ISO}} = \frac{4\pi}{\lambda^2} A_{RX}$$

It can be shown that the effectiva are of the isotropic antenna is:

$$A_{ISO} = \frac{\lambda^2}{4\pi}$$

Note that A_{ISO} becomes smaller with increasing frequency, i.e. with smaller wavelength.

A note on antenna gain

Sometimes the notation **dBi** is used for antenna gain (instead of dB).

The "**i**" indicates that it is the gain relative to the isotropic antenna (which we will use in this course).

Another measure of antenna gain frequently encountered is **dBd**, which is relative to the λ/2 dipole.

$$G|_{dBi} = G|_{dBd} + 2.15$$

Be careful! Sometimes it is not clear if the antenna gain is given in dBi or dBd.

EIRP
Effective Isotropic Radiated Power

EIRP = Transmit power (fed to the antenna) + antenna gain

$$EIRP\,\big|_{dB} = P_{TX\,|dB} + G_{TX\,|dB}$$

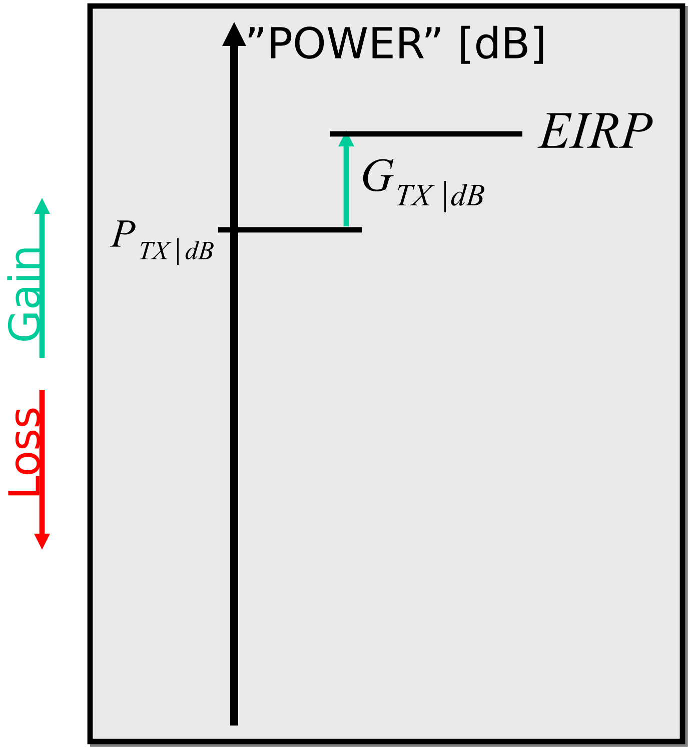
Answers the questions:

How much transmit power would we need to feed an isotropic antenna to obtain the same maximum on the radiated power?

How ”strong” is our radiation in the maximal direction of the antenna?

This is the more important one, since a limit on EIRP is a limit on the radiation in the maximal direction.

EIRP and the link budget



$$EIRP\big|_{dB} = P_{TX|dB} + G_{TX|dB}$$

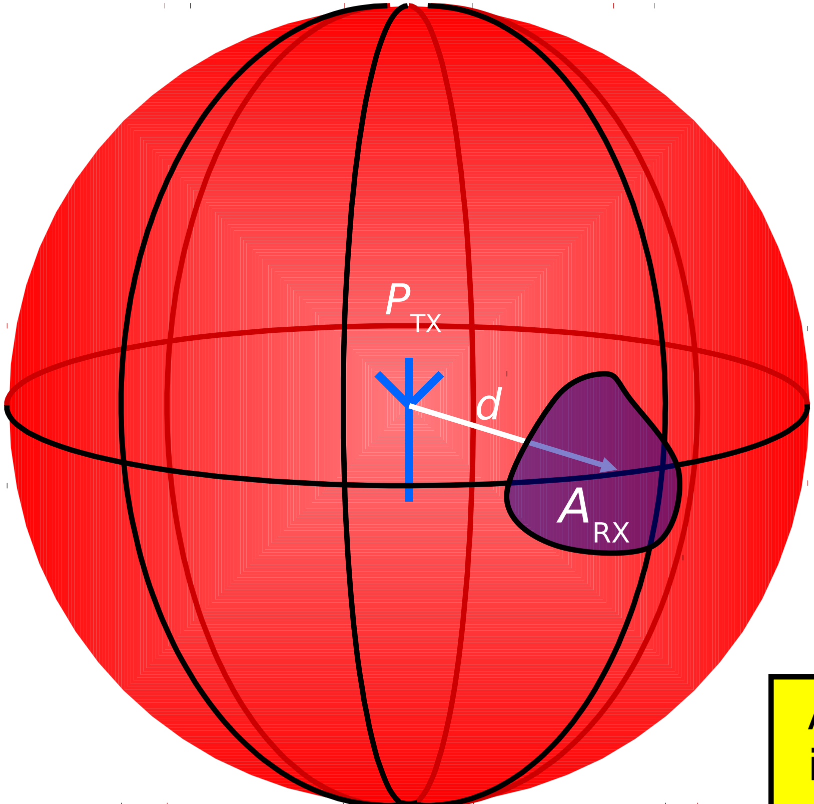
PROPAGATION MECHANISMS

Propagation mechanisms

- We are going to study the fundamental propagation mechanisms
- This has two purposes:
  - Gain an understanding of the basic mechanisms
  - Derive propagation losses that we can use in calculations
- For many of the mechanisms, we just give a brief overview

FREE SPACE PROPAGATION

Free-space loss
Derivation



Assumptions:

Isotropic TX antenna

TX power P_{TX}
Distance d

RX antenna with effective area A_{RX}

Relations:

Area of sphere: $A_{\mathrm{tot}} = 4\pi d^2$

Received power: $P_{RX} = \frac{A_{RX}}{A_{\mathrm{tot}}} P_{TX} = \frac{A_{RX}}{4\pi d^2} P_{TX}$

If we assume RX antenna to be isotropic:

$$P_{RX} = \frac{\lambda^2/4\pi}{4\pi d^2} P_{TX} = \left(\frac{\lambda}{4\pi d}\right)^2 P_{TX}$$

Attenuation between two isotropic antennas in free space is (free-space loss):

$$L_{\mathrm{free}}(d) = \left(\frac{4\pi d}{\lambda}\right)^2$$

Free-space loss
Non-isotropic antennas

Received power, with isotropic antennas (G_{TX}=G_{RX}=1):

$$P_{\mathrm{RX}}(d) = \frac{P_{\mathrm{TX}}}{L_{\mathrm{free}}(d)}$$

Received power, with antenna gains G_{TX} and G_{RX}:

$$P_{RX}(d) = \frac{G_{RX} G_{TX}}{L_{free}(d)} P_{TX} \quad \Longleftrightarrow \quad P_{RX|dB}(d) = P_{TX|dB} + G_{TX|dB} - L_{free|dB}(d) + G_{RX|dB}$$

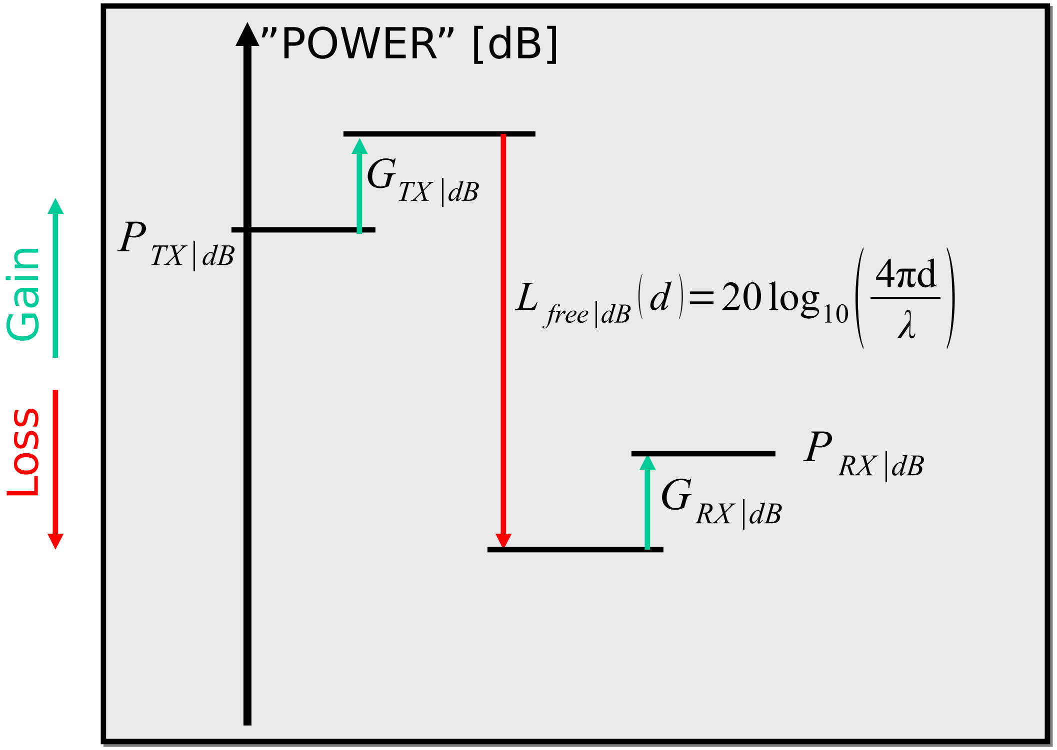
$$= P_{TX|dB} + G_{TX|dB} - 20\log_{10}\left(\frac{4\pi d}{\lambda}\right) + G_{RX|dB}$$

$$= \frac{G_{RX} G_{TX}}{\left(\frac{4\pi d}{\lambda}\right)^2} P_{TX}$$

This relation is called **Friis' law**

Free-space loss
Non-isotropic antennas (cont.)

Let's put Friis' law into the link budget



Received power decreases as $1/d^2$, which means a **propagation exponent** of $n = 2$.

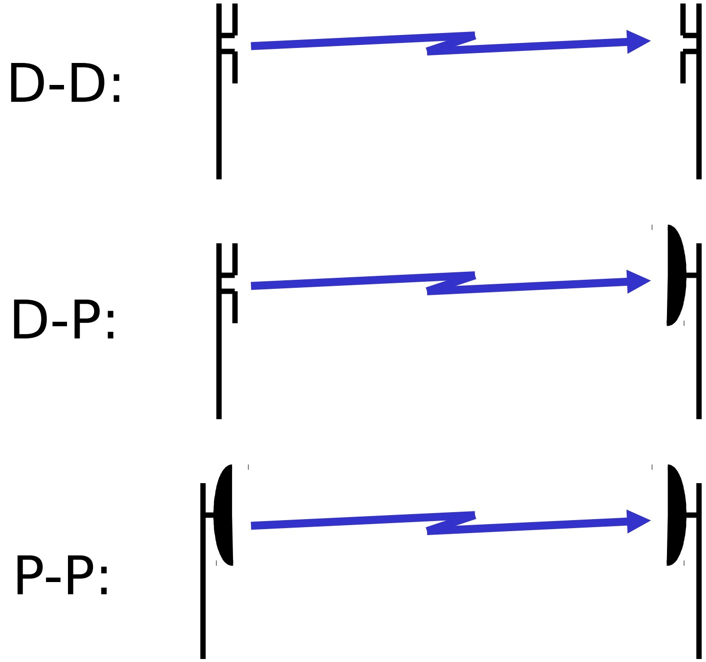
How come that the received power decreases with increasing frequency (decre-asing λ)?

Does it?

$$P_{RX|dB}(d) = P_{TX|dB} + G_{TX|dB} - L_{free|dB}(d) + G_{RX|dB}$$

Free-space loss
Example: Antenna gains

Assume following three free-space scenarios with λ/2 dipoles and parabolic antennas with fixed effective area A_{par}:



Antenna gains

$$G_{dip|dB} = 2.15$$

$$G_{par|dB} = 10\log_{10}\left(\frac{A_{par}}{A_{iso}}\right) = 10\log_{10}\left(\frac{A_{par}}{\lambda^2/4\pi}\right) = 10\log_{10}\left(\frac{4\pi A_{par}}{\lambda^2}\right)$$

Free-space loss
Example: Antenna gains (cont.)

Evaluation of Friis' law for the three scenarios:

D-D:

$$P_{RX|dB}(d) = P_{TX|dB} + 2.15 - 20\log_{10}\left(\frac{4\pi d}{\lambda}\right) + 2.15$$

$$= P_{TX|dB} + 4.3 - 20\log_{10}(4\pi d) + 20\log_{10}\lambda$$

Received power decreases with decreasing wavelength λ, i.e. **with increasing frequency**.

D-P:

$$P_{RX|dB}(d) = P_{TX|dB} + 2.15 - 20\log_{10}\left(\frac{4\pi d}{\lambda}\right) + 10\log_{10}\left(\frac{4\pi A_{par}}{\lambda^2}\right)$$

$$= P_{TX|dB} + 2.15 - 20\log_{10}(4\pi d) + 10\log_{10}(4\pi A_{par})$$

Received power independent of wavelength, i.e. **of frequency**.

P-P:

$$P_{RX|dB}(d) = P_{TX|dB} + 10\log_{10}\left(\frac{4\pi A_{par}}{\lambda^2}\right) - 20\log_{10}\left(\frac{4\pi d}{\lambda}\right) + 10\log_{10}\left(\frac{4\pi A_{par}}{\lambda^2}\right)$$

$$= P_{TX|dB} + 20\log_{10}(4\pi A_{par}) - 20\log_{10}(4\pi d) - 20\log_{10}\lambda$$

Received power increases with decreasing wavelength λ, i.e. **with increasing frequency**.

Free-space loss
Validity - the Rayleigh distance

The free-space loss calculations are only valid in the **far field** of the antennas.

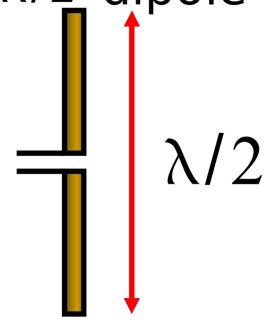
Far-field conditions are assumed ”**far beyond”** the Rayleigh distance:

$$d_R = 2\frac{L_a^2}{\lambda}$$

where L_a is the largest dimesion of the antenna.

Another rule of thumb is:
”**At least** 10 wavelengths”

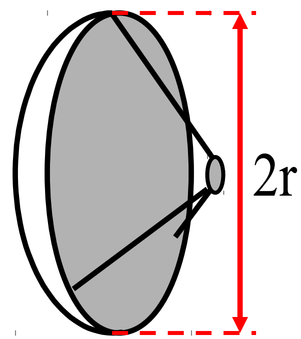
$\lambda/2$-dipole



$$L_a = \lambda/2$$

$$d_R = \lambda/2$$

Parabolic

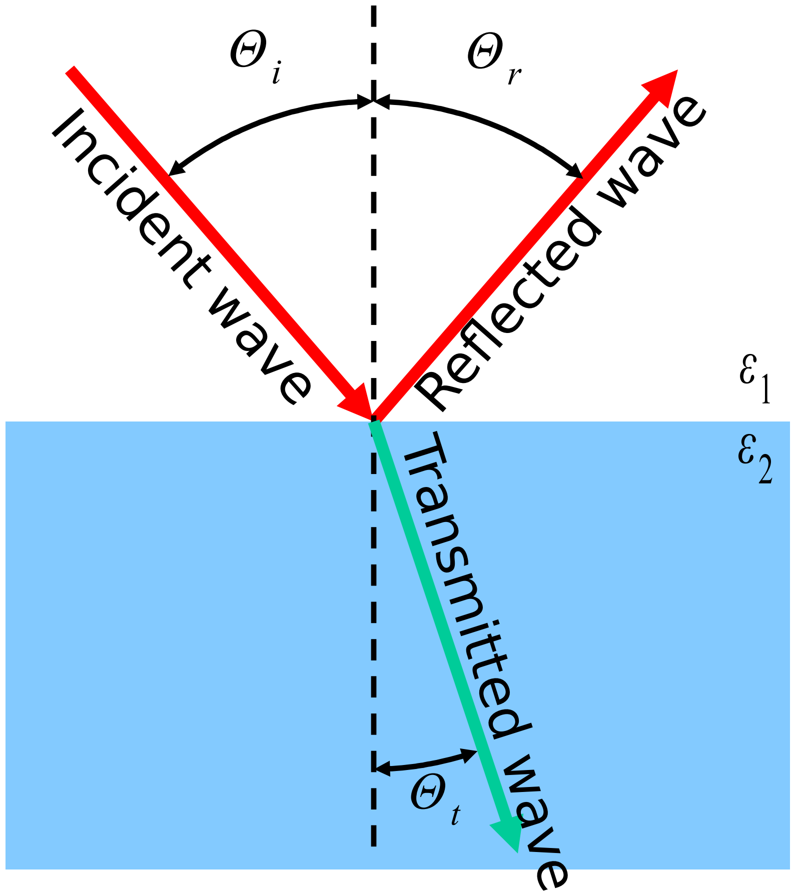


$$L_a = 2r$$

$$d_R = \frac{8r^2}{\lambda}$$

REFLECTION AND TRANSMISSION

Reflection and transmission
Snell's law



$$\begin{cases} \Theta_i = \Theta_r \\ \dfrac{\sin \Theta_t}{\sin \Theta_i} = \dfrac{\sqrt{\varepsilon_1}}{\sqrt{\varepsilon_2}} \end{cases}$$

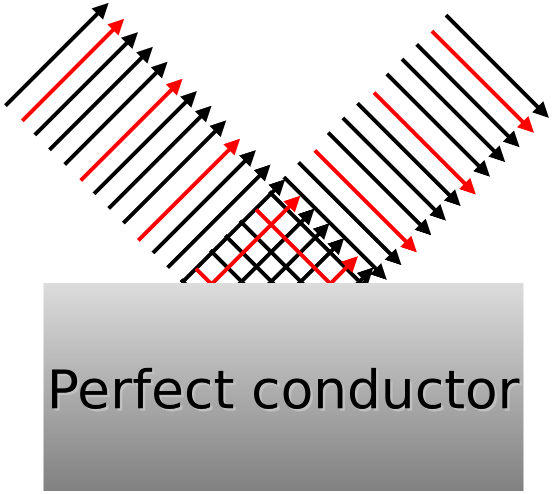
ε_1 ε_2 Dielectric constants

Reflection and transmission
Refl./transm. coefficcients

Given complex dielectric constants of the materials, we can also compute the reflection and transmission coefficients for incoming waves of different polarization.

[See textbook.]

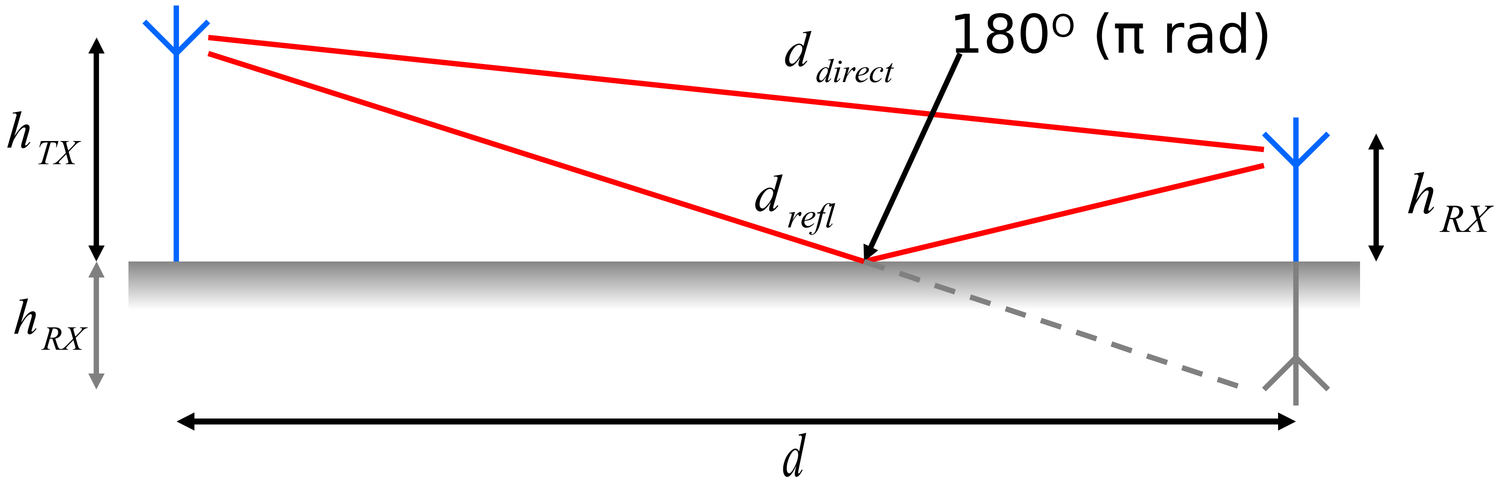
The property we are going to use:



No loss and the electric field is phase shifted 180^{o} (changes sign).

PROPAGATION OVER A GROUND PLANE

Propagation over ground plane
Geometry



Propagation distances:

$$d_{direct} = \sqrt{d^2 + \left(h_{TX} - h_{RX}\right)^2}$$

$$d_{refl} = \sqrt{d^2 + \left(h_{TX} + h_{RX}\right)^2}$$

$$\Delta d = d_{refl} - d_{direct}$$

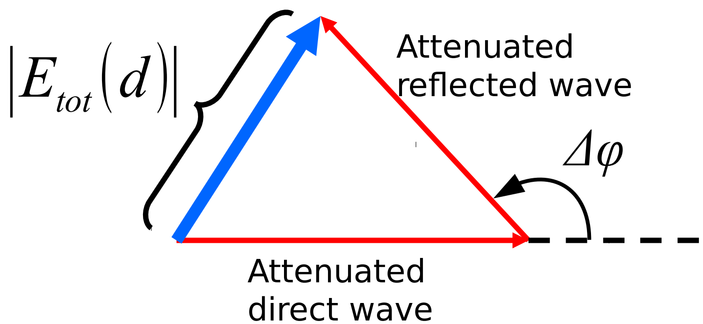
Phase difference at RX antenna:

$$\Delta\varphi = 2\pi \frac{\Delta d}{\lambda} + \pi = 2\pi \left(f \frac{\Delta d}{c} + \frac{1}{2} \right)$$

Propagation over ground plane
Geometry

What happens when the two waves are combined?

Vector addition of electric fields



Taking the free-space propagation losses into account for each wave, the exact expression becomes rather complicated.

Assuming equal free-space attenuation on the two waves we get:

$$|E_{tot}(d)| = |E(d)| \times |1 + e^{j\Delta\varphi}|$$

Free space attenuated — Extra attenuation

Finally, after applying an approximation of the phase difference:

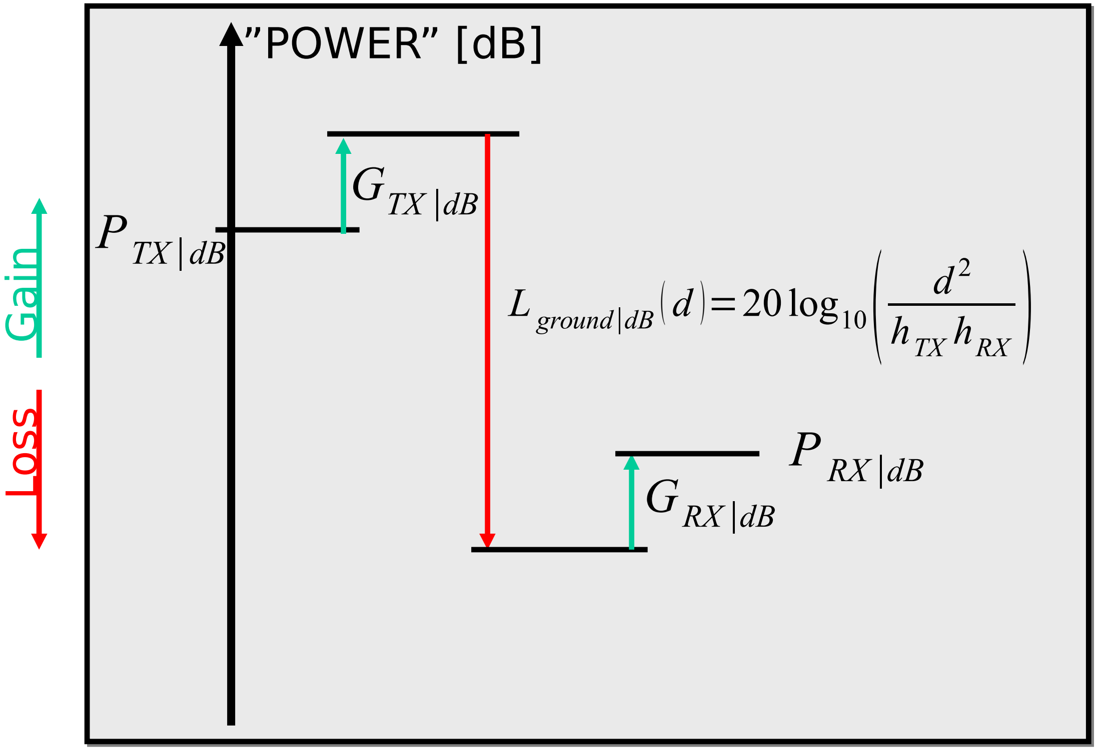
$$L_{ground}(d) \approx \left(\frac{4\pi d}{\lambda}\right)^2 \left(\frac{\lambda d}{4\pi h_{TX} h_{RX}}\right)^2 = \frac{d^4}{h_{TX}^2 h_{RX}^2}$$

Approximation valid beyond:

$$d_{\text{limit}} \geq \frac{4 h_{TX} h_{RX}}{\lambda}$$

Propagation over ground plane
Non-isotropic antennas

Let's put L_{ground} into the link budget

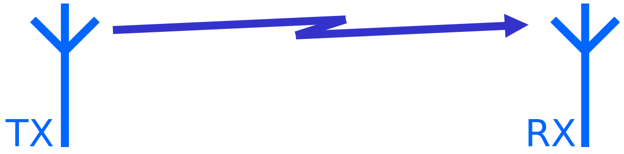


Received power decreases as $1/d^4$, which means a **propagation exponent** of $n = 4$.

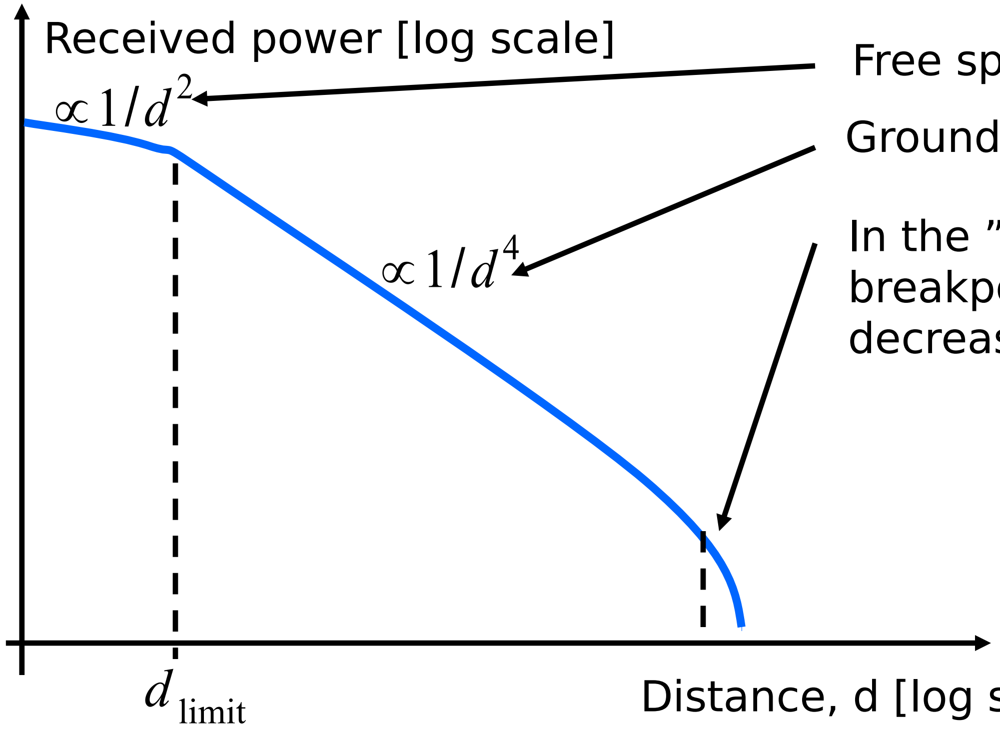
There is no frequency dependence on the propagation attenuation, which was the case for free space.

$$P_{RX|dB}(d) = P_{TX|dB} + G_{TX|dB} - L_{ground|dB}(d) + G_{RX|dB}$$

Rough comparison to ”real world”



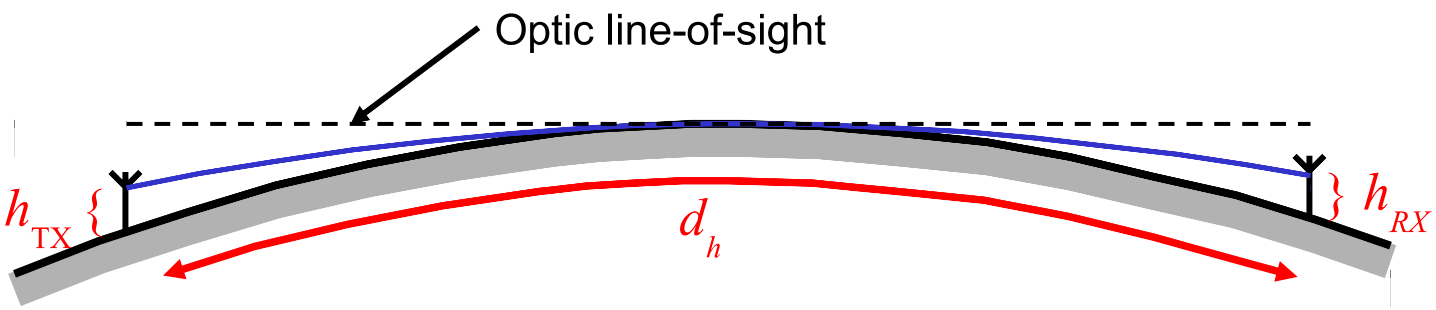
We have tried to explain ”real world” propagation loss using theoretical models.



In the ”real world” there is one more breakpoint, where the received power decreases much faster than $1/d^4$.

Rough comparison to ”real world” (cont.)

One thing that we have not taken into account: **Curvature of earth**!



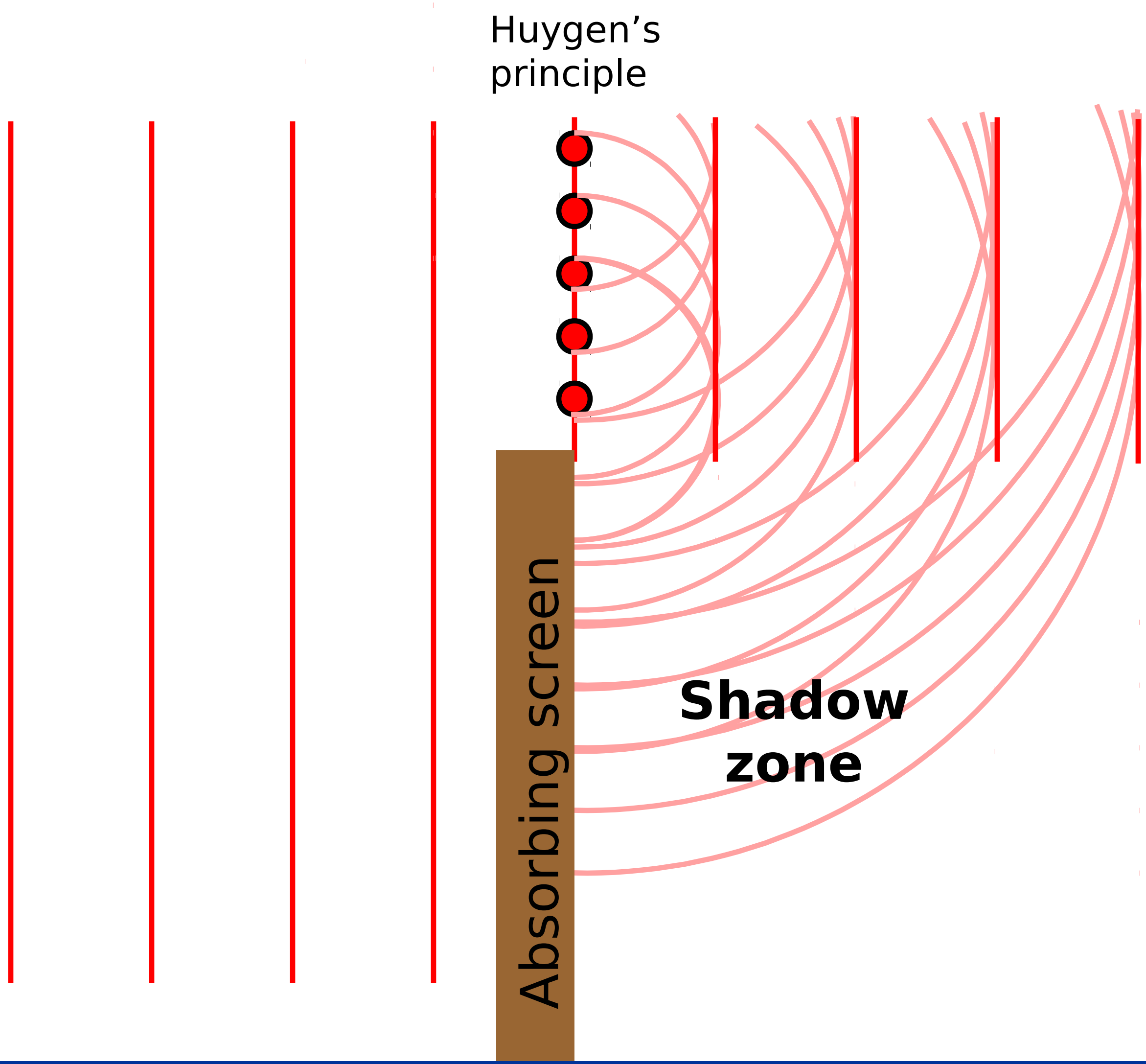
An approximation of the radio horizon:

$$d_h \approx 4.1 \left(\sqrt{h_{TX|m}} + \sqrt{h_{RX|m}} \right) \Big|_{km}$$

beyond which received power decays very rapidly.

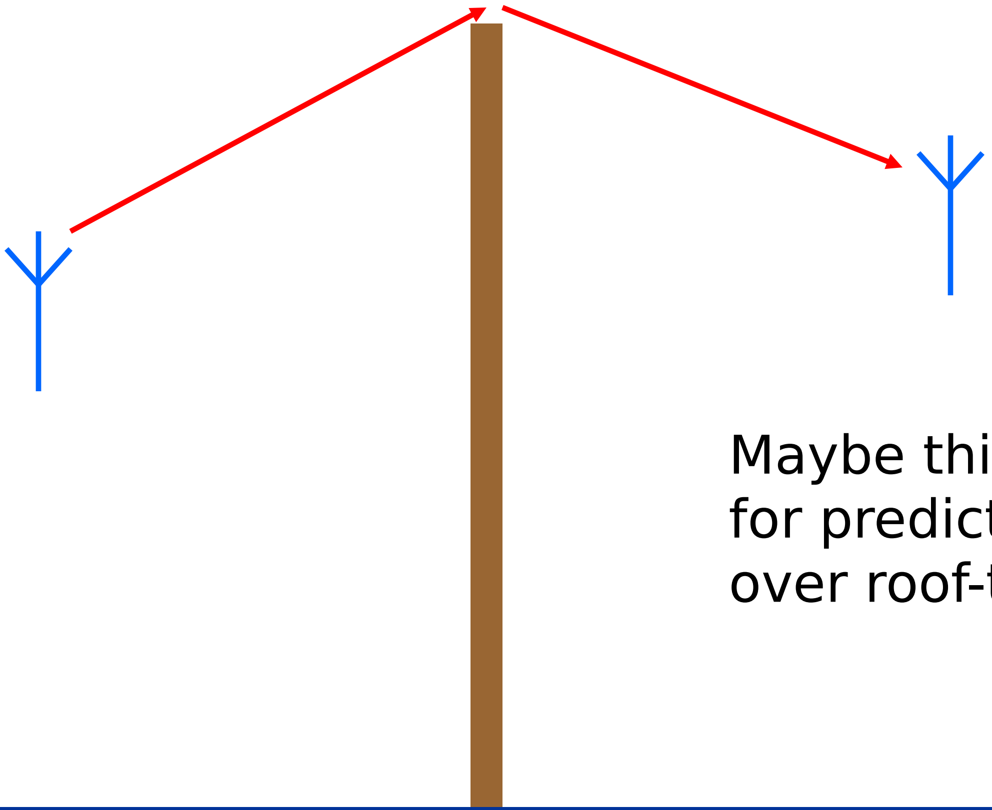
DIFFRACTION

Diffraction
Absorbing screen



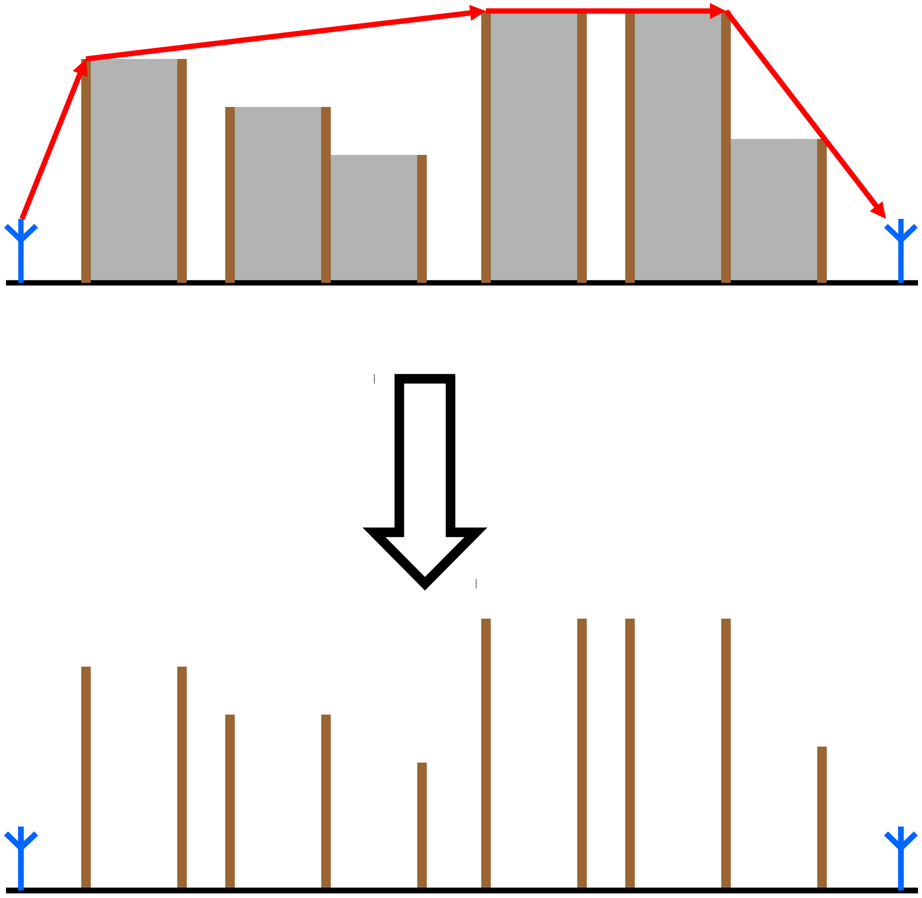
Diffraction
Absorbing screen (cont.)

For the case of one screen we have exact solutions or good approximations



Maybe this is a good solution for predicting propagation over roof-tops?

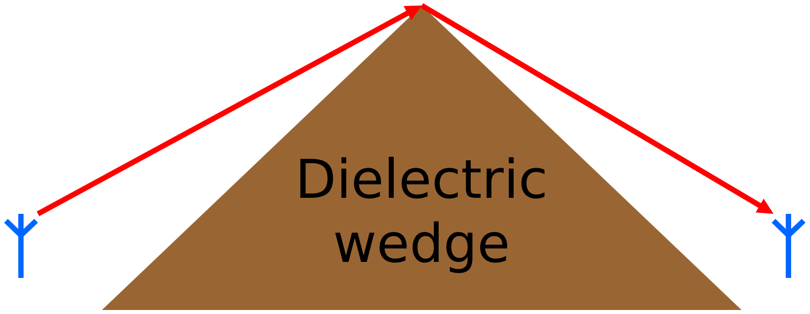
Diffraction
Approximating buildnings



There are no solutions for multiple screens, except for very special cases!

Several approximations of varying quality exist.
[See textbook]

Diffraction
Wedges

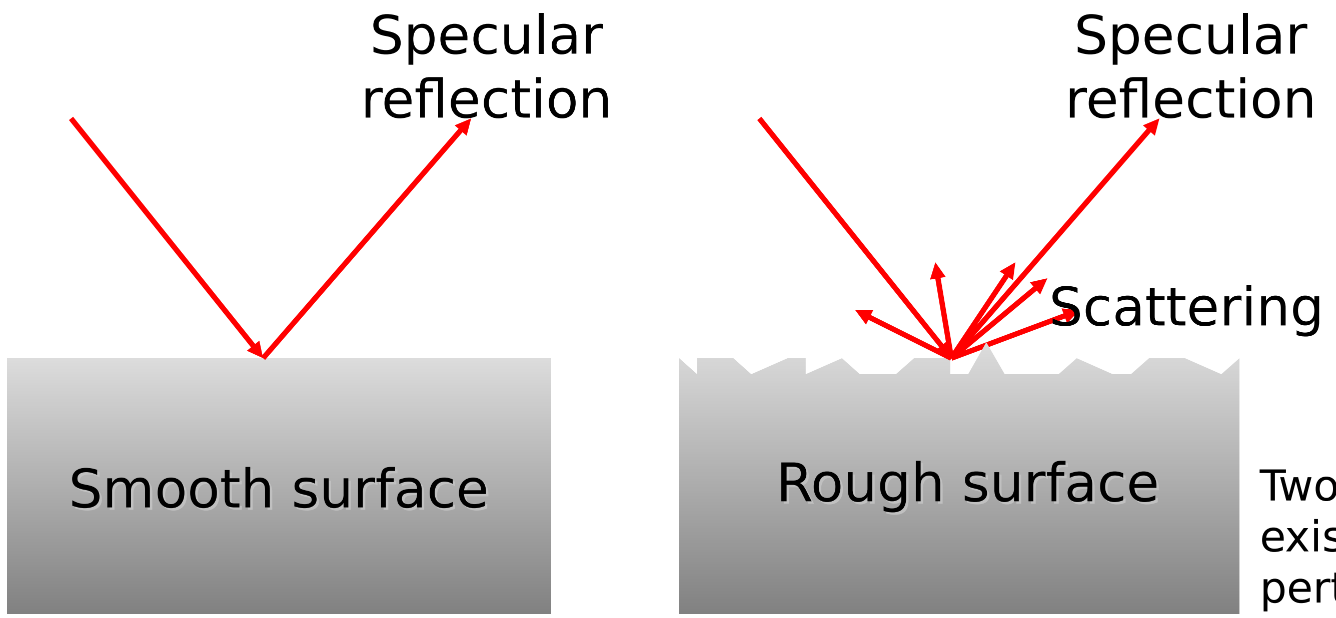


Reasonably simple far-field approximations exist.

Can be used to model terrain or obstacles

SCATTERING BY ROUGH SURFACES

Scattering by rough surfaces
Scattering mechanism



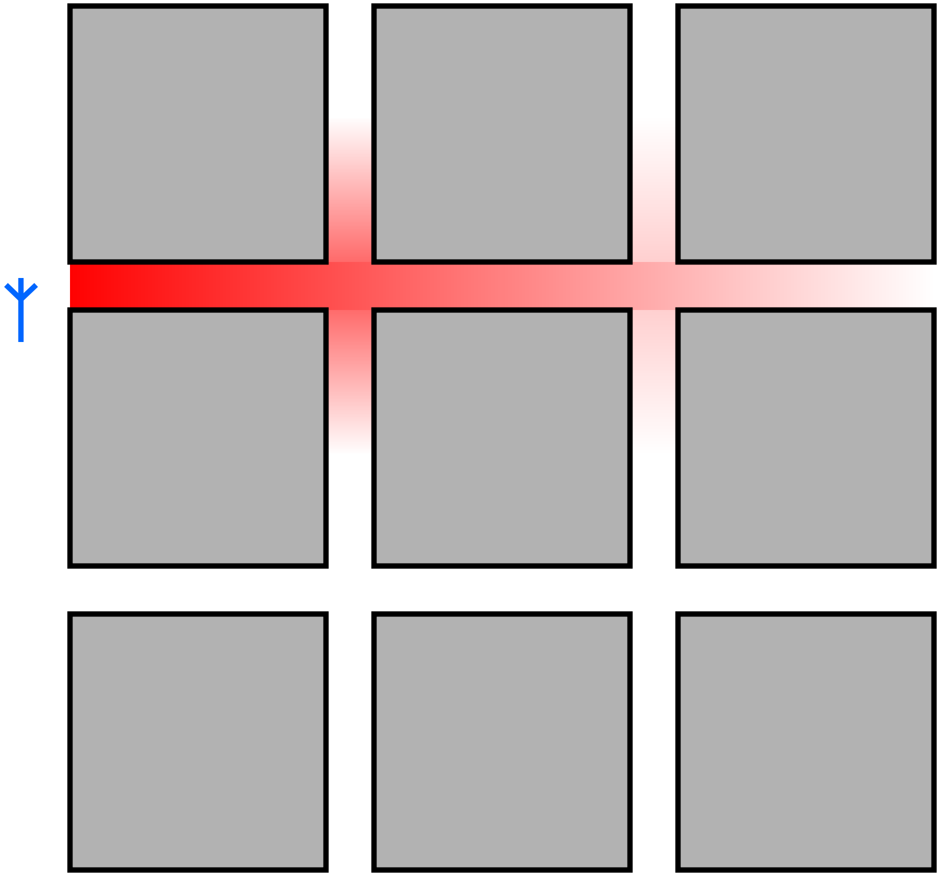
Two main theories exist: Kirchhoff and pertubation.

Both rely on statistical descriptions of the surface height.

Due to the ”roughness” of the surface, some of the power of the specular reflection lost and is scattered in other directions.

WAVEGUIDING

Waveguiding
Street canyons, corridors & tunnels



Conventional waveguide theory predicts exponential loss with distance.

The waveguides in a radio environment are different:

- Lossy materials
- Not continuous walls
- Rough surfaces
- Filled with metallic and dielectric obstacles

Majority of measurements fit the $1/d^n$ law.

Summary

- Some **dB** calculations
- Antenna **gain** and **effective area**.
- Propagation in **free space**, **Friis' law** and **Rayleigh distance**.
- Propagation over a **ground plane.**
- Diffraction
  - Screens
  - Wedges
  - Multiple screens
- Scattering by rough surfaces
- Waveguiding