Module 1 : **Radiocommunication equipment and subsystems**

Noise in communications

UNIVERSITAT POLITÈCNICA DE CATALUNYA
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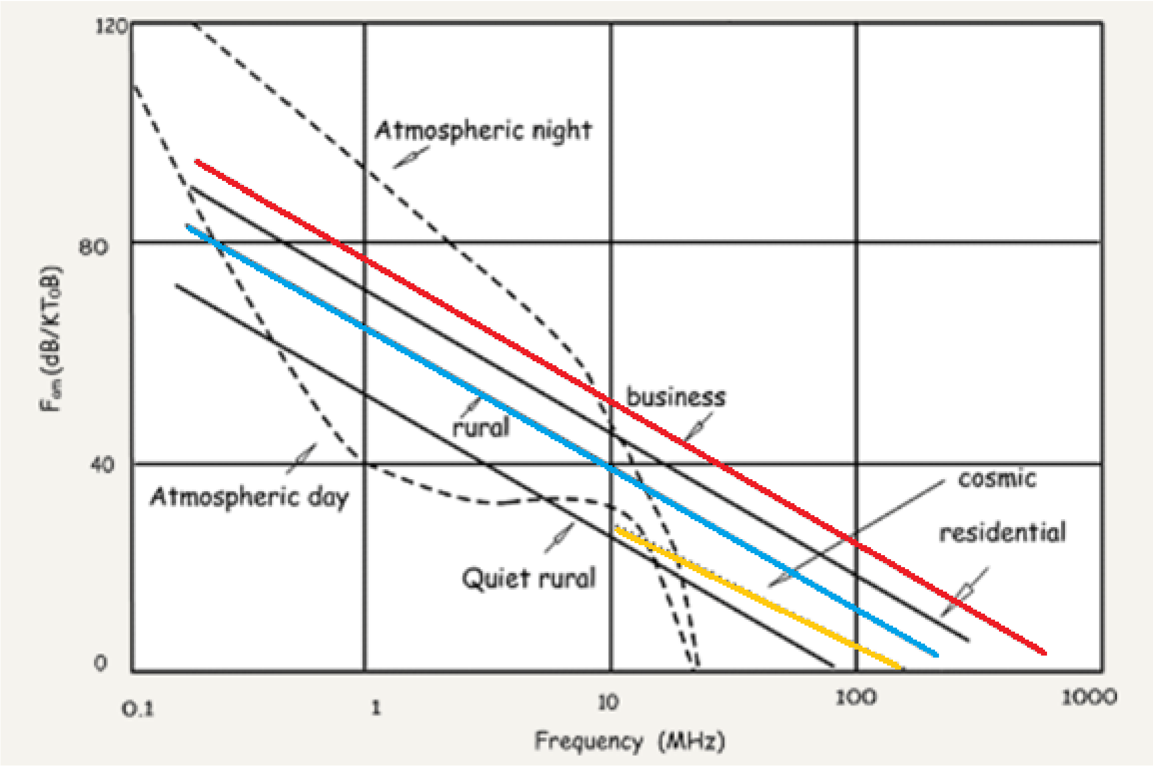
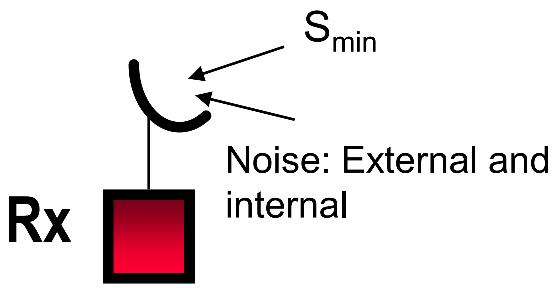
Noise and interference



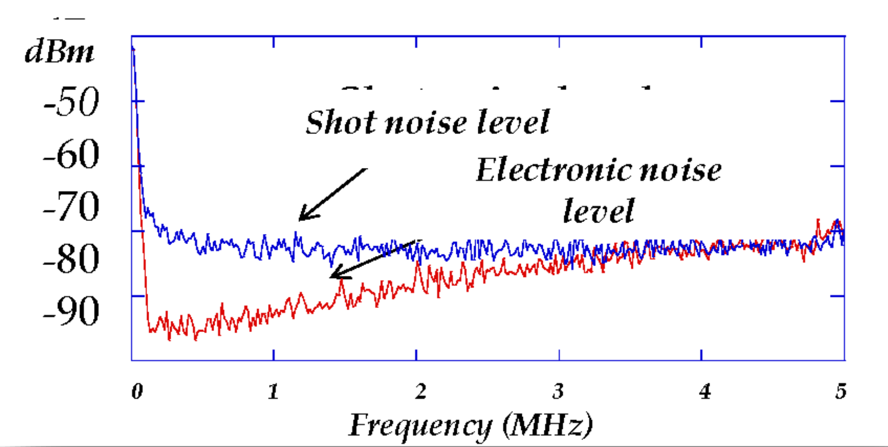
Noise and interference



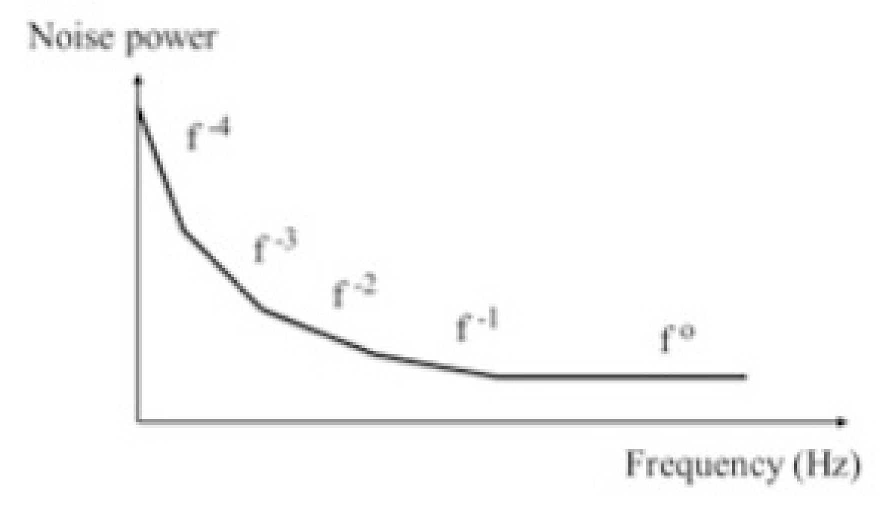
- External noise
  - Atmospheric noise
    - Dominant external noise source for f<30 MHz
    - Caused by thunderstorms all over the world
    - "Gaussian" background noise, with impulse noise in the foreground due to nearby strikes
  - Cosmic noise ("antenna temperature")
    - Thermal (=Gaussian)
    - Lower when the antenna is pointed towards "cold" outer space
    - No filtering possible → just have to deal with it…
  - Interference
    - Usually from man-made sources (radio stations, spurious from equipment, oscillating TV antenna)
    - Can be intentional (jammers) or unintentional
- Internal noise: noise across input impedance of Rx
  - Amplifiers (noise current, noise voltage) → SHOT NOISE, FLICKER NOISE
  - Resistors, lossy cables → THERMAL NOISE

Noise due to the semiconductors

- SHOT noise:
  - Appears in semiconductors (diodes, transistors, etc), and it is proportional to the DC current through the semiconductor union.
  - Its power spectral density is like a white noise, that is, equal for all the frequencies.

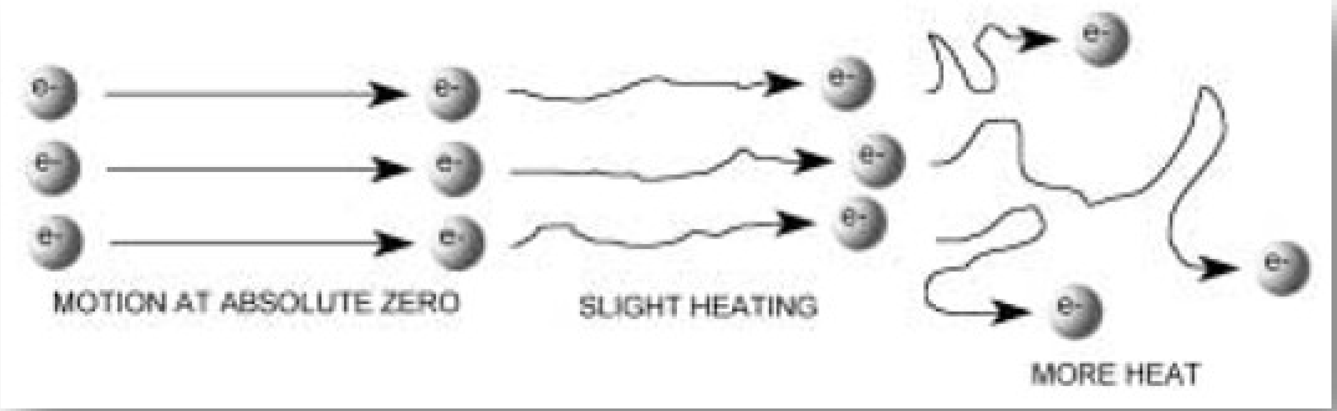


- FLICKER noise:
  - Has power spectral density proportional to **1/f**, being f the frequency (also named ***pink*** noise).
  - It decreases with the frequency.
  - Is the origin of the phase noise in oscillators.



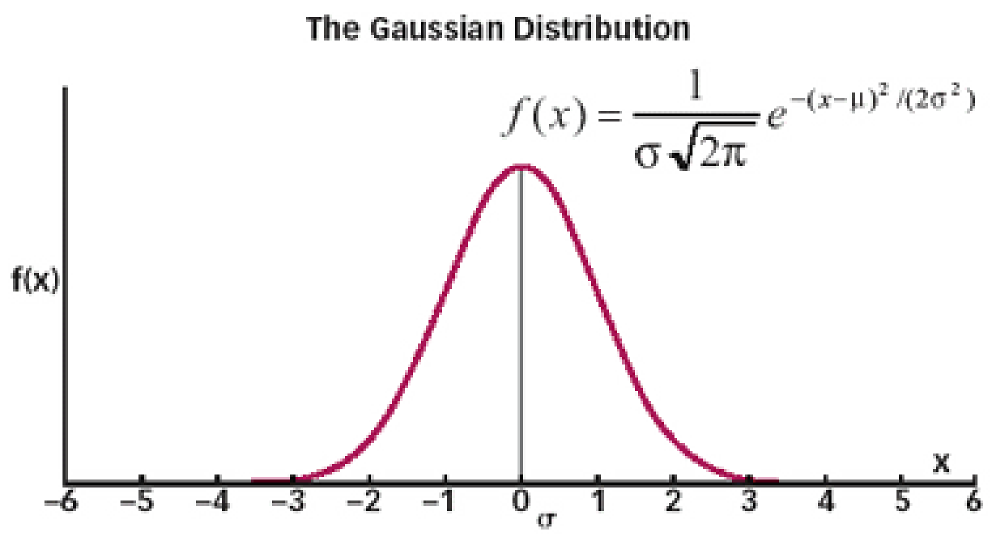
Thermal noise

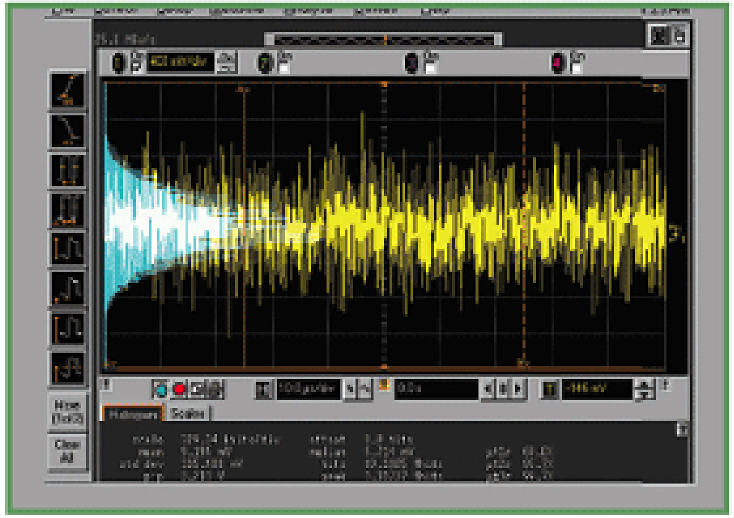
- Also called Johnson noise.
- Generated by the thermal agitation of the electrons inside an electrical conductor at equilibrium.
- It depends of the temperature T of the conductor, expressed in Kelvins.



T = ºC + 273 ⇒ at 17 ºC → 290 K

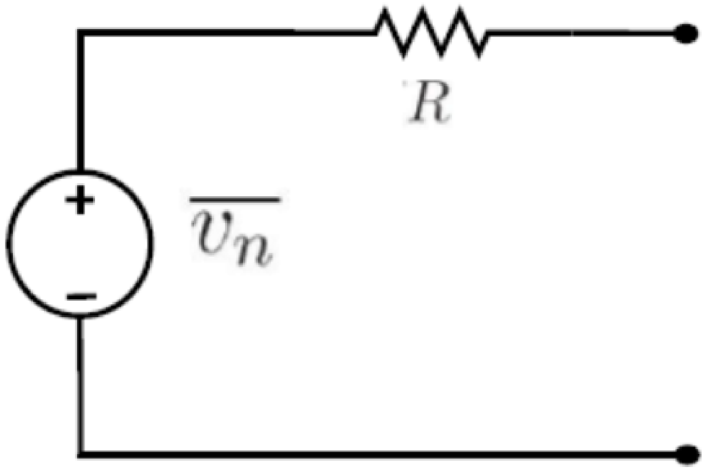
Thermal noise





It has a Gaussian probability density function , with a zero mean value.

Thermal noise



$$\overline{v_n^2} = 4kTR\Delta f$$

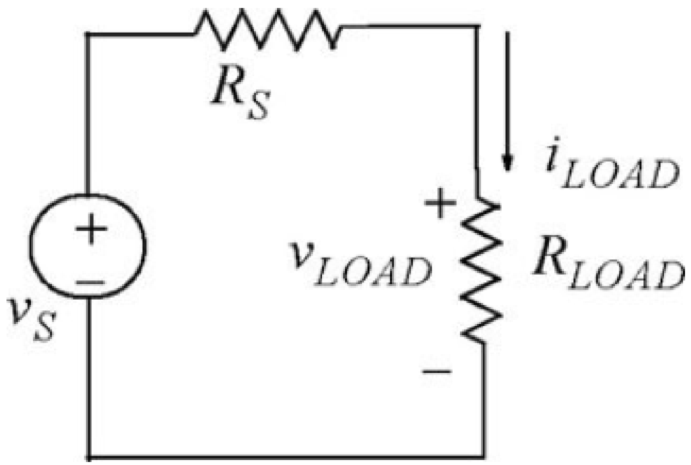
where,

$k = 1.38 \times 10^{-23}$ J/K is Boltzman constant

T is absolute temperature of resistor in Kelvin.

Δf is the measurement bandwidth

Thermal noise



$$P_L = V_L I_L = \frac{R_L V_S}{R_S+R_L}\frac{V_S}{R_S+R_L} = \frac{R_L V_S^2}{(R_S+R_L)^2}$$

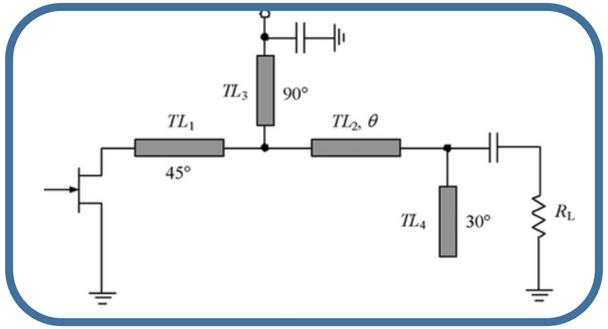
If matched: Rs = RL → $P_L = \frac{R_L\ V_S^2}{(2\ R_L)^2} = \frac{V_S^2}{4\ R_L}$

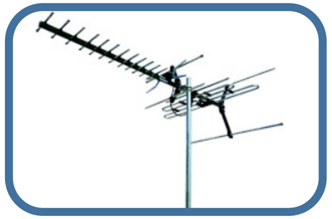
$$\overline{v_n^2} = 4kTR\Delta f$$

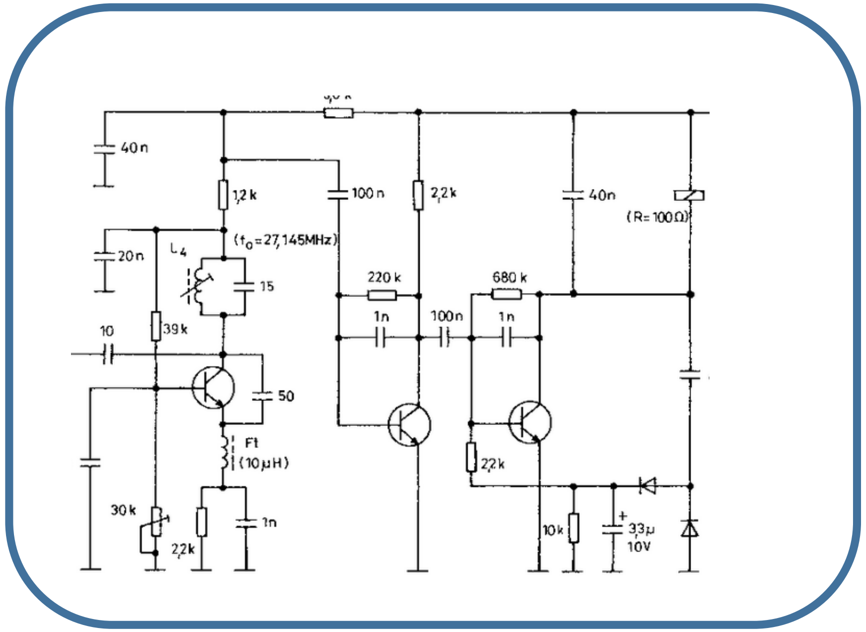
→ $P_L = \frac{4kTR\ \Delta f}{4\ R_L} = k\ T\Delta f\ \ (or\ kTB, being\ B = \Delta f\ )$

Notice that: **The noise power transferred to a matched load is independent of the value of the load !!**

Thermal noise







Rout

Rin

If Rout = Rin (matched) → **Pin (noise) = KTB**

Thermal noise

Pin (noise) = KTB

In dB:

P noise (dBW) = 10 log KT + 10 log B = -204 dBW + 10 log B

P noise (dBm) = **-174 dBm** + 10 log B → - 174dBm/Hz

I.e: if B= 1 KHz, P = -174 dBm **+** 10 log(1000) = -144 dBm

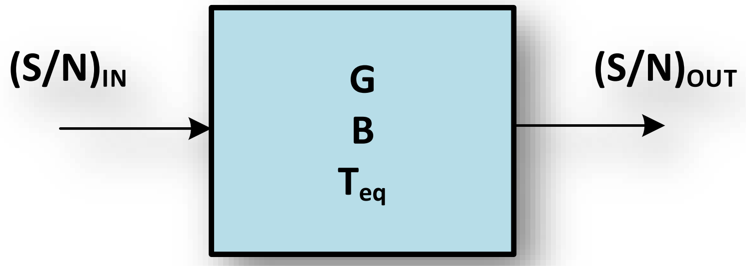
Noise in quadrupoles (two-poles):

Temperature Equivalent (T_{eq}) at the input

Noise in quadrupoles. Temperature Equivalent (T_{eq}) at the input

PROBLEM: the noise due to semiconductors in not thermal.

$$N_{in} = kT_{in}B$$



$$S_{out} = S_{in}G$$

$$N_{out} = N_{in}G + N_{added}$$

$$N_{out} = N_{in}G + N_{added} = kT_{in}BG + N_{added}$$

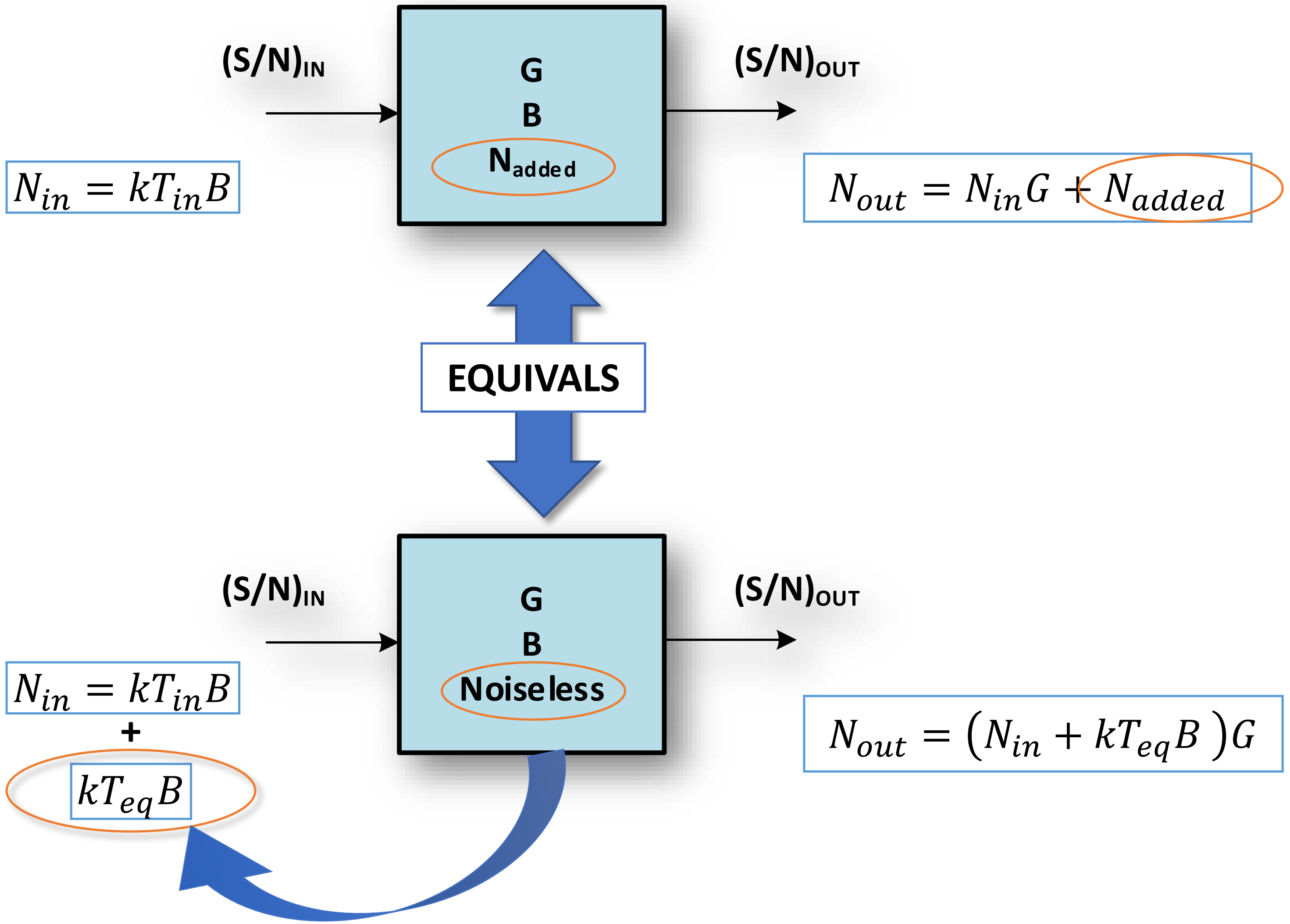
$$N_{added} \triangleq kT_{eq}BG$$

The **noise added** by the quadrupole **is equivalent** to the noise produced at his input **by a noise source** at **T_{eq}**.

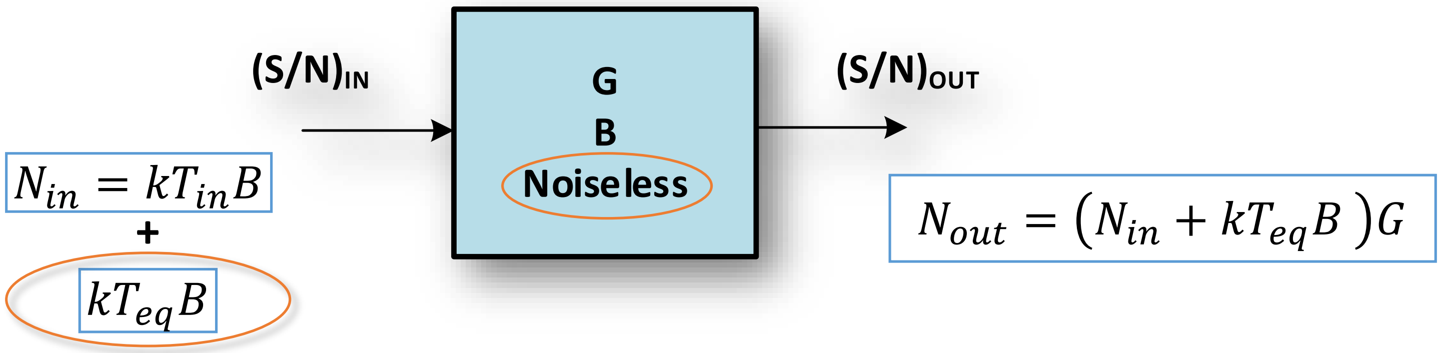
$$N_{out} = k\left(T_{in} + T_{eq}\right)BG$$

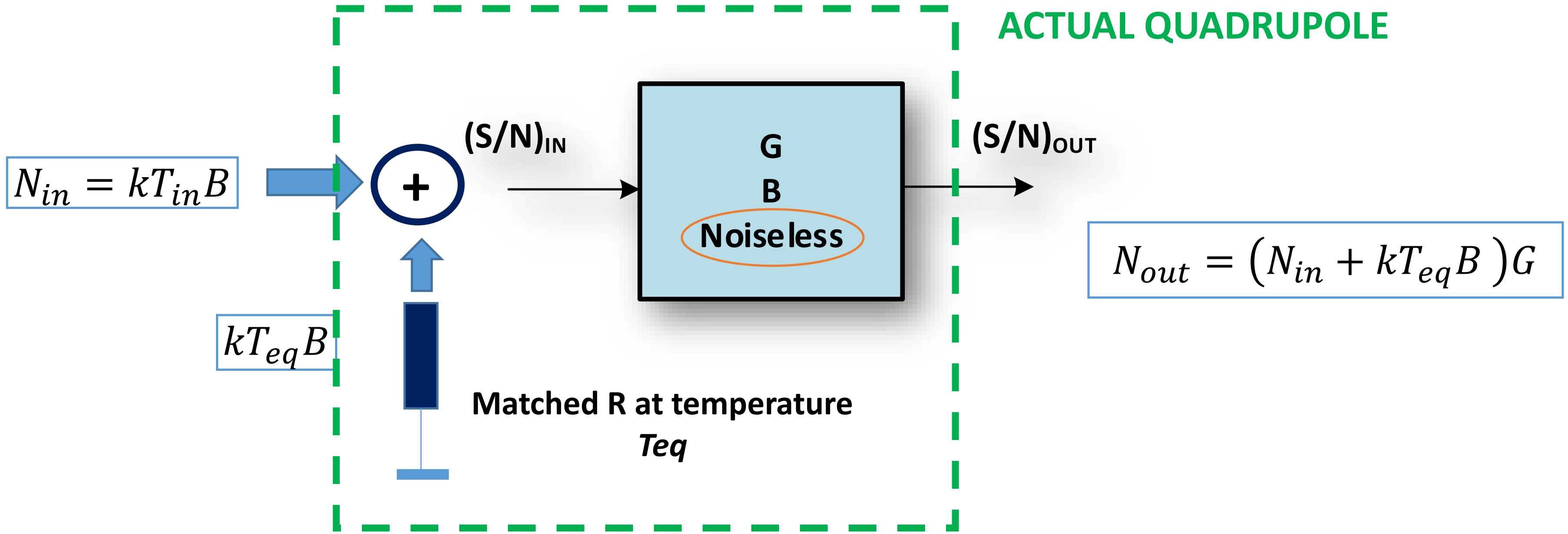
$$(S/N)_{out} = \frac{(S/N)_{in}}{\left(1 + \frac{T_{eq}}{T_{in}}\right)}$$

Noise in quadrupoles:
Temperature Equivalent (Teq) at the input



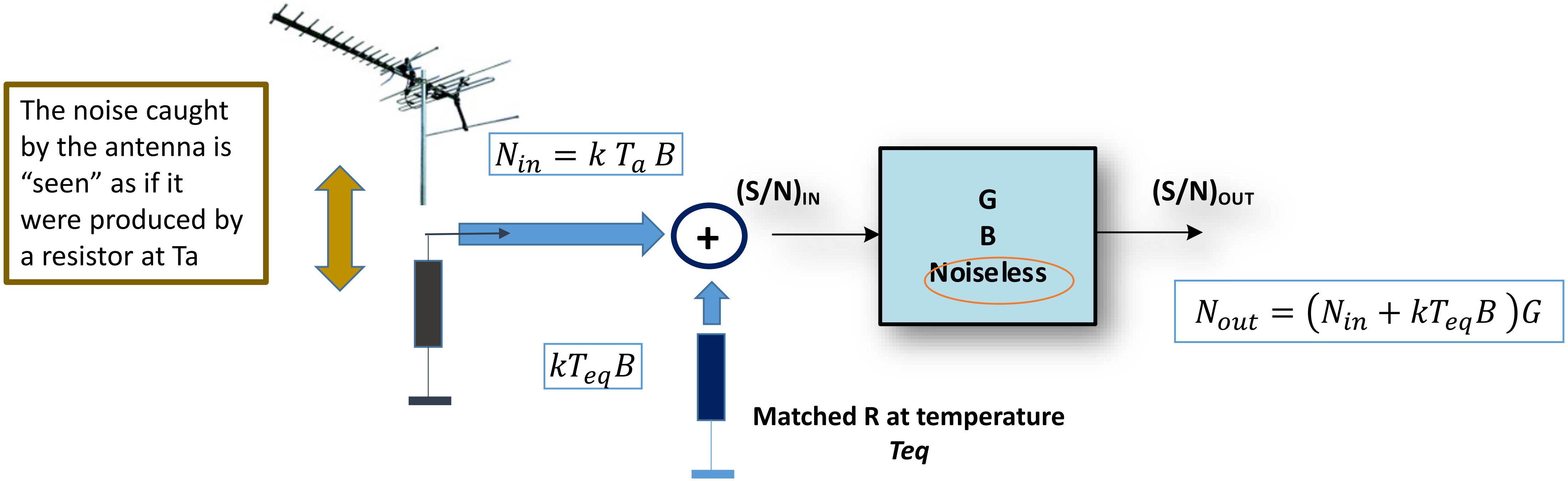
Noise in quadrupoles: Temperature Equivalent (Teq) at the input





Noise in quadrupoles: Antenna Temperature

A similar approach may be made if the entry comes from an antenna: ANTENNA TEMPERATURE



Noise in quadrupoles: Antenna Temperature

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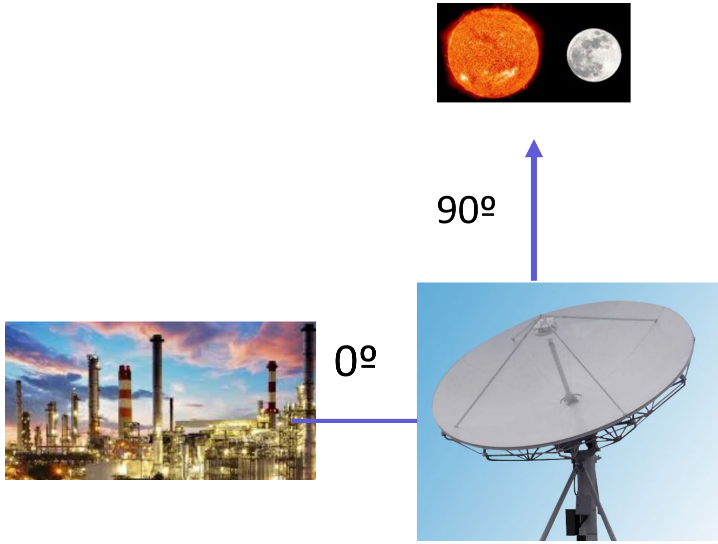
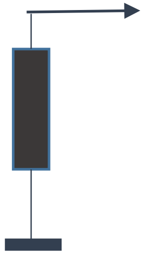
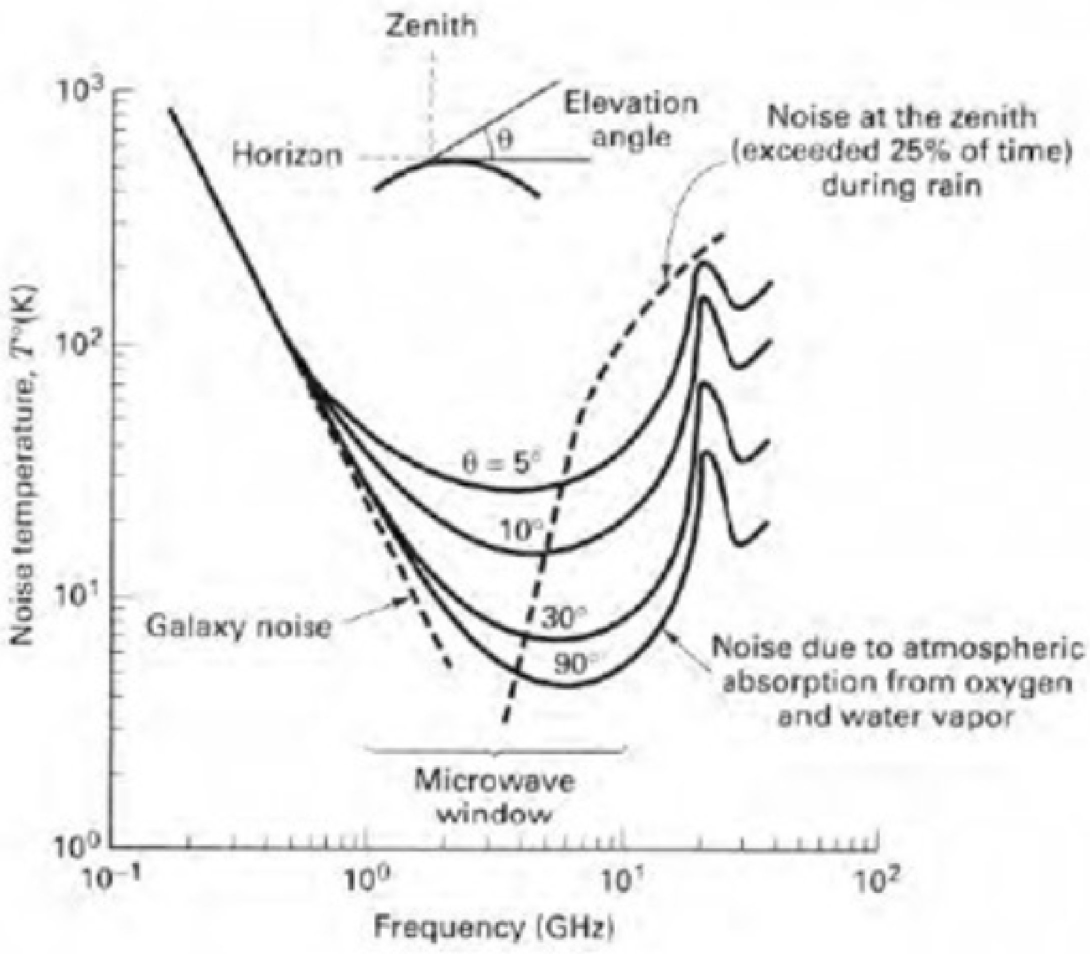


$$N_{in} = k\, T_a\, B$$



Ta at 0º > Ta at 90º



Noise in quadrupoles:

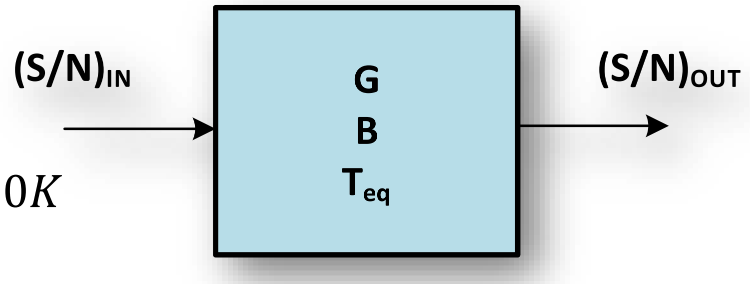
Noise Factor (F)

Noise Factor: F

Temperature of reference

$T_{in} = T_0 = 290K$

$N_{in} = kT_0B$



$S_{out} = S_{in}G$

$N_{out} = k(T_0 + T_{eq})BG$

Noise Factor:

$$F \triangleq \frac{Total\ noise\ output\ power}{Output\ noise\ power\ only\ due\ by\ an\ input\ source\ at\ T_0}$$

$$F = \frac{k(T_0 + T_{eq})BG}{kT_0BG} = 1 + \frac{T_{eq}}{T_0}$$

Noise Figure: $NF(dB) = 10\log_{10}(F)$

$$T_{eq} = T_0(F - 1)$$

Noise Factor: F

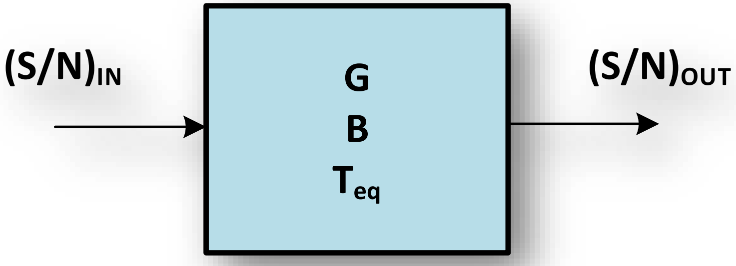
An amplifier at ambient temperature and with 50 Ω of input resistance has a noise figure of 4 dB when it is excited by a generator with 50 Ω of internal resistance. The BW of the amplifier is 300 kHz.

- What is the noise equivalent temperature of the amplifier? (sol: 438.45 K)

- What is the noise power at the input? (sol: 1.2 · 10 ^(-15) = -119.2 dBm)

- What is the noise power at the output if the amplifier gain is 20 dB? (sol: 3.016 10^(-13) = -95.2 dBm)

Noise Factor: F



$$S_{out} = S_{in} G$$

$$N_{in} = k T_{in} B$$

$$N_{out} = k\left(T_{in} + T_{eq}\right)BG$$

$$(S/N)_{out} = \frac{G\,S_{in}}{N_{out}} = \frac{G\,S_{in}}{k\left(T_{in}+T_{eq}\right)BG} = \frac{S_{in}/N_{in}}{k(T_{in}+T_{eq})B\big/N_{in}} = \frac{(S/N)_{in}}{k(T_{in}+T_{eq})B\big/kT_{in}B} =$$

$$= \frac{(S/N)_{in}}{\left(1+\frac{T_{eq}}{T_{in}}\right)} = \frac{(S/N)_{in}}{\left(1+\frac{T_0}{T_{in}}(F-1)\right)}$$

Generic expression

If $T_{in}=T_0$, then,

$$(S/N)_{out} = \frac{1}{F}(S/N)_{in}$$

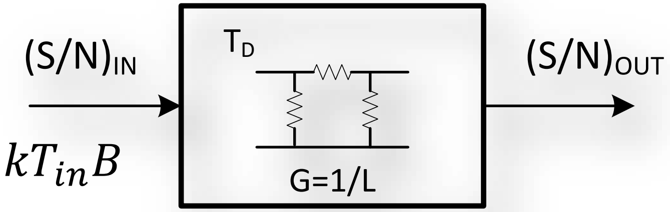
Particular case

Noise in quadrupoles:

Thermal noise in passive devices

Thermal noise in matched passive devices

T_{in} = Temperature of a passive matched load at input port



$$N_{in} = kT_{in}B$$

As a quadrupole, $N_{out} = k(T_{in} + T_{eq})BG = k(T_{in} + T_{eq})B\frac{1}{L}$

Assuming that $T_{in} = T_D$ (being T_D the physical temperature of the device) the whole set is a passive one-port device at thermal equilibrium so: $N_{out} = kT_DB$

Equating both expressions, $k(T_{in} + T_{eq})B\frac{1}{L}\Big|_{T_{in}=T_D} = kT_DB$, we obtain, $T_{eq} = T_D(L-1)$.

General expression

In the general situation where the input temperature is different from the device temperature:

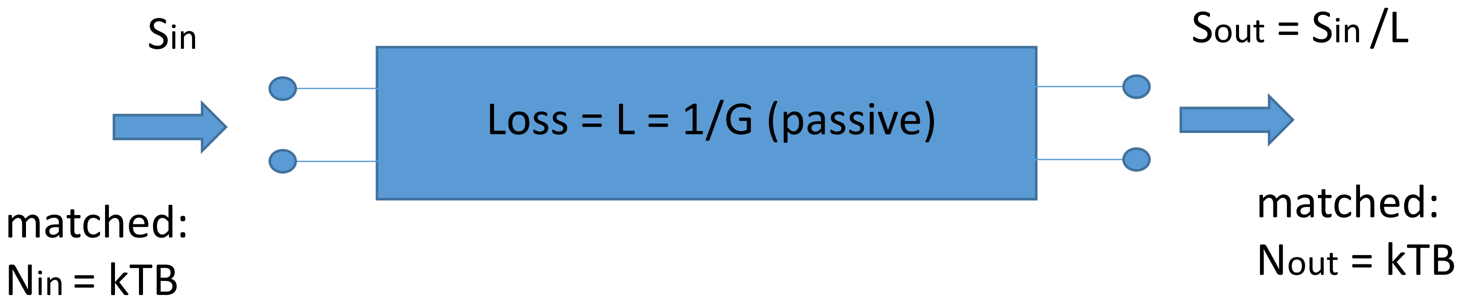
$$N_{out} = k(T_{in} + T_D(L-1))B\frac{1}{L} \neq kT_DB$$

If the device temperature equals the reference temperature, $T_D = T_0$, then $T_{eq} = T_0(L-1)$, thus

$$F = 1 + \frac{T_{eq}}{T_0} = 1 + \frac{T_0(L-1)}{T_0} = L$$

Particular case

Thermal noise in matched passive devices (alternative approach for $T_{in} = T_0$)



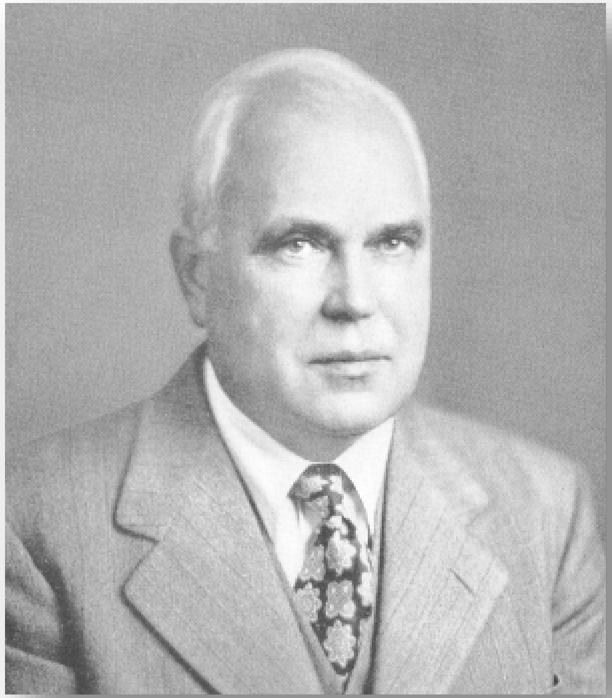
$$\left(\frac{S}{N}\right)_{out} = \frac{S_{in}/L}{kTB} = \frac{1}{L}\frac{S_{in}}{\boldsymbol{N}_{in}}$$

$$(S/N)_{out} = \frac{1}{F}(S/N)_{in}$$

$$F = L$$

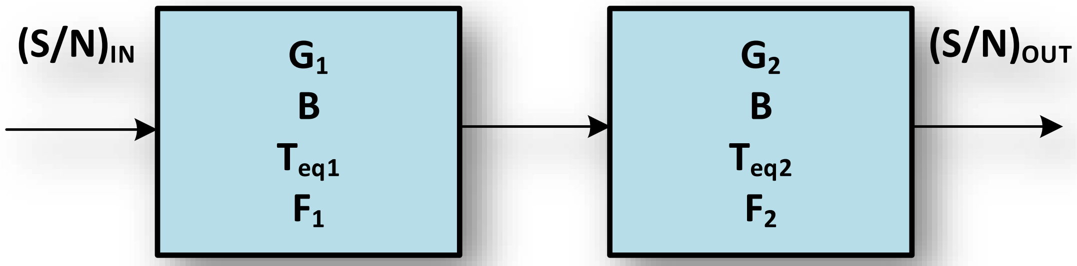
Noise in quadrupoles:

Components in cascade. Harald T. Friis noise equation.



Harald Trap Friis (February 22, 1893 – June 15, 1976), who published as H. T. Friis, was a Danish-American radio engineer whose work at Bell Laboratories included pioneering contributions to radio propagation, radio astronomy, and radar. His two Friis formulas remain widely used.
https://www.smecc.org/harald_friis.htm

Noise in cascaded quadrupoles



$$S_{out} = S_{in} G_1 G_2$$

$$N_{in} = kT_{in}B$$

$$N_{out} = kT_{in}BG_1G_2 + kT_{eq1}BG_1G_2 + kT_{eq2}BG_2$$

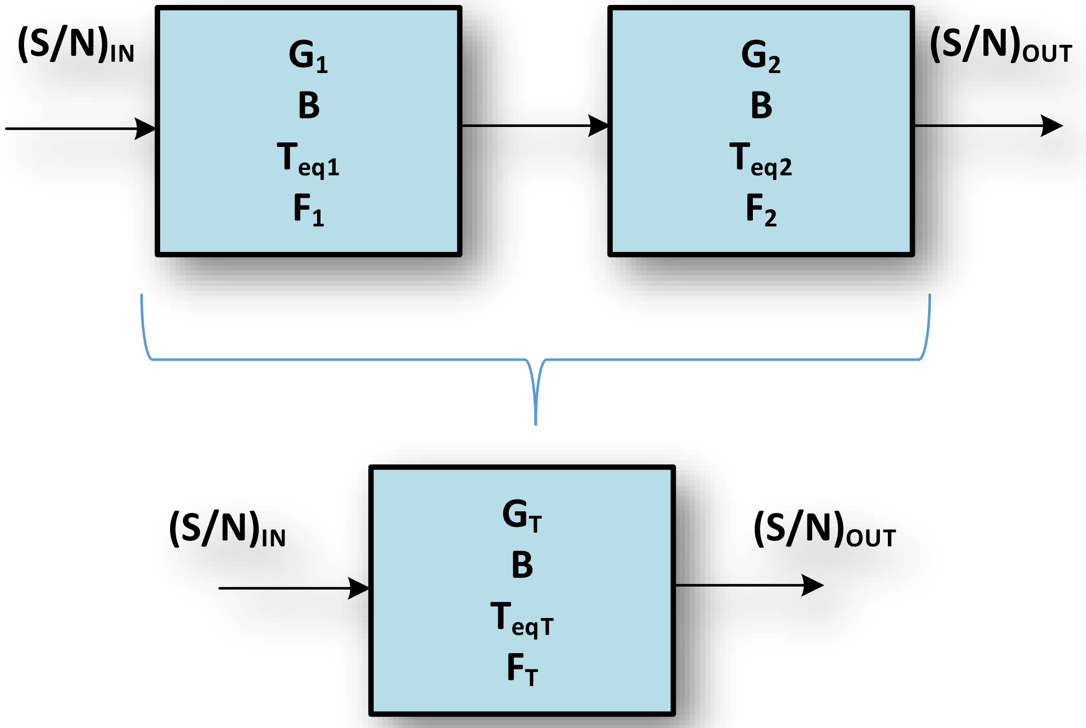
$$N_{out} = kBG_1G_2\left(T_{in} + T_{eq1} + \frac{T_{eq2}}{G_1}\right) = kBG_T\left(T_{in} + T_{eqT}\right)$$

$$G_T = G_1G_2$$

$$T_{eqT} = T_{eq1} + \frac{T_{eq2}}{G_1}$$

$$F_T = F_1 + \frac{F_2 - 1}{G_1}$$

Noise in cascaded quadrupoles

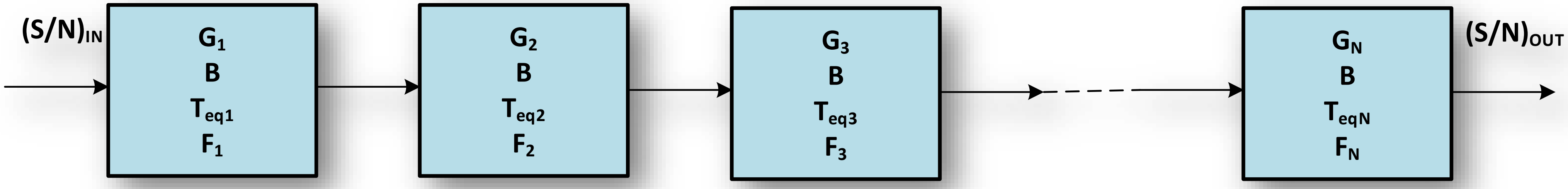


$$G_T = G_1 G_2$$

$$T_{eqT} = T_{eq1} + \frac{T_{eq2}}{G_1}$$

$$F_T = F_1 + \frac{F_2 - 1}{G_1}$$

Friis noise equations



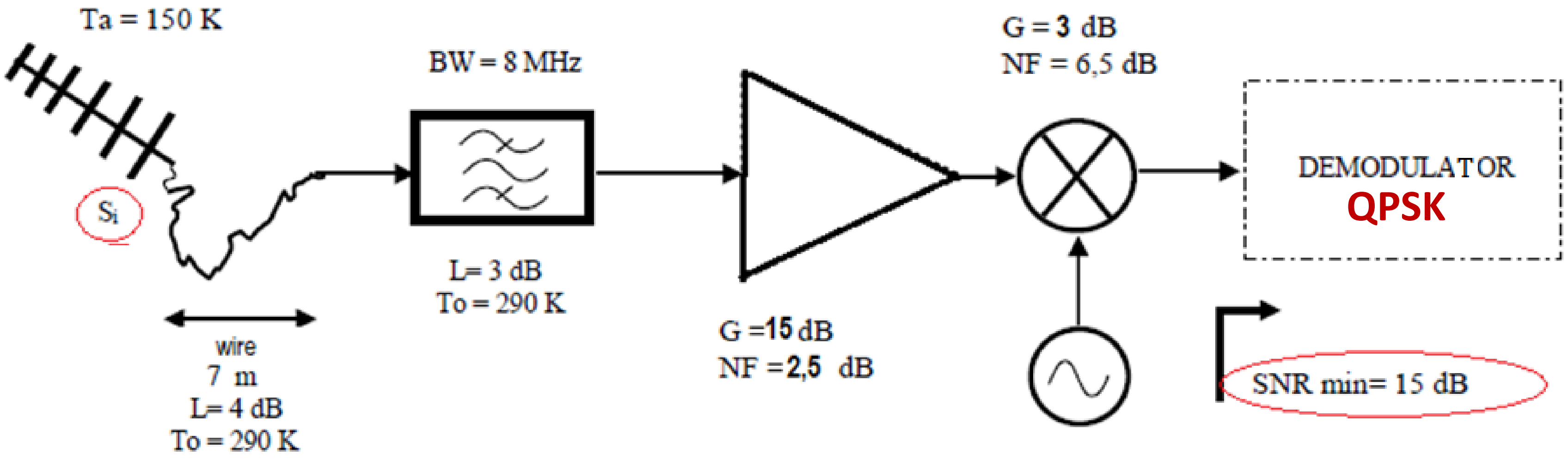
$$G_T = G_1 G_2 \cdots G_N$$

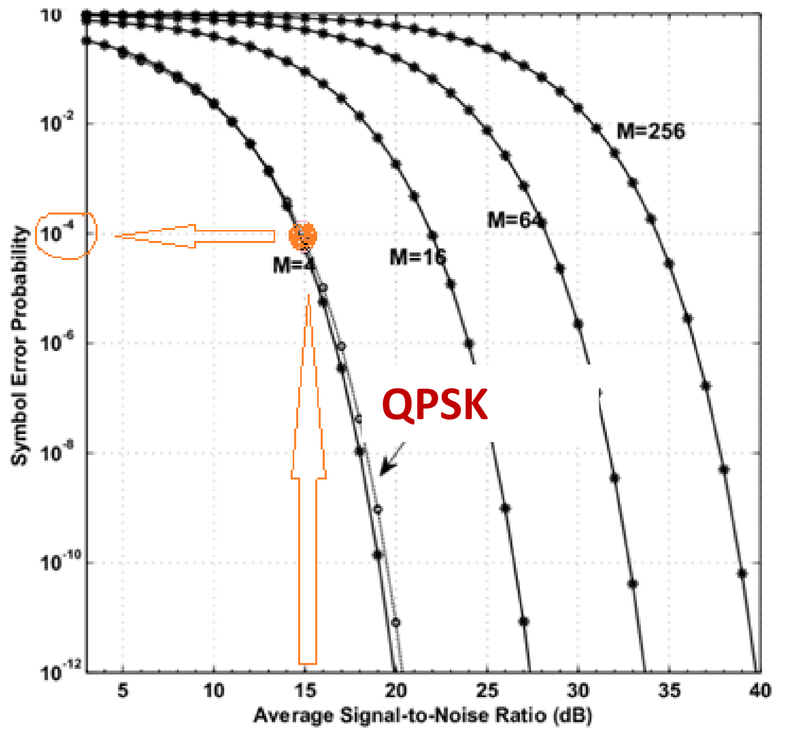
$$T_{eqT} = T_{eq1} + \frac{T_{eq2}}{G_1} + \frac{T_{eq3}}{G_1 G_2} + \cdots + \frac{T_{eqN}}{G_1 G_2 \cdots G_{N-1}}$$

$$F_T = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots + \frac{F_N - 1}{G_1 G_2 \cdots G_{N-1}}$$

1st device is the most critical !!!!

$$(S/N)_{out} = \frac{(S/N)_{in}}{\left(1 + \frac{T_{eqT}}{T_{in}}\right)}$$

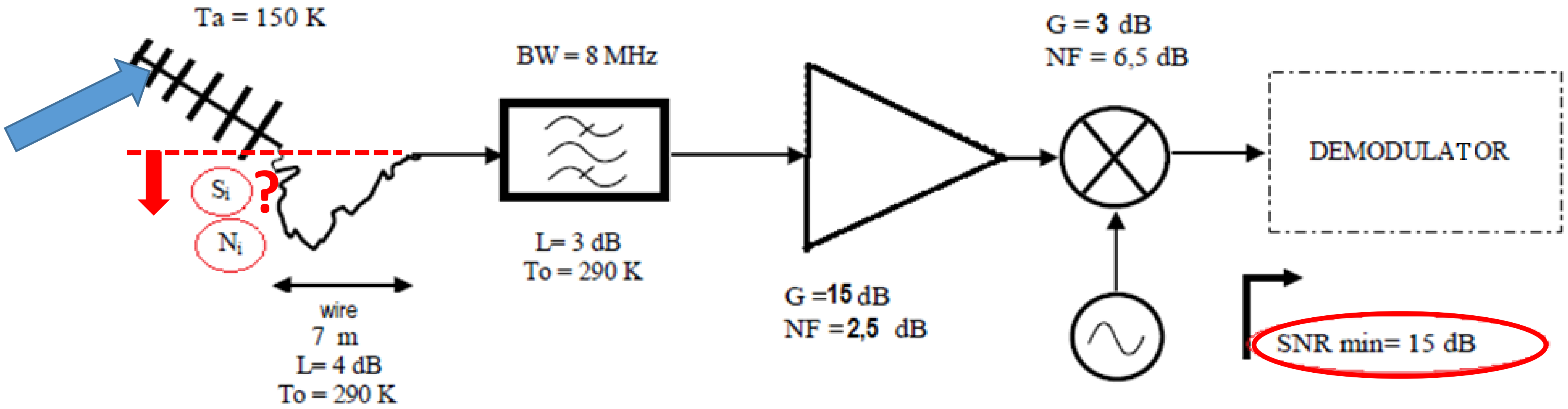




PREVIOUS COURSE

$$T_{eqT} = T_{eq1} + \frac{T_{eq2}}{G_1} + \frac{T_{eq3}}{G_1 G_2} + \cdots + \frac{T_{eqN}}{G_1 G_2 \cdots G_{N-1}}$$

$$F_T = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots + \frac{F_N - 1}{G_1 G_2 \cdots G_{N-1}}$$



"gains" of the wire and the passive filter

$-4\ dB \rightarrow 0{,}4$

$-3\ dB \rightarrow 0{,}5$

$$F = 10^{0,4} + \frac{10^{0,3}-1}{0{,}4} + \frac{10^{0,25}-1}{0{,}4 \cdot 0{,}5} + \frac{10^{0,65}-1}{0{,}4 \cdot 0{,}5 \cdot 10^{1,5}} = 9{,}44 \rightarrow 9{,}75\ dB$$

$$T_{eq} = T_0 (F-1) = 290\,(9{,}44 - 1) = 2447\ K$$

G

$$N_0 = K\,G\,B\,(T_o + T_{eq}) = 1{,}38\,e^{-23} \cdot (0{,}4 \cdot 0{,}5 \cdot 10^{1,5} \cdot 10^{0,3}) \cdot 8 \cdot 10^6\,(290 + 2447) = 3{,}813 \cdot 10^{-12}$$

$$\rightarrow -114{,}18\ dBW \rightarrow -84{,}18\ dBm$$

Where the error is?

$$G = 12{,}62 \Rightarrow 11dB$$

$$N_0 = K\,G\,B\,(T_a + T_{eq}) = 1{,}38\,e^{-23} \cdot (0{,}4 \cdot 0{,}5 \cdot 10^{1,5} \cdot 10^{0,3}) \cdot 8 \cdot 10^6\,(150 + 2447) = 3{,}618 \cdot 10^{-12}$$

$$\rightarrow -126{,}14\,dBW \rightarrow -96{,}14\,dBm$$

$$SNR = 15\,dB \quad , \quad S_0 = N_0 + 15\,dB = -81{,}14\,dBm$$

$$S_i = S_0 - G = S_0 - 10\log(0{,}4 \cdot 0{,}5 \cdot 10^{1,5} \cdot 10^{0,3}) =$$

$$= -81{,}14\,dBm - 10\log(12{,}62) = \boxed{-92{,}14\,dBm}$$

If the antenna can't provide this power:

- To better point the antenna (if possible)
- To change the antenna (size or type)
- To use a LNA (low-noise amplifier) with lower NF
- To amply at intermediate stages is worse: it amplifies both the S and the N, and besides it adds its own noise.

$$F_T = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots + \frac{F_N - 1}{G_1 G_2 \cdots G_{N-1}}$$