Telecommunicatie A (EE2T11)

Lecture 3 overview:

Signal propagation

- Received signal power:
  *** propagation of radio signals: free-space loss**
  *** antenna gain**
  *** wireless v.s. cable transmission**

- Noise in communication systems
  *** noise power v.s. noise temperature**
  *** equivalent noise temperature**
  *** Noise Figure**

EE2T11 Telecommunicatie A

Dr.ir. Gerard J.M. Janssen

February 1, 2016

Faculty of Electrical Engineering, Mathematics, and Computer Science

TU Delft

Colleges en Werkcolleges Telecommunicatie A

Colleges:

Maandag	22-2, 7-3, 21-3	5^e en 6^e uur, EWI-Pi
Dinsdag	1-3, 15-3	7^e en 8^e uur, EWI-Pi

Werkcolleges:

Maandag	29-2, 14-3, 4-4	5^e en 6^e uur, EWI-Pi

Signal quality

Signal quality is determined by:

- received signal power
- noise- and interference power at the receiver input

Quality measure: Signal-to-Noise Ratio (SNR) also indicated as Carrier-to-Noise ratio at the detector input

$$\frac{C}{N} = \frac{\text{received signal power}}{\text{noise power}}$$

Determines: - SNR after detection for analog signals

- bit error probability (BER) for digital signals

Wireless transmission

In radio communication EM-waves are used to transport information without using cables:
$\Rightarrow$ wireless communication.

The signals can be received at many locations.
Radio communication is especially suited to reach a receiver without precisely known location.

Frequency bandwidth in the radio spectrum is a scarce resource and therefore expensive: it has to be used as efficiently as possible.

Wireless communication system

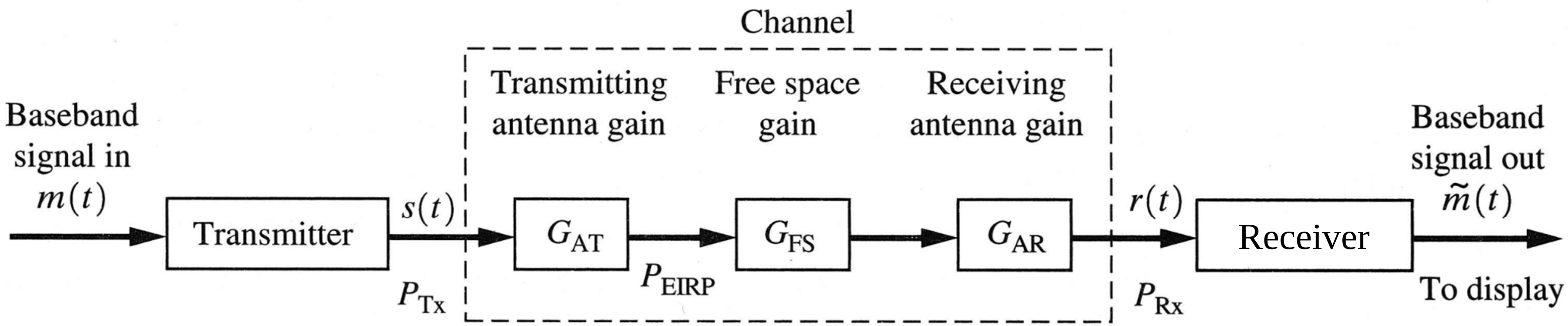


Figure 8–16 Block diagram of a communication system with a free-space transmission channel.

Electromagnetic waves

EM-waves were:

* predicted by James Clark Maxwell in 1864
* demonstrated by Heinrich Hertz in 1887

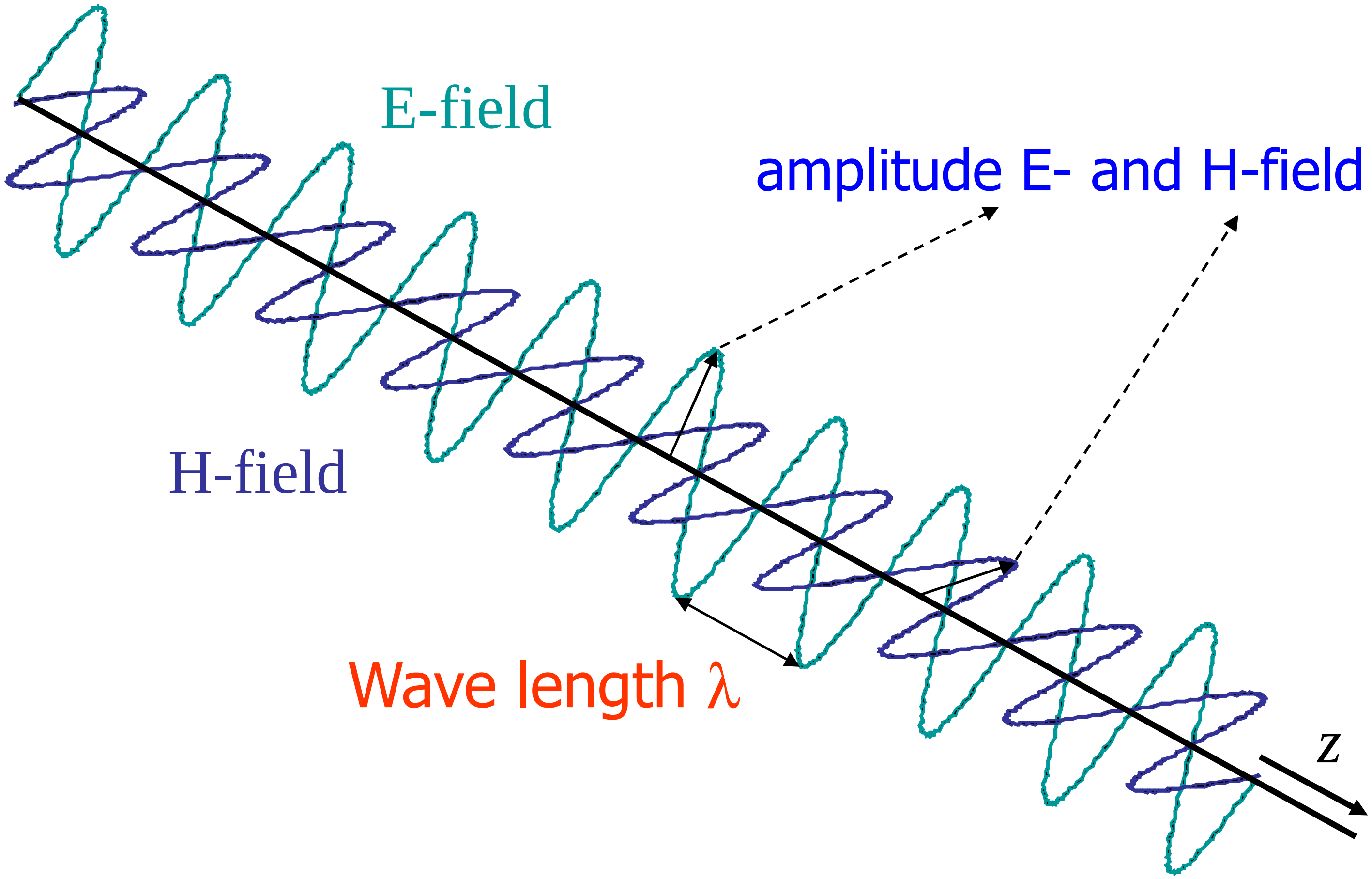
EM-waves propagated through the atmosphere (even through vacuum) with a speed of:

$$c \approx 3 \cdot 10^8 \text{ m/s} \Rightarrow$$ *speed of light*.

TU Delft

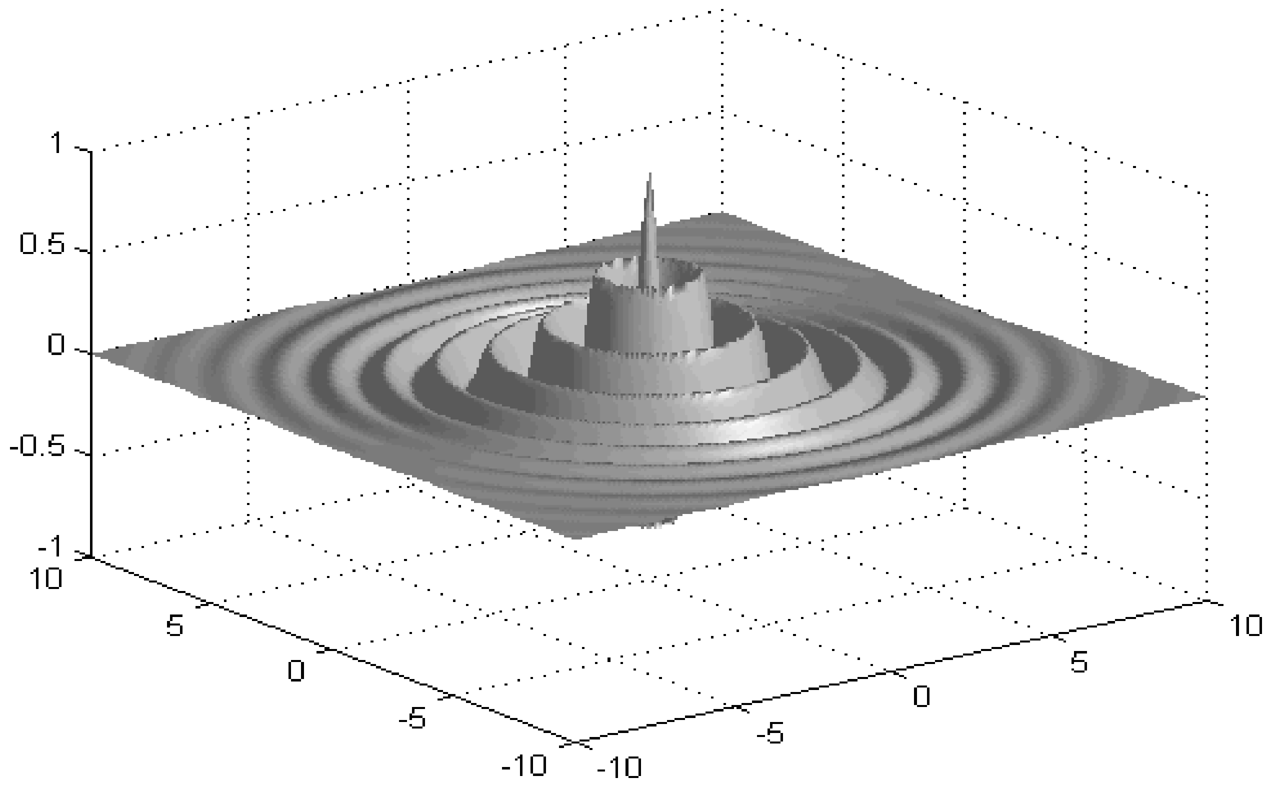
Propagation of EM-waves (1)

Impression of EM-wave propagation in vacuum



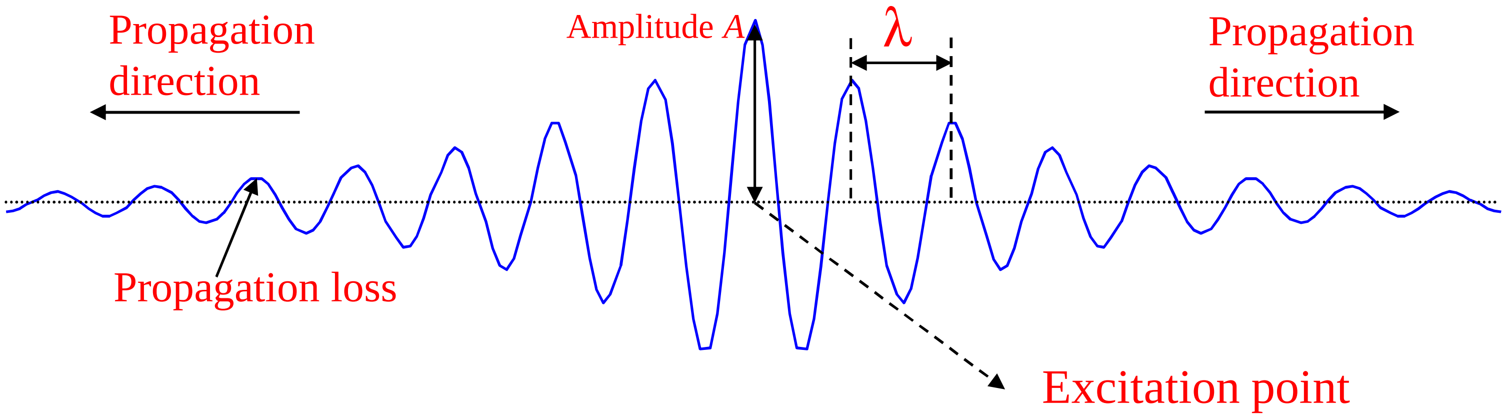
Propagation of EM-waves (2)

Analogy of wave propagation at the water surface:



TU Delft

Wave characteristics

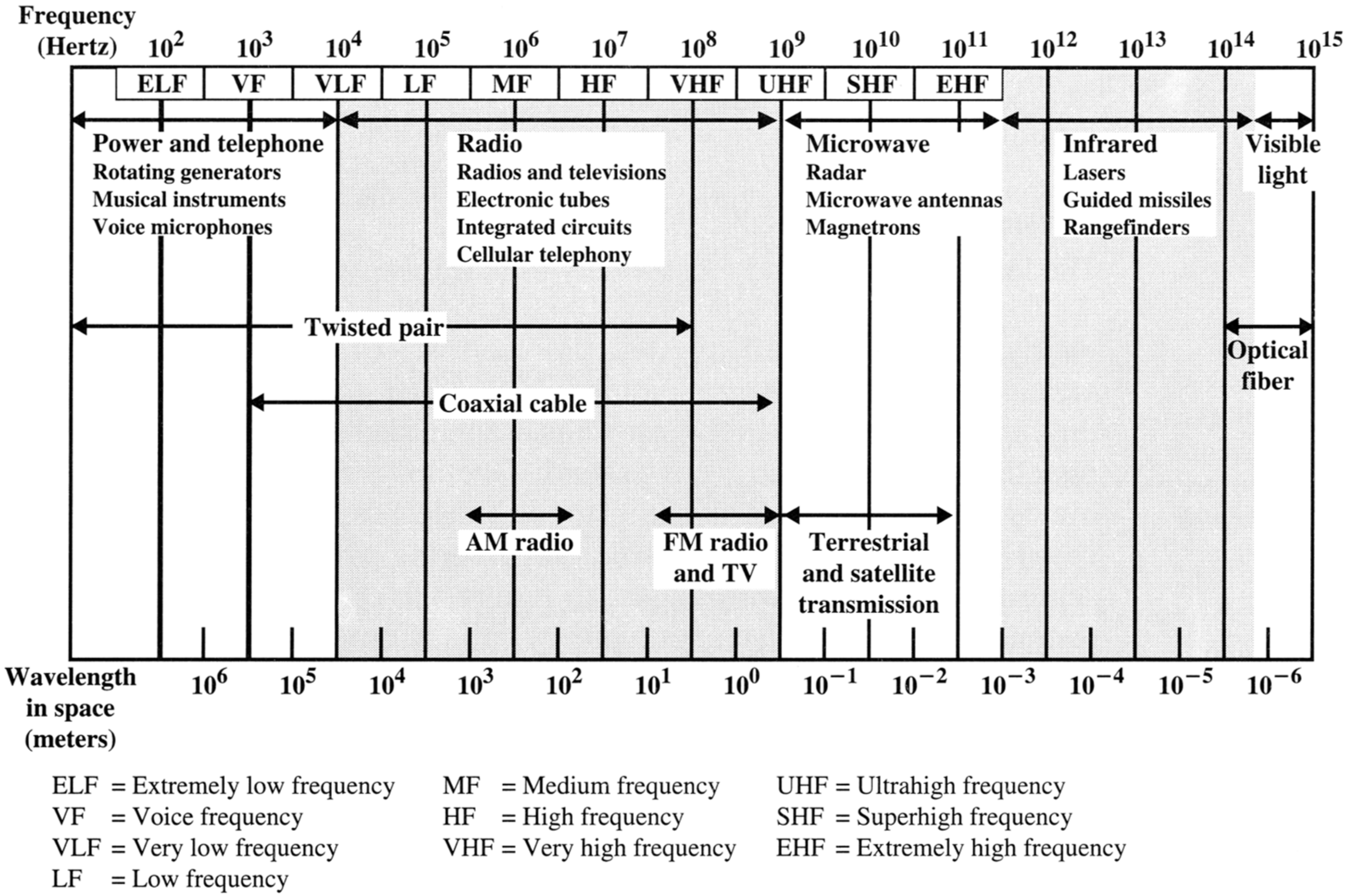


Fundamental relation between frequency f [Hz], wave length λ [m] and propagation speed c [m/s]:

$$\lambda = \frac{c}{f}$$

TU Delft

Frequency bands (1)



The electro-magnetic spectrum and its use in telecommunications.
(*Business Data Communications*, W. Stallings)

Frequency bands (2)

Name	Band	Wave length λ
LF	30 - 300 kHz	10 - 1 km
MF	300 - 3000 kHz	1 - 0.1 km
HF	3 - 30 MHz	100 - 10 m
VHF	30 - 300 MHz	10 - 1 m
UHF	300 - 3000 MHz	100 - 10 cm
SHF	3 - 30 GHz	10 - 1 cm
EHF	30 - 300 GHz	10 - 1 mm
THF	300 - 3000 GHz	1 - 0.1 mm

Antennas (1)

The antenna is a transducer:
- an electrical signal is converted into an electromagnetic wave and vice versa
- it is the interface between a guided medium (usually a cable) and the free space

But … it is also a means to focus the transmitted energy!

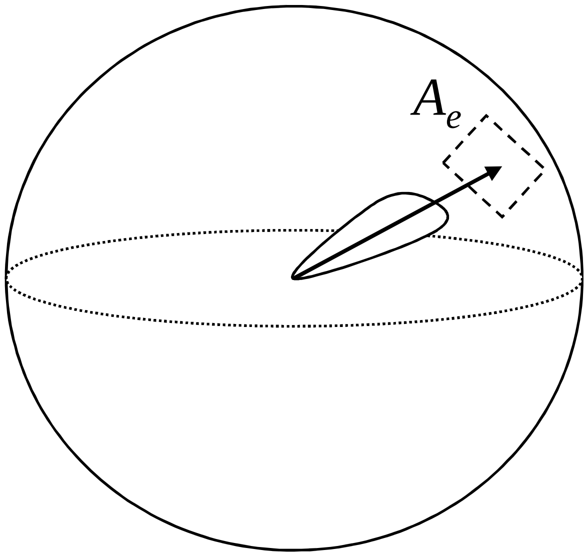
The *isotropic antenna* is a hypothetical antenna which radiates the signal power uniformly dispersed in all directions.

By definition, the gain of the *isotropic antenna* equals:

$$G_{iso} \triangleq 1 \equiv 0 \text{ dB}$$

Antennas (2)

The transmitted EM-power is dispersed over the 3-dimensional space. This dispersion is the cause of free-space attenuation of the signal power.



$$\text{EM-flux: } S = \frac{P_{TX}}{4\pi d^2} \quad [\text{W/m}^2]$$

The power density (flux) S is the power which passes a 1 m^2 surface at a distance d from the transmitter.

Antennes (3)

In practice, the antenna will concentrate the transmitted power in certain directions. The antenna gain is direction dependent:

$$G_{ant} = G(\theta, \phi)$$

(θ = elevation, ϕ = azimuth).

The antenna gain G_{ant} is defined as the maximum of $G(\theta, \phi)$:

$$G_{ant} \triangleq \frac{\text{power density in the direction of the maximum } G(\theta, \phi)}{\text{power density of the isotropic antenna}}$$

for equal input powers.

Antennas (4)

Effective isotropic radiated power: *EIRP*

$$P_{EIRP} = G_{AT} \cdot P_{in}$$

To obtain the same power density (or *flux*) with an isotropic antenna, we need to increase the input power with a factor G_{AT}, the gain of the transmit antenna.

$$S = \frac{P_{EIRP}}{4\pi d^2} = \frac{P_{in} \cdot G_{AT}}{4\pi d^2} \quad [\mathrm{W/m^2}]$$

Reciprocity

The received signal power:

$$P_{RX} = S \cdot A_{e\_AR} = \frac{P_{TX} \cdot G_{AT}}{4\pi d^2} A_{e\_AR} = \frac{P_{EIRP}}{4\pi d^2} A_{e\_AR}$$

where A_{e_RX} is the effective area of the receive antenna.

Reciprocity:

When transmitter and receiver change role in a transmission system, while the other system parameters remain the same, the received signal power does not change.

$\Rightarrow$ *the link is reciprocal*

Implication: the power gain of an antenna is independent of use of the antenna as a transmit- or receive antenna.

Antennas (5)

The relation between the (effective) antenna area A_e and the antenna gain is given by:

$$A_e = \frac{G \cdot \lambda^2}{4\pi} \quad \Leftrightarrow \quad G = \frac{4\pi \cdot A_e}{\lambda^2}$$

Now, it follows for the effective area of the isotropic antenna:

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

Thus, for a fixed A_e the antenna gain is frequency dependent.

Antennas (6)

TABLE 8–4 ANTENNA GAINS AND EFFECTIVE AREAS

Type of Antenna	Power Gain, G_A (absolute units)	Effective Area, A_e (m^2)
Isotropic	1	$\lambda^2/4\pi$
Infinitesimal dipole or loop	1.5	$1.5\lambda^2/4\pi$
Half-wave dipole	1.64	$1.64\lambda^2/4\pi$
Horn (optimized), mouth area, A	$10A/\lambda^2$	$0.81A$
Parabola or "dish" with face area, A	$7.0A/\lambda^2$	$0.56A$
Turnstile (two crossed dipoles fed 90° out of phase)	1.15	$1.15\lambda^2/4\pi$

$A_e = \eta A$ $\qquad$ $\eta =$ efficiency factor

$A =$ physical area $\qquad$ $A_e =$ effective area

Free-space loss

The received signal power is now:

$$P_{RX} = \frac{P_{EIRP} \cdot A_e}{4\pi d^2} = \frac{P_{TX} \cdot G_{AT}}{4\pi d^2} \cdot \frac{G_{AR} \cdot \lambda^2}{4\pi}$$

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

Free-space gain: G_{FS}

The free-space loss is defined as:

$$L_{FS} \triangleq \frac{1}{G_{FS}} = \left(\frac{4\pi d}{\lambda} \right)^2$$

Note: L_{FS} depends on the distance as well as the used frequency.

TU Delft

Exercise: antenna gain

A parabolic antenna has a diameter of 1 m. Due to the "shadow" of the support of the feed and diffraction at the edges, the effective area is reduced to 75% of the physical area.

Calculate the antenna gain in dB at the frequencies:

- f = 1 GHz
- f = 2 GHz
- f = 12 GHz

Exercise: antenna gain

For: - f = 1 GHz $\Rightarrow \quad \lambda = 0.30\ \mathrm{m}$

- f = 2 GHz $\Rightarrow \quad \lambda = 0.15\ \mathrm{m}$
- f = 12 GHz $\Rightarrow \quad \lambda = 0.025\ \mathrm{m}$

efficiency factor

The antenna gain is given by:

$$G_{ant} = \frac{4\pi A_e}{\lambda^2} = \eta \frac{4\pi A}{\lambda^2} \qquad A_e = \eta A = \eta \cdot \pi R^2 = \frac{3}{4}\frac{\pi}{4} m^2$$

$$= \frac{3}{4}\frac{4\pi \frac{\pi}{4}}{c^2} f^2 = 8.22 \cdot 10^{-17} f^2$$

$$G_{ant}(1\ \mathrm{GHz}) = 82.25 \equiv 19.15\ \mathrm{dB}$$

$$G_{ant}(2\ \mathrm{GHz}) = 329 \equiv 25.15\ \mathrm{dB}$$

$$G_{ant}(12\ \mathrm{GHz}) = 11844 \equiv 40.73\ \mathrm{dB}$$

Causes of propagation loss

A number of physical phenomena result in signal power loss or even complete extinction of the radio signal:

- free-space loss
- radio horizon
- atmospheric absorption
- reflection and refraction (buiging)

Free-space loss

Free-space loss is a fundamental cause of power loss in radio signal propagation due to spatial dispersion of the transmitted power.

The free-space attenuation:

$$L_{FS} = \left(\frac{4\pi d}{\lambda}\right)^2 \equiv 10\log_{10}\left(\frac{4\pi d}{\lambda}\right)^2 = 20\log_{10}\frac{4\pi d}{\lambda} \quad [\mathrm{dB}]$$

increases with f^2 and d^2.

A doubling of the distance d results in an increase of the attenuation with 6 dB (a factor 4).

TU Delft

Interaction with the environment

While propagating, radio waves interact with the environment: reflection, diffraction, refraction, absorption, etc.

This results in a larger attenuation than in free-space:

$$L = \left(\frac{4\pi d}{\lambda}\right)^{\alpha} \equiv 10\alpha \log_{10}\left(\frac{4\pi d}{\lambda}\right) \text{ [dB]}$$

α = path-loss exponent

$\alpha = 2 \Rightarrow$ Free-space

with:

α = 3 - 5 in an urban environment (mobile communication),

α = 1.5 - 6 in an indoor environment (indoor communication).

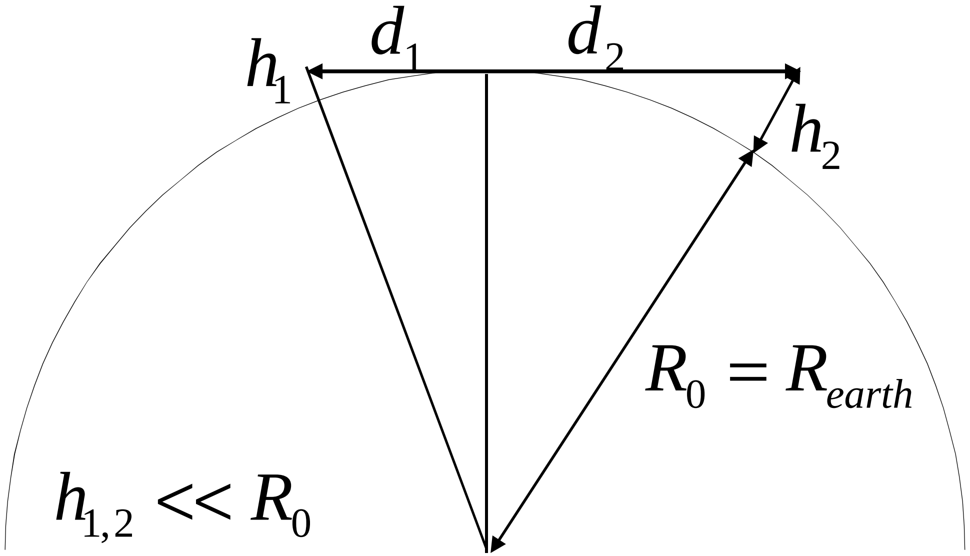
Radio-horizon

In free-space, EM-waves behave like light: they propagate in a straight line. This principle also holds when the wave length is small compared to the obstacles that are present.

Because the earth is spherical, a transmitted signal will move away from the surface with increasing distance to the transmitter, and therefore can only be received up to a certain distance: the radio-horizon.

The radio-horizon is determined by the height of the transmit- and receive antennas.

Radio-horizon



The distance d_1 can be approximated by:

$$(R_0 + h_1)^2 = R_0^2 + d_1^2$$

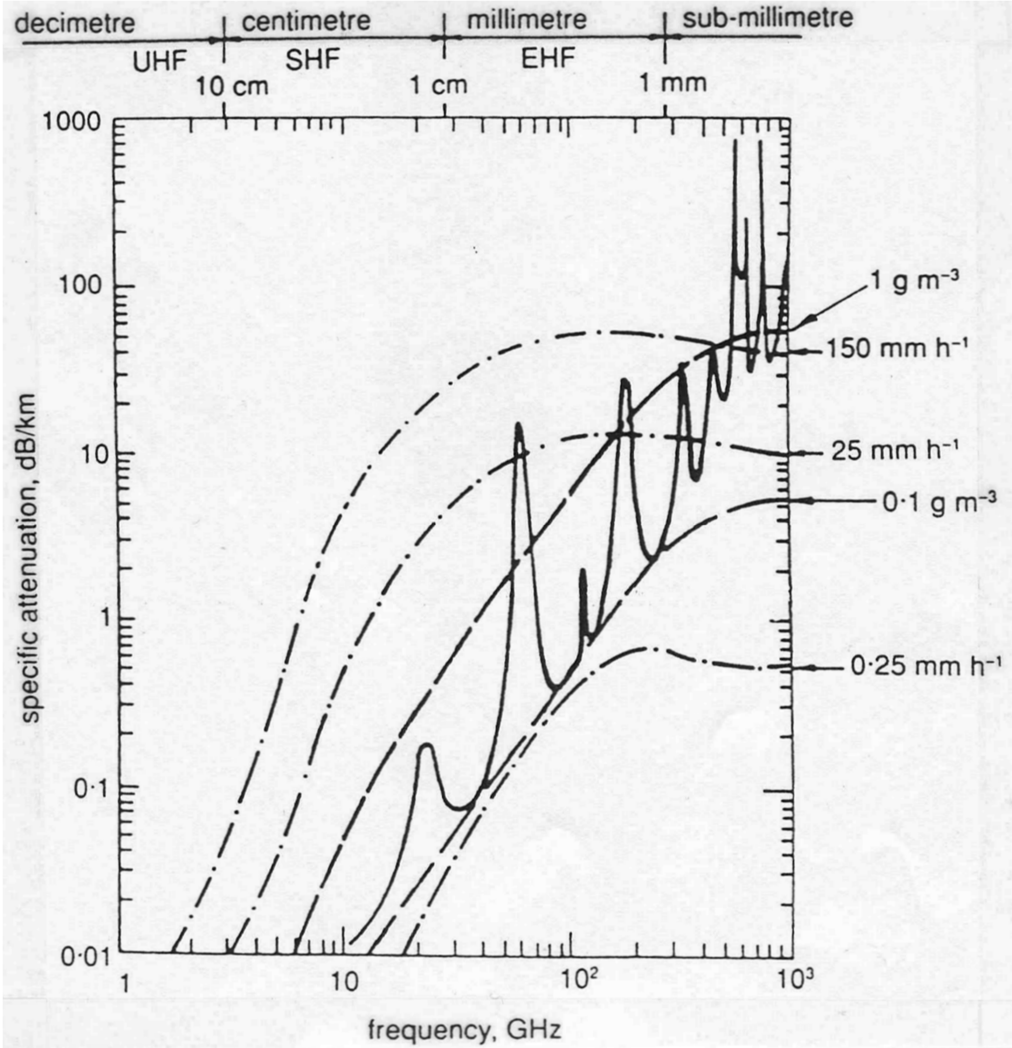
$$d_1^2 = h_1^2 + 2h_1R_0$$

$$d_1 \approx \sqrt{2h_1R_0}$$

The radio-horizon is now given by:

$$d = d_1 + d_2 \approx \sqrt{2h_1R_0} + \sqrt{2h_2R_0}$$

Atmospheric absorption



Comparison of specific attenuation due to gasses (—), rain (-.-,-) and fog(----).

Guided transmission

In guided transmission, the information is transported by EM-energy which is "captured" in a cable or optical fibre:

$\Rightarrow$ wired communication.

The signal can only be received at a location connected to the cable carrying the signal: cable communication is only applicable if the receiver location is known.

The capacity of a cable depends on the type of cable. Installment of a cable connection is very expensive.

Cable attenuation

Let the voltage gain of a cable with length l be g *(g<1).*

This corresponds to a power gain: $G = g^2$
or

$$G_{dB} = 10 \cdot \log_{10} g^2 = 20 \cdot \log_{10} g = \alpha \text{ [dB]}$$

For a cable with length $m \cdot l$:

- the amplitude gain is: $g(m) = g^m$
- the power gain is:

$$G_{dB}(m) = 10 \cdot \log_{10} g^{2m} = m \cdot \alpha \text{ [dB]}$$

Thus, the cable loss in [dB] linearly increases with cable length.

Exercise: cable v.s. wireless transmission (1)

Compare signal power attenuation due to propagation loss for a transmitted signal with a frequency of 200 MHz for:

- free-space transmission with transmitter and receiver antenna gains: $G_{TX} = G_{RX} = 10 \text{ dB}$

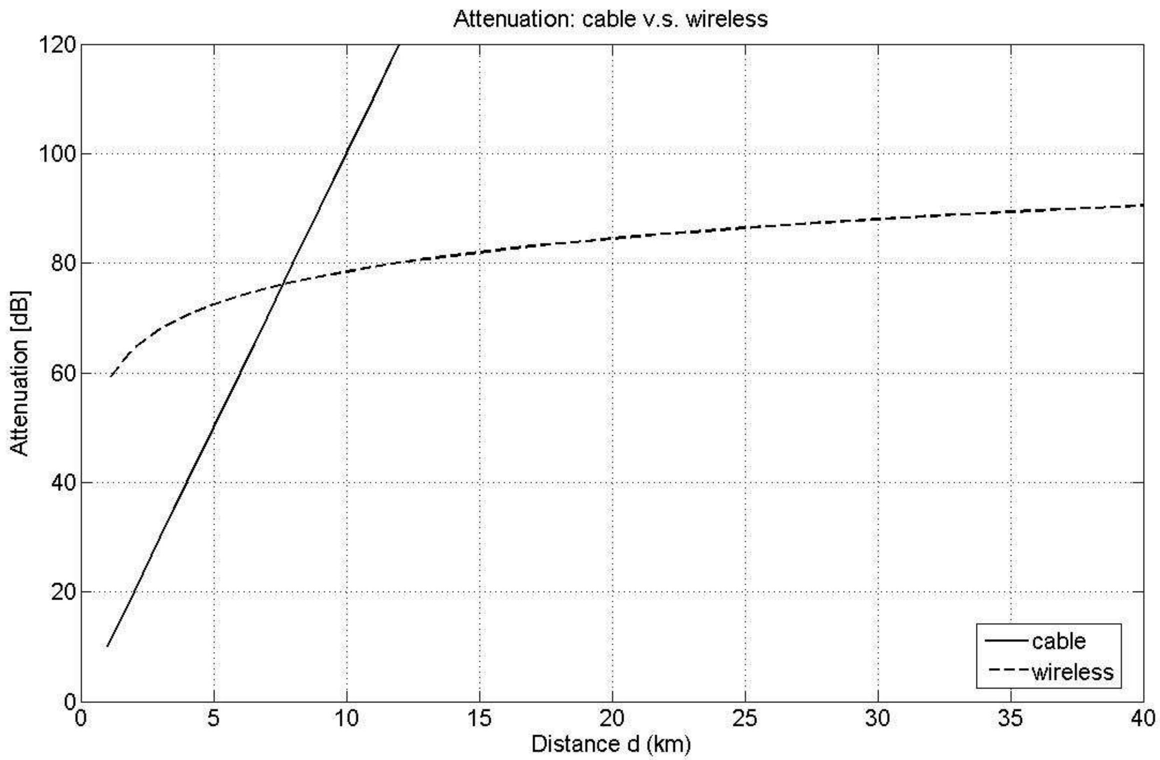
- cable transmission with a cable attenuation of 10 dB/km at 200 MHz

as a function of the distance d for d = 0 - 40 km

What is your conclusion?

TU Delft

Exercise: cable v.s. wireless transmission (2)



$$L_{FS} = 20 \cdot \log_{10}\left(\frac{4\pi \cdot d \cdot 1000}{\lambda}\right) - G_{TX} - G_{RX} \text{ [dB]}$$

$$L_{cable} = 10d \text{ [dB]}$$

with d in km

TU Delft

Noise (1)

Noise: fundamental physical limitation of the performance of telecommunication systems.

Sources of noise:

- thermal resistor noise
- noise caused in active components:
  shot noise, 1/f-noise, etc.
- noise like signals received by the antenna:
  * atmospheric noise
  * man-made noise
  * interference

Noise (2)

Thermal resistor noise: due to the random thermal movement of electrons a noise voltage is generated.

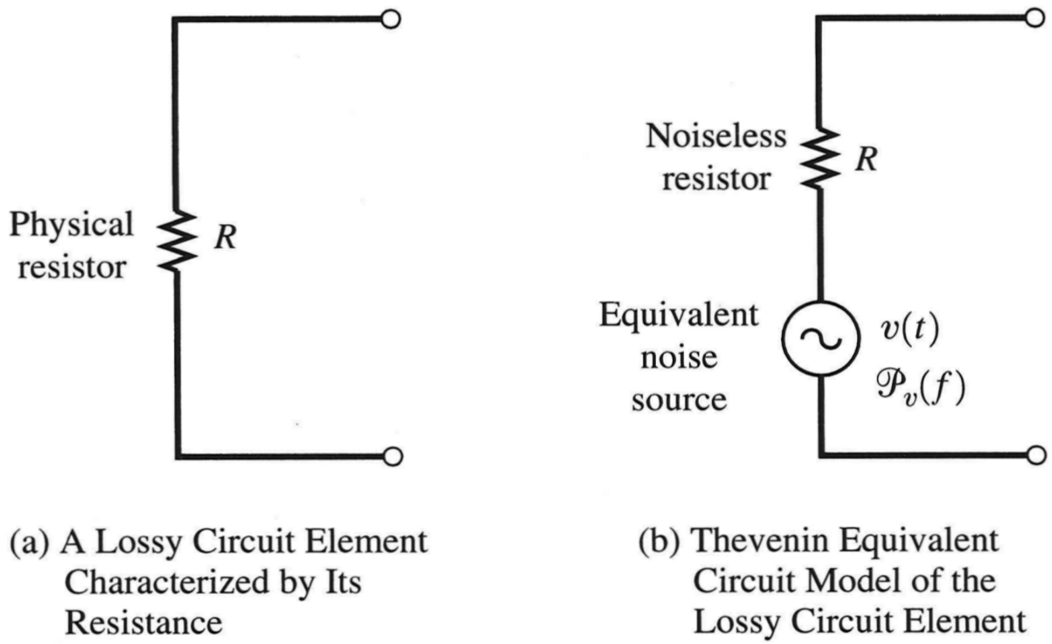


Figure 8–17 Thermal noise source.

This thermal noise voltage is very small, however, the same holds for the received signal of interest!

Without noise an infinitely small signal power would be sufficient for reliable communication: after "infinite" amplification reliable detection would be possible.

Noise Power Spectral Density (1)

Using quantum physics, the PSD of the noise voltage of a resistor at temperature T is given by:

$$P_v(f) = 2R\left[\frac{h|f|}{2} + \frac{h|f|}{\exp(h|f|/kT)-1}\right] \quad \text{[W/Hz]}$$

where: h : Planck's const., k = 1.38·10^{-23} [W/Hz K] Boltzmann's const., and T: absolute temperature [K].

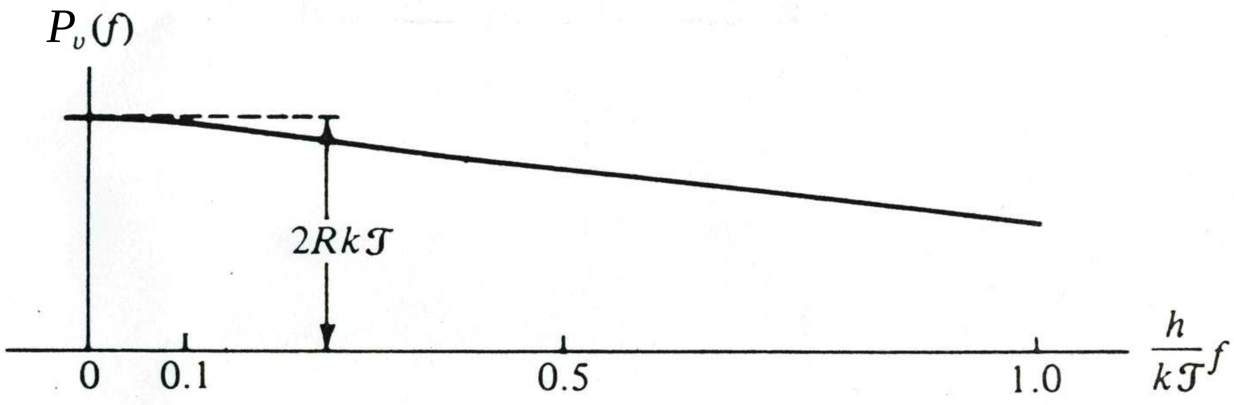


Figure 5.3-1 Thermal noise spectral density, V^2/Hz.

TU Delft

Noise Power Spectral Density (2)

For T = 290 K (room temperature) and f < 1000 GHz, we can apply the following approximation:

$$x = h|f|/kT < 0.2 \;\Rightarrow\; e^x \approx 1 + x$$

which results in:

$$P_v(f) \approx 2RkT \text{ [W/Hz]} \;\Rightarrow\; V(f) \approx \sqrt{2RkT}$$

In practice, this is a good approximation is T >> 0K.

$P_v(f)$ (double sided power spectral density) is independent of f $\Rightarrow$ a flat noise spectrum = white noise.

RMS noise voltage

The root-mean-square (RMS) noise voltage in an equivalent noise-bandwidth B_n is given by:

$$V_{rms} = \sqrt{\overline{V^2}} = \sqrt{2\int_0^{B_n} P_v(f)\,df} = \sqrt{4kTB_nR}$$

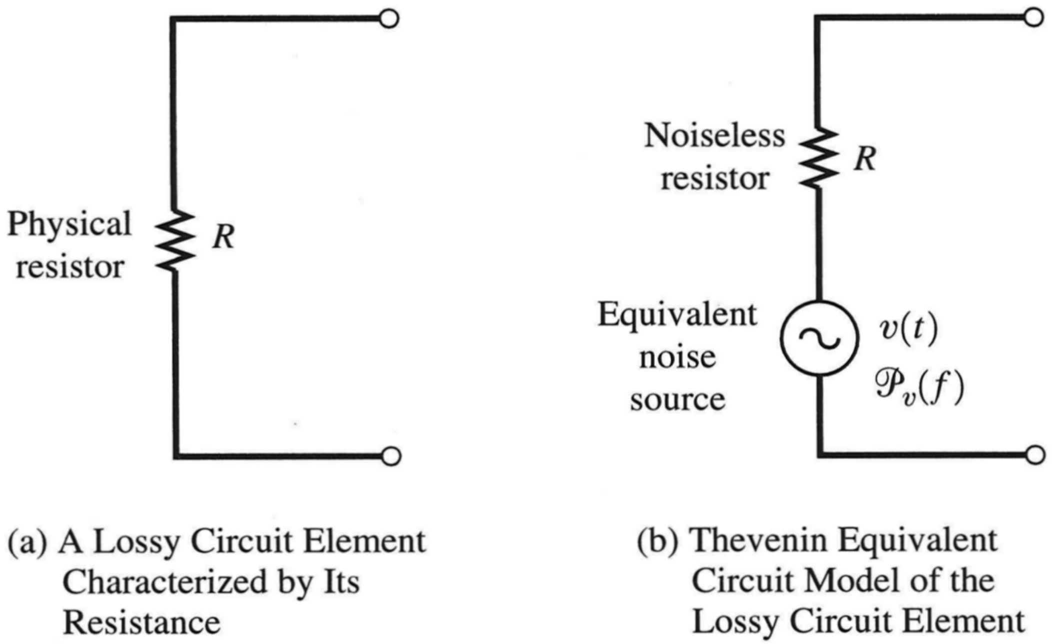


Figure 8–17 Thermal noise source.

Available noise power (1)

For $R_L = R$, the amplitude spectrum of the available noise power (transferred to the load) is equal to:

$$V_L(f) = \frac{V_v(f)}{2} \ [\mathrm{V}/\sqrt{\mathrm{Hz}}] = \tfrac{1}{2}\sqrt{2kTR}$$

double sided

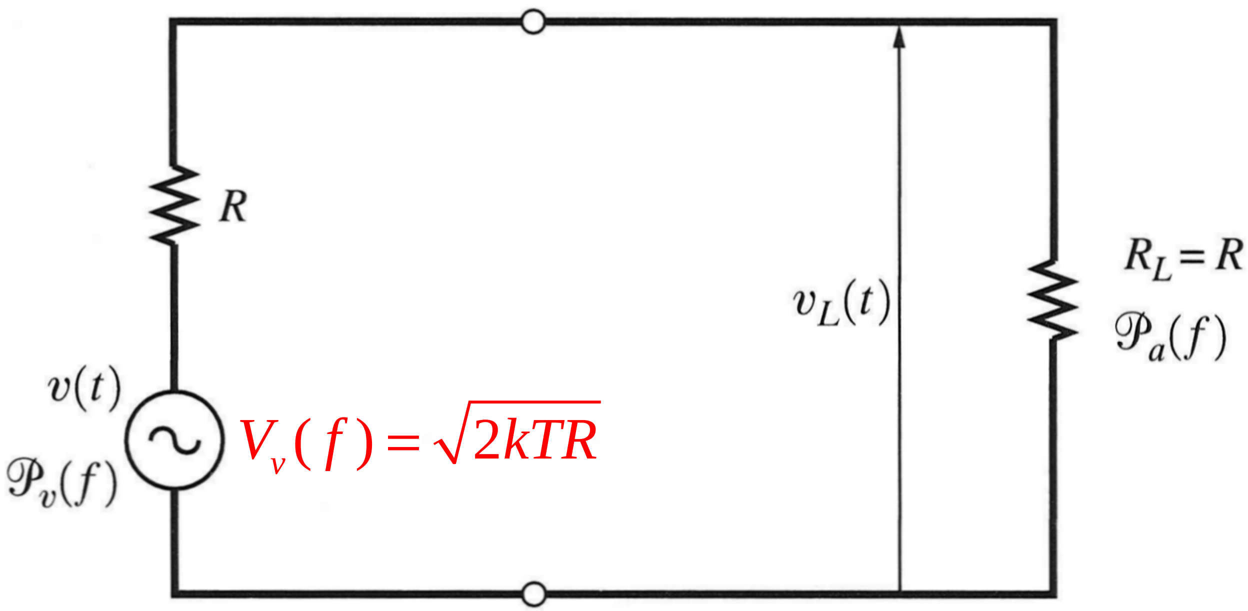


Figure 8–18 Thermal source with a matched load.

TU Delft

Available noise power (2)

For the PSD of the available noise, we can write:

$$P_a(f) = \frac{V_L^2(f)}{R} = \frac{V_v^2(f)}{4R} = \frac{kT}{2} \triangleq \frac{N_0}{2}$$

white noise

$N_0 = kT$ is the single sided noise power spectral density.

In general:

$$P_a(f) = \frac{P_v(f)|H(f)|^2}{R}$$

The available noise power is given by:

$$P_a = \int_{-B_n}^{B_n} P_a(f)df = kTB_n \text{ [W]}$$

- proportional with B_n and T
- independent of f and R

Note: 1. $P_a(f)$ and P_a are independent of R for a matched load,

2. for $B_n \to \infty \Rightarrow P_a \to \infty$ because of the "white noise approximation".

Equivalent noise temperature (1)

An arbitrary white noise source can be characterized by an equivalent noise temperature. We represent the source as a noise generating resistor at temperature:

$$\text{Equivalent noise temperature } T_n = \frac{P_a}{kB_n} = \frac{2P_a(f)}{k}$$

When the noise is not caused by thermal effects, T_n is not related to the physical temperature of the component.

Noise characterization of a linear device (1)

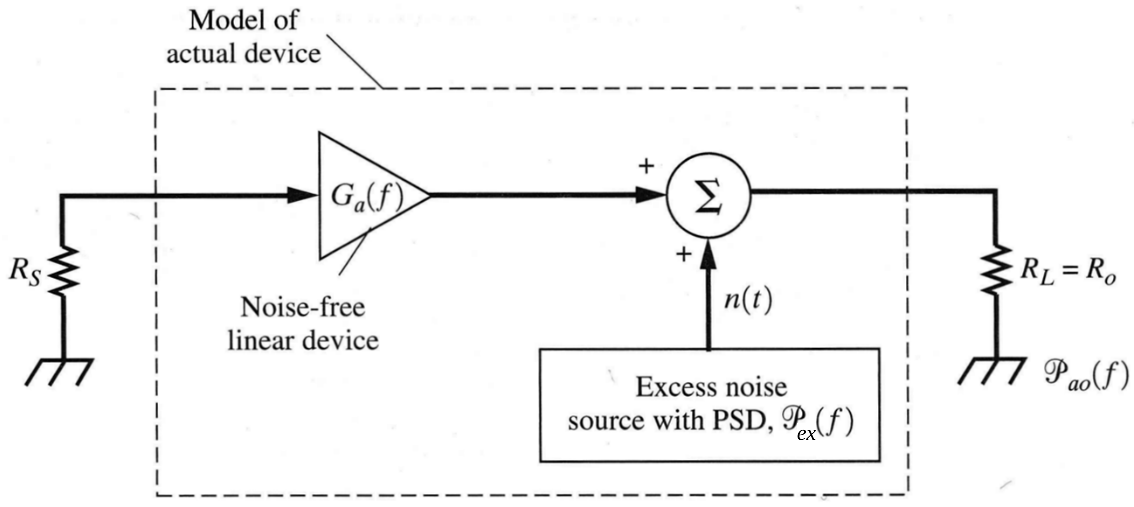


Figure 8–19 Noise model for an actual device.

The output noise of the device consists of the amplified input noise and excess noise P_{ex} added by the device:

$$P_{ao} = \underbrace{G_a P_{n\_in}}_{\text{input noise}} + \underbrace{P_{ex}}_{\text{noise added by the component}}$$

TUDelft

Noise characterization of a linear device (2)

When modeling a communication system, we prefer to work with noise-free components.

This can be obtained by replacing an actual component by its noise-free counterpart (with otherwise identical characteristics) and add an equivalent noise power to its input which results in the same output excess noise as with the actual device.

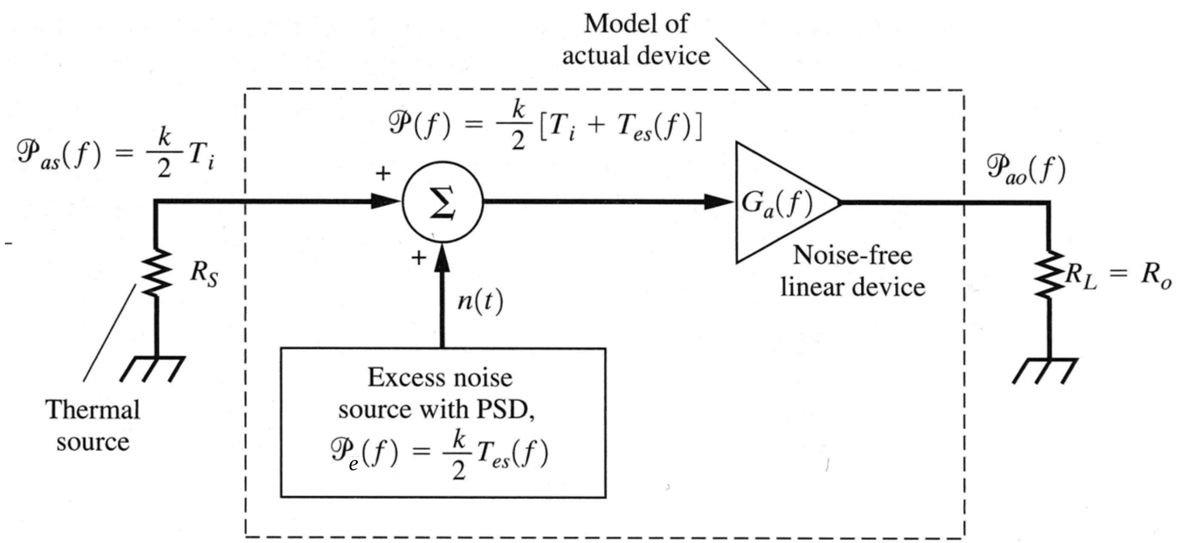


Figure 8–20 Another noise model for an actual device.

Noise characterization of a linear device (2)

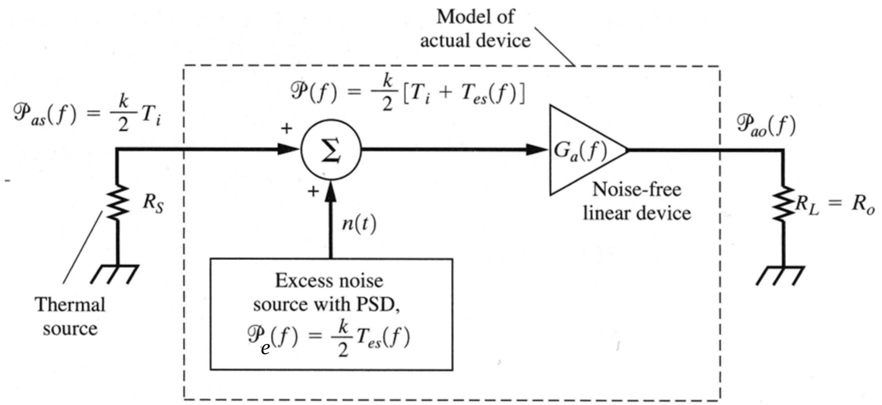


Figure 8–20 Another noise model for an actual device.

$$P_{ao} = G_a(P_{n\_in} + P_e) = G_a P_{n\_in} + P_{ex}$$

$$\Rightarrow \quad P_e \triangleq \frac{P_{ex}}{G_a}$$

The input noise powers P_{n_in} and P_e can now be represented by their equivalent noise temperatures [K]:

double sided noise spectral density

$$T_{n\_in} = \frac{P_{n\_in}}{kB_n} = \frac{2P_{n\_in}(f)}{k} \quad \text{and} \quad T_e = \frac{P_e}{kB_n} = \frac{P_{ex}}{kG_a B_n} = \frac{2P_e(f)}{k}$$

T_e can be seen as the additional temperature increase of the input resistor R_s that is required to obtain the same output noise power for the ideal noise-free device as for the actual device.

Noise characterization of a linear device (3)

The output noise power P_{ao} of the device, measured in an equivalent noise bandwidth B_n, can now be written as:

input resistor temperature, antenna noise temperature, etc.

$$P_{ao} = G_a \int_{-B_n}^{B_n} \frac{k(T_{n\_in} + T_e)}{2} df = k(T_{n\_in} + T_e) G_a B_n$$

and the equivalent noise temperature T_e is:

$$T_e = \frac{P_{ao} - kT_{n\_in} G_a B_n}{kG_a B_n} = \frac{P_{ex}}{kG_a B_n}$$

T_e = 0 implies a noise-free component

In general $G_a = G_a(f)$ and $T_e = T_e(f)$, so also $P_{ao}(f)$ are non-white due to filtering effects. However, in practical cases theses variables usually can be assumed frequency independent over the bandwidth of interest.

Noise Figure

In stead of the equivalent noise temperature, often the noise figure F or NF is used to characterize the noise contribution of a device, defined as:

$$F \triangleq \left. \frac{\text{output noise power}}{\text{output noise power ideal component}} \right|_{T_i = T_0 = 290\,K}$$

$$= \frac{k(T_0 + T_e)G_a B_n}{kT_0 G_a B_n} = \frac{T_0 + T_e}{T_0} = 1 + \frac{T_e}{T_0} \geq 1$$

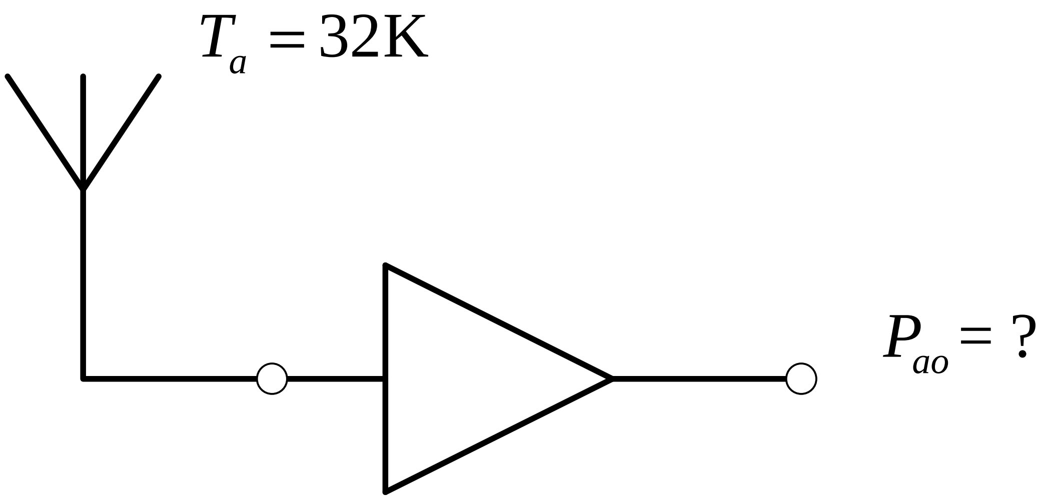
where T_0 = 290 K is an internationally agreed upon reference temperature: standard room temperature.

Note that F is the relative increase of the output noise power due to the noise generated by the device for $T_i = T_0$.

$$F_{dB} = 10 \cdot \log_{10}(1 + \frac{T_e}{T_0}) \geq 0 \text{ dB} \quad \text{and} \quad T_e = (F-1)T_0$$

TUDelft

Exercise: device noise (1)

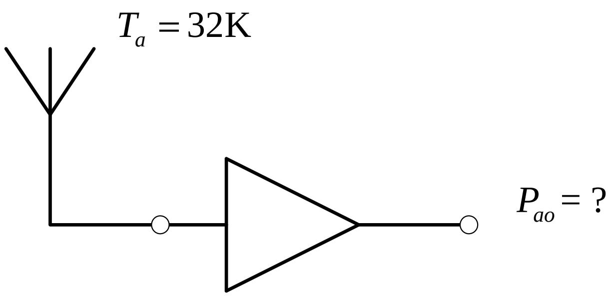


$$G_{amp} = 20 \text{ dB}$$

$$F_{amp} = 2 \text{ dB}$$

$$B_n = 1 \text{ MHz}$$

Exercise: device noise (2)



$G_{amp} = 20 \text{ dB} \equiv 100$

$F_{amp} = 2 \text{ dB} \equiv 1.58$

$B_n = 1 \text{ MHz}$

$$\left.\begin{aligned} T_e &= (F_{amp}-1)T_0 = 0.58\cdot 290 = 168 \text{ K} \\ T_{tot} &= T_a + T_e = 32 + 0.58\cdot 290 = 32 + 168 = 200 \text{ K} \end{aligned}\right\} \Rightarrow$$

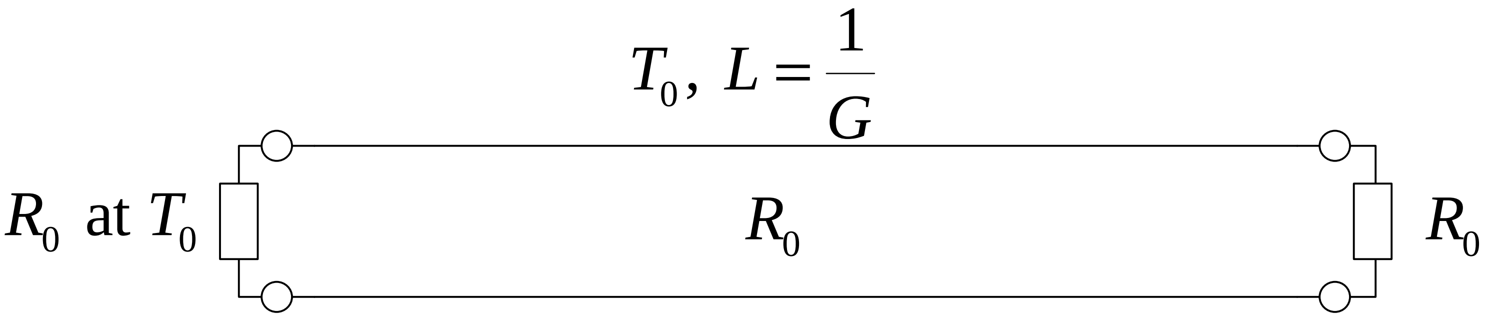
$$P_{ao} = G_{amp} k T_{tot} B_n = 100\cdot 1.38\cdot 10^{-23}\cdot 200\cdot 10^{6}$$

$$= 2.76\cdot 10^{-13} \text{ W} \equiv \text{-95.6 dBm}$$

TU Delft

Noise Figure and equivalent noise temperature of a transmission line (1)

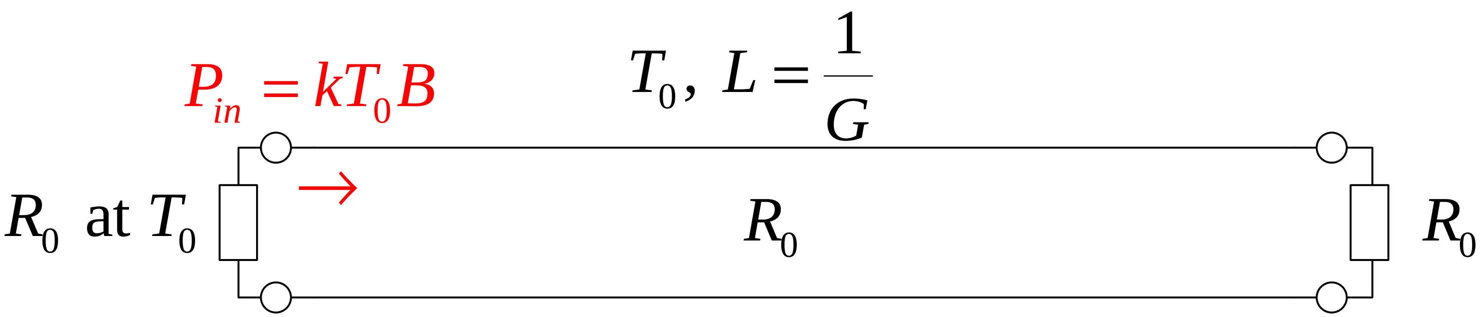
Assume a transmission line with attenuation $L = 1/G$, loaded at the input and output with the characteristic impedance R_0. The whole system is at room temperature T_0. What is F, T_e of a "lossy" transmission line?



The source (impedance R_0) at temperature T_0 sees a load R_0 (line + termination load) $\rightarrow$ maximum power is transferred into the transmission line + load. The transferred power in a bandwidth B is;

$$P_{in} = kT_0 B$$

Noise Figure and equivalent noise temperature of a transmission line (2)



The output load sees a source impedance (line + termination load) R_0 at temperature T_0, so:

$$P_{out} = kT_0B = \frac{P_{in}}{L} + P_{\text{cable noise}}$$

$$\Rightarrow T_e = \frac{P_{\text{cable noise}}}{kGB} = \frac{P_{\text{out}} - \frac{P_{in}}{L}}{\frac{kB}{L}} = \frac{kT_0B(1-\frac{1}{L})}{\frac{kB}{L}} = (L-1)T_0$$

and $F = 1 + \frac{T_e}{T_0} = L$ $\Rightarrow$ the Noise Figure of a cable at T_0 is equal to its loss.