ECE 453
Wireless Communication Systems

Noise

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Noise

Random fluctuations of voltage and current

Properties

- Establishes minimum detectable signal
- Sets bounds on range of signals that can be processed
- Comes in different types (thermal, flicker, shot)
- Has frequency and time-domain characteristics
- Not fully understood

Sources of Noise

Shot Noise

- Associated with direct current flows
- Present in diodes, MOS and BJTs
- Passage of carriers through junction is a random event
- External current composed of large independent pulses
- Instantaneous value of waveform cannot be predicted at any time
- Only information available concerns mean square value of signal

Sources of Noise

Thermal Noise

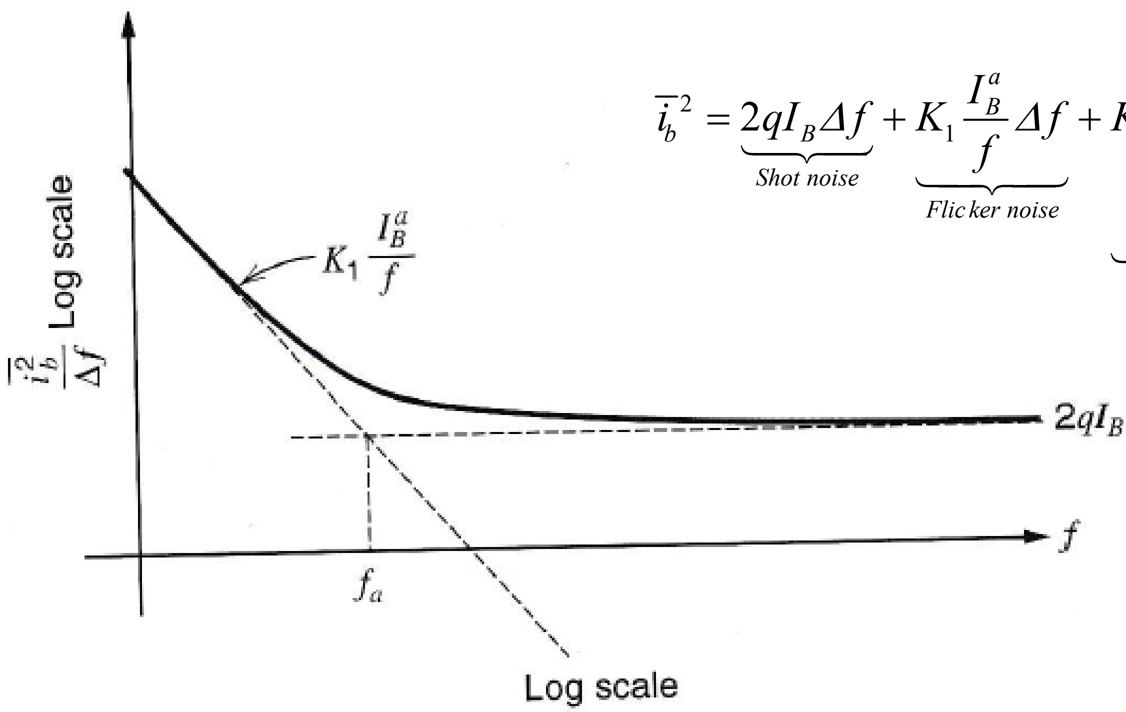
- Present in linear resistors
- Caused by thermal random motion of electrons
- Unaffected by presence or absence of direct current
- Proportional to absolute temperature T
- RMS noise voltage varies as square root of bandwidth

Sources of Noise

Flicker (1/f) Noise

- Found in all active devices
- Present in discrete passive devices (carbon resistors)
- Caused by traps associated with contaminations and crystal defects
- Traps capture and release carriers in random fashion
- Noise spectral density has *1/f* behavior

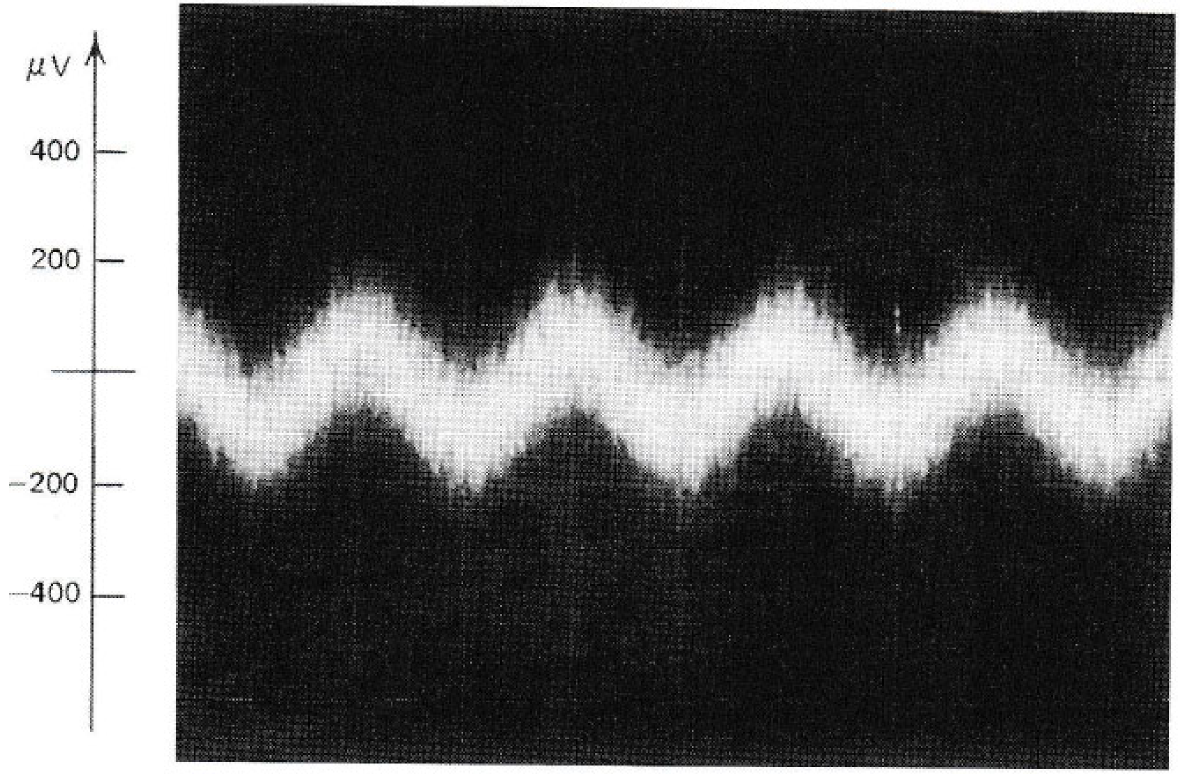
Noise in Transistors



$$\overline{i_b}^2 = \underbrace{2qI_B\Delta f}_{\text{Shot noise}} + \underbrace{K_1\frac{I_B^a}{f}\Delta f}_{\text{Flicker noise}} + \underbrace{K_1\frac{I_B^c}{1+\left(\frac{f}{f_c}\right)^2}\Delta f}_{\text{Burst noise}}$$

Shot noise and flicker noise asymptotes meet at corner frequency *f_a*

Effects of Noise

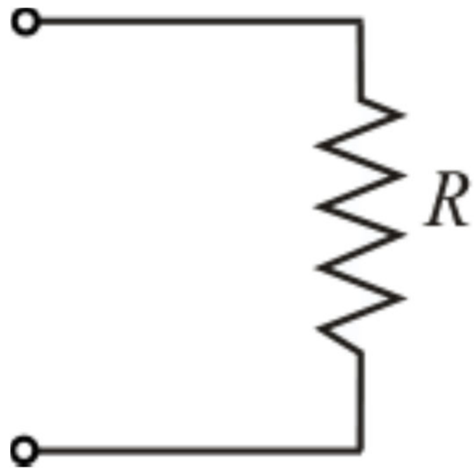


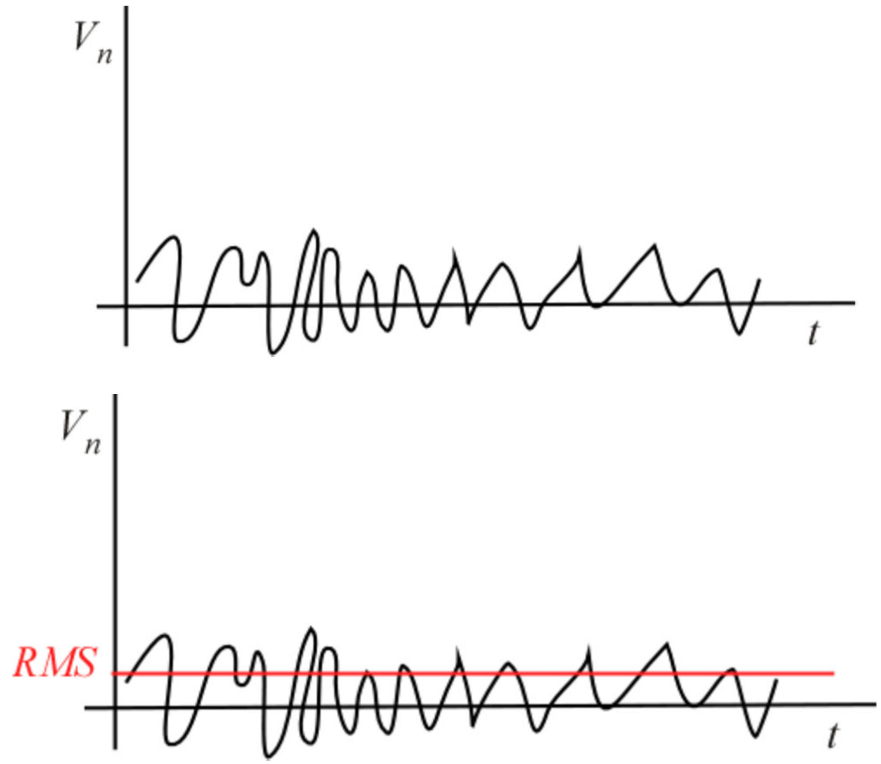
Output voltage waveform for input level comparable to noise level*

*Gray & Meyer, Analysis and design of Analog Integrated Circuits, 4th Edition, J. Wiley, 2001

Noise from a Resistor

Random fluctuations of charge carriers in a conductor will produce thermal noise





At room temperature a resistor has available noise power ~ -174 dBm in 1 Hz of bandwidth

Nyquist Noise Formula

The spectral density of noise voltage at the terminals of a resistor is given by

$$S_n(f) = 4R\frac{hf}{e^{hf/kT}-1}\left(\text{Volts}^2/\text{Hz}\right)$$

f = frequency in Hz
h = Plank's constant = 6.62 x 10^{-34} joules-sec
k = Boltzman's constant =1.38 x 10^{-23} joules/^{o}K
T = absolute temperature ^{o}K
R = resistance in ohms

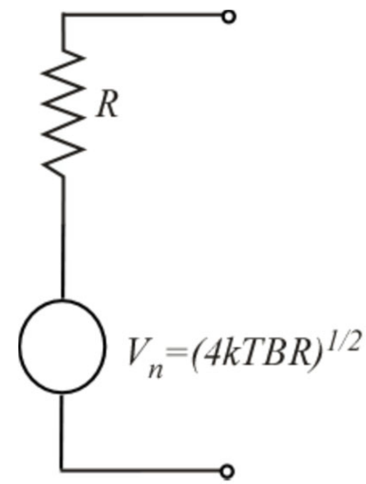
Noise from a Resistor

If $f << kT/h$, then S_n can be approximated as:

$$S_n = 4kTR \ (\text{Volts}^2 / \text{Hz})$$

Noise voltage at the terminals of a resistor is given by

$$V_n^2 = 4kTBR$$



B = bandwidth in Hz

Noise from a Resistor

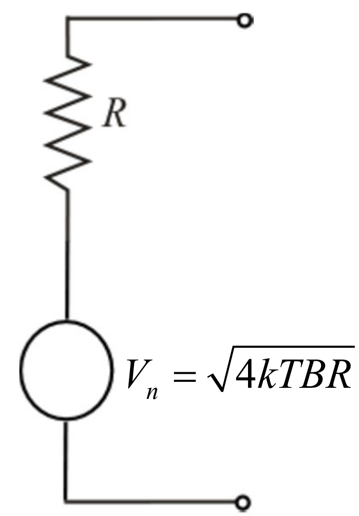
AC Voltmeter

Input resistance = 10 MΩ
Bandwidth = 40 MHz

$$V_n^2 = 4 \times 1.38 \times 10^{-23} \times 300 \times 4 \times 10^6 \times 10^7$$

$$V_n^2 = 66.24 \times 10^{-8}$$

$$V_n \simeq 8 \times 10^{-4} = 0.8\, mV$$

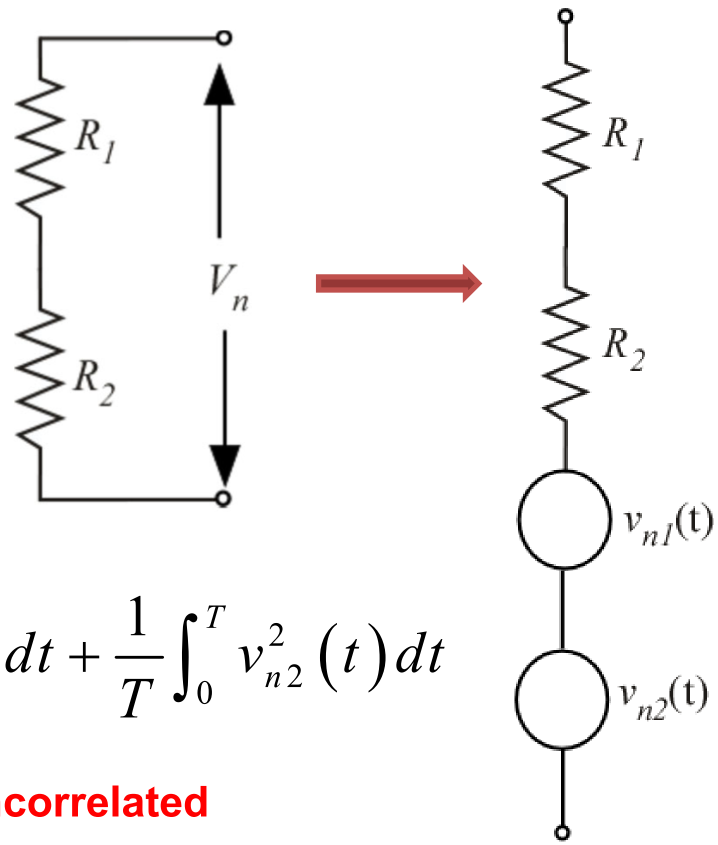


Resistors in Series

$$V_{n1}^2 = \frac{1}{T}\int_0^T v_{n1}^2(t)\,dt$$

$$V_{n2}^2 = \frac{1}{T}\int_0^T v_{n2}^2(t)\,dt$$

$$V_{nT}^2 = \frac{1}{T}\int_0^T \left[v_{n1}(t) + v_{n2}(t)\right]^2 dt$$

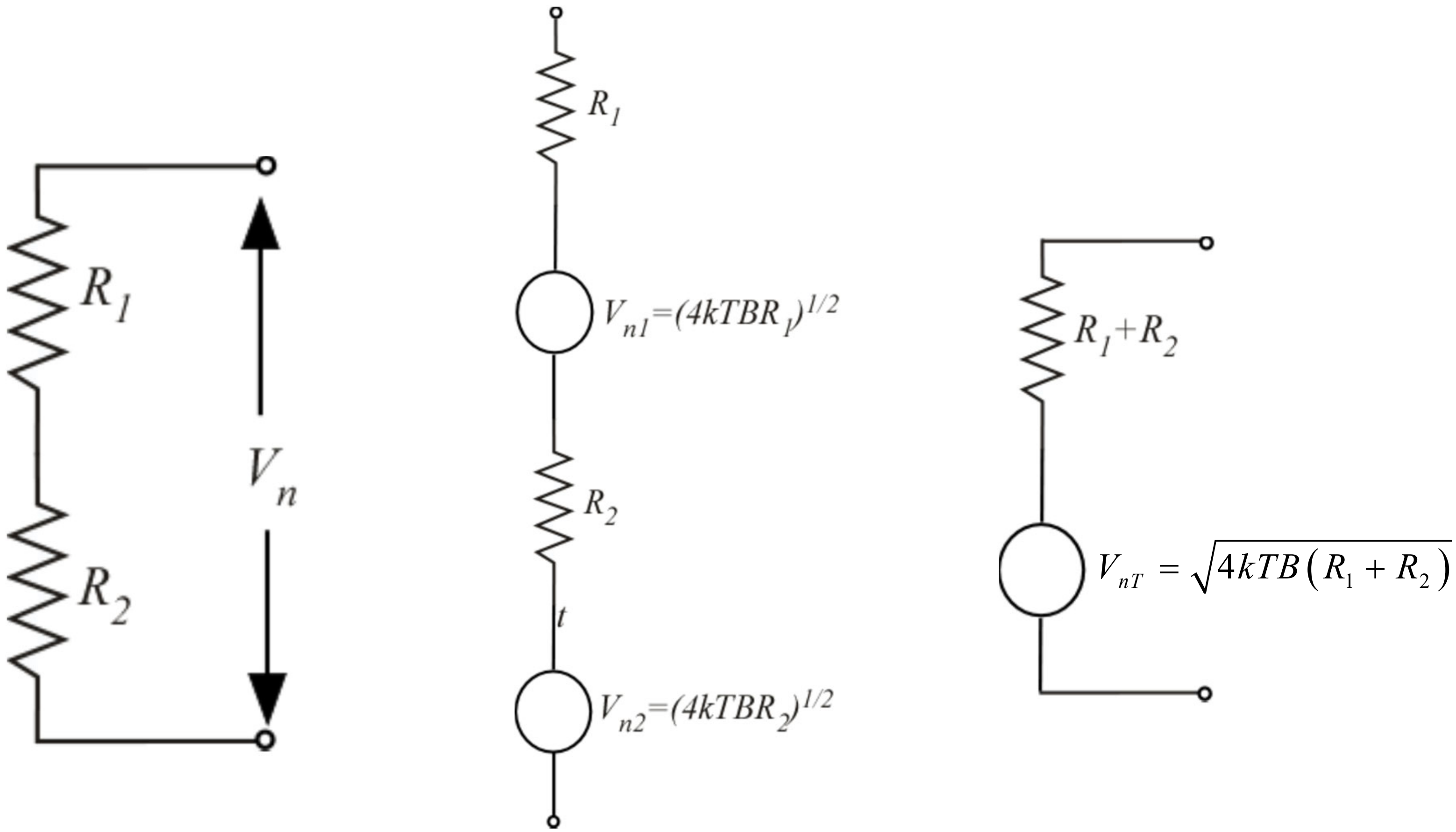


$$V_{nT}^2 = \frac{1}{T}\int_0^T v_{n1}^2(t)\,dt + \frac{1}{T}\int_0^T 2v_{n1}(t)v_{n2}(t)\,dt + \frac{1}{T}\int_0^T v_{n2}^2(t)\,dt$$

0 if v_{n1} and v_{n2} are uncorrelated

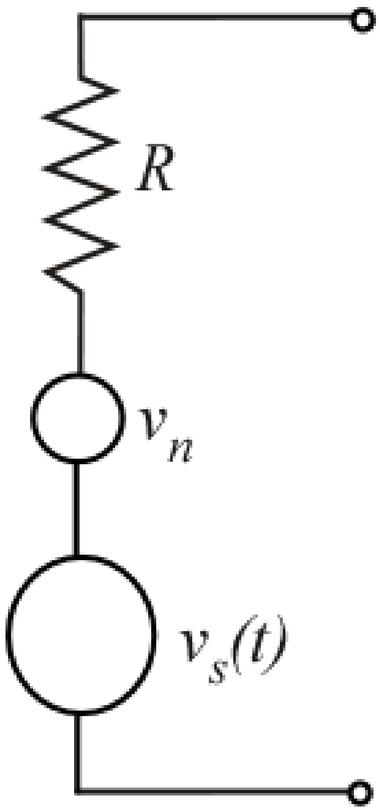
$$V_{nT}^2 = V_{n1}^2 + V_{n2}^2 = 4kTBR_1 + 4kTBR_2$$

Resistors in Series

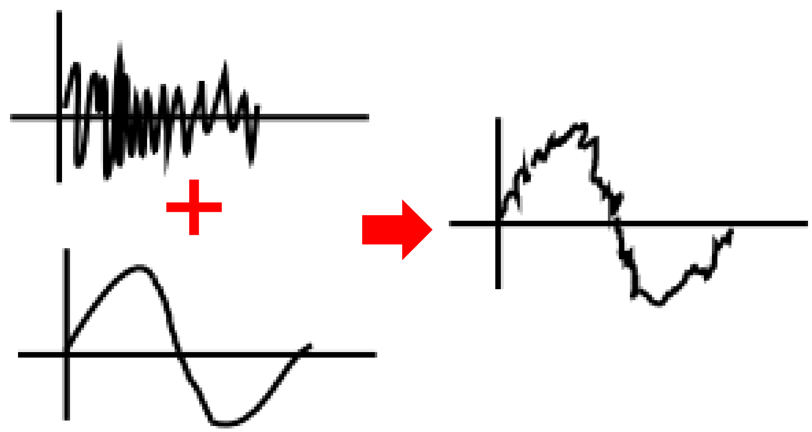


$$V_{nT}^2 = V_{n1}^2 + V_{n2}^2 \ \textit{for 2 uncorrelated noise sources}$$

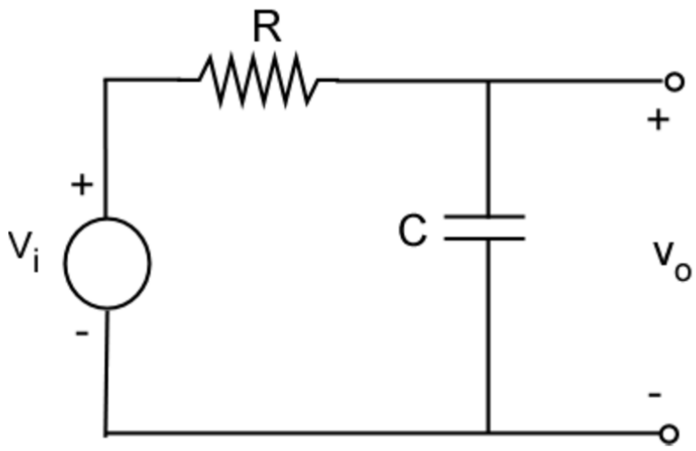
Effective Value of Noise Sources

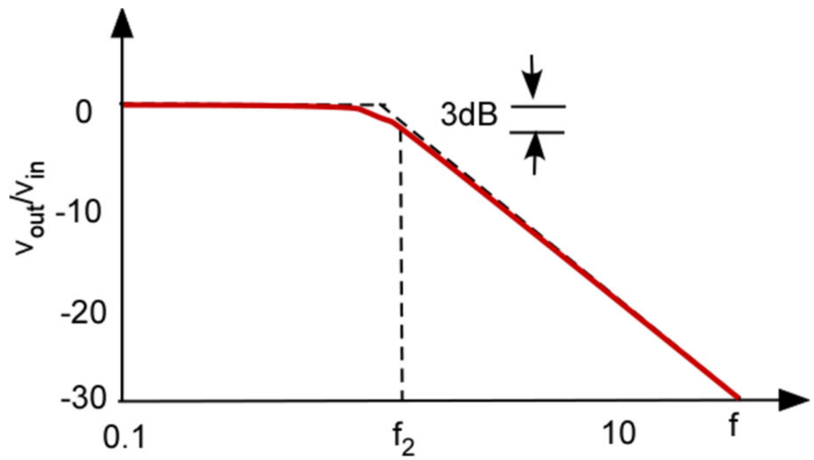


$$V_{nT}^2 = V_n^2 + V_S^2$$



Bandwidth





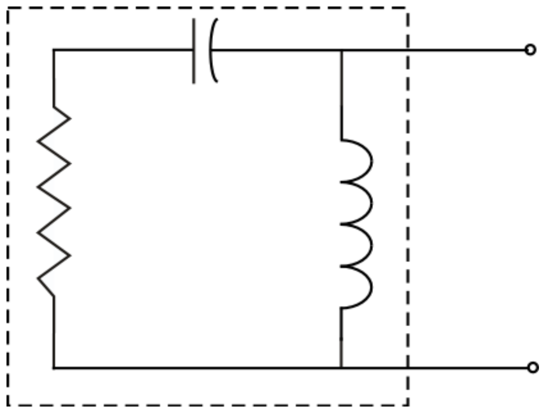
$$\frac{V_o}{V_{in}} = \frac{1}{1 + j\omega RC}$$

The output voltage drops to 0.707 of its low-frequency value when $\omega RC = 1$

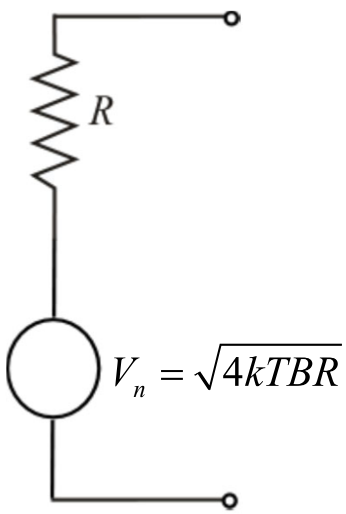
The half-power frequency is given by $2\pi f_2 RC = 1$

➔ $f_2 = 1/2\pi RC$

Noise from a Circuit



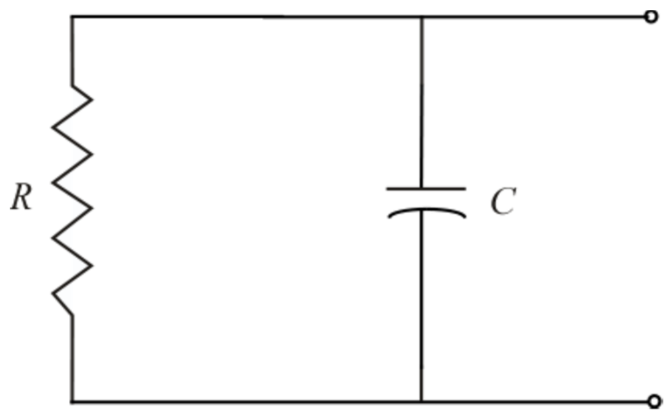
$$V_n^2 = 4kT\left[\int_0^{\infty} R(f)\,df = BR\right]$$

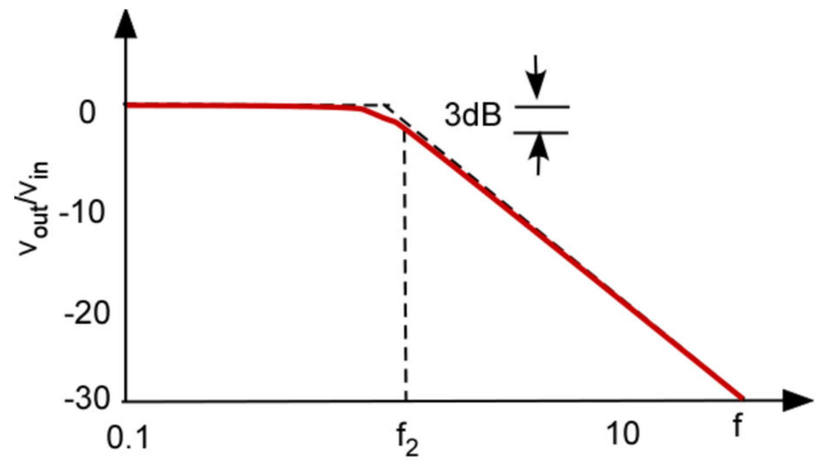


R(f) is the real part of the impedance at each frequency

Noise from a Circuit

For an RC circuit





For coherent signals, the bandwidth of an *RC* circuit is

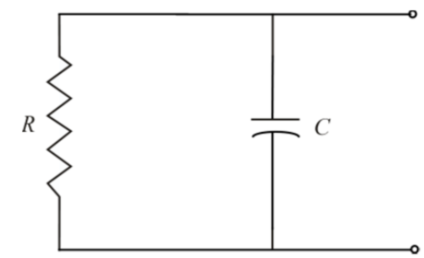
$$f_2 = \frac{1}{2\pi RC}$$

$|Z|$ is *0.707R* when $\omega_2 R = 1/R$ ➔ $2\pi f_2 = 1/RC$

RC Circuit

The noise from the *RC* circuit is given by

$$V_n^2 = 4kT\int_0^\infty R(f)\,df$$



$$R(f) = Re(Z) = \frac{G}{G^2 + \omega^2 C^2}$$

$$Z = \frac{G - j\omega C}{G^2 + \omega^2 C^2}$$

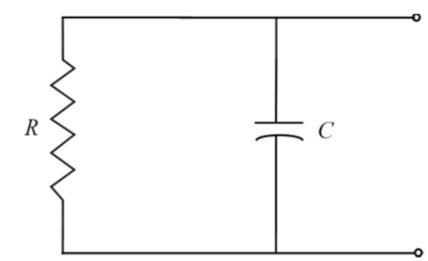
In terms of $\omega_2 = 1/RC$, $R(f) = \frac{1}{R\left[\frac{1}{R^2} + \frac{\omega^2}{\omega_2^2 R^2}\right]}$

$$R(f) = \frac{R}{\left[1 + \frac{\omega^2}{\omega_2^2}\right]}$$

RC Circuit

The noise from the *RC* circuit is given by

$$V_n^2 = 4kT\int_0^\infty R(f)\,df = \frac{4kT}{2\pi}\int_0^\infty \frac{R}{1+\frac{\omega^2}{\omega_2^2}}\,d\omega$$



Using $\int \frac{dx}{a^2+b^2x^2} = \frac{1}{ab} tan^{-1}\frac{bx}{a}$

$$V_n^2 = \frac{4kTR}{2\pi}\omega_2\frac{\pi}{2} = 4kTRf_2\frac{\pi}{2}$$

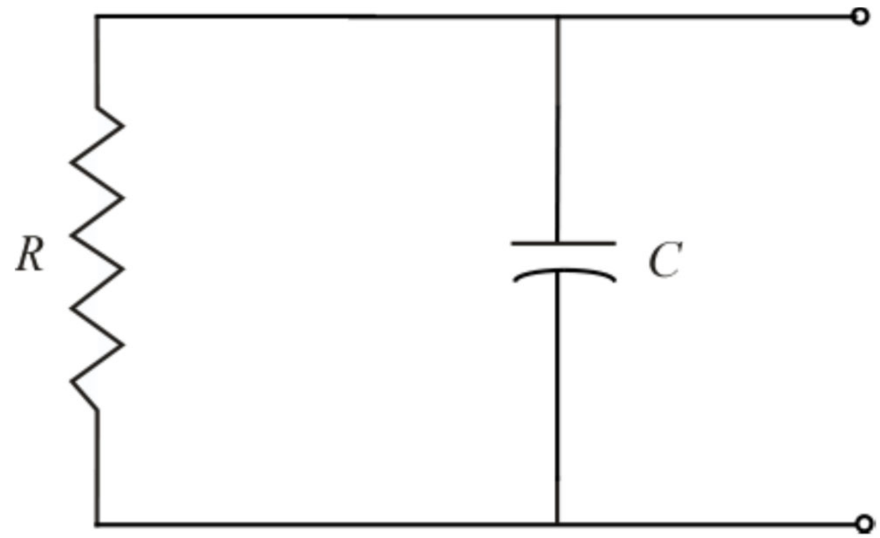
The coherent signal bandwidth is from 0 to f_2

RC Circuit

For an *RC* circuit,

$$V_n^2 = \frac{4kTR}{2\pi}\omega_2\frac{\pi}{2} = 4kTRf_2\frac{\pi}{2}$$

where $f_2 = \dfrac{1}{2\pi RC}$

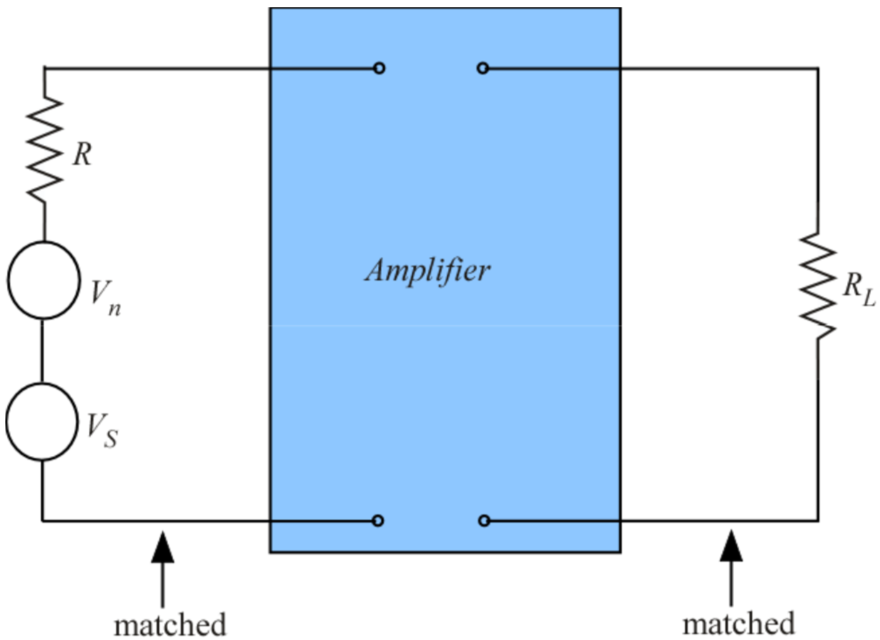


Consequently,

$$V_n^2 = 4kTR\frac{\pi}{2\pi RC2} = \frac{kT}{C}$$

Independent of resistance!

Noise Factor

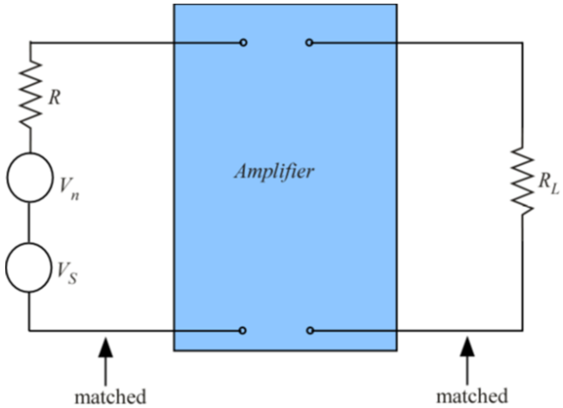


The noise at the input N_{in} is given by

$$N_{in} = \frac{V_n^2}{R_{in}} = \frac{4kTBR}{(2)^2 R} = kTB$$

S_{in} – Signal power into the amplifier
N_{in} – Noise power into the amplifier
S_o – Signal power at the output
N_o – Noise power at the output

Noise Factor



Let N_{int} be the noise power generated in the amplifier referenced to the amplifier input

The total noise power at the amplifier output is:

$$N_o = N_{in}G + N_{int}G$$

where G is the power gain. We define the noise factor as:

$$Noise\ Factor = F = \frac{S_{in} / N_{in}}{S_o / N_o} > 1$$

if noise is generated by the amplifier

Noise Figure

$$F = \frac{S_{in}/N_{in}}{S_o/N_o} = \frac{S_{in}}{N_{in}} \times \frac{N_o}{S_o} = \frac{S_{in}}{N_{in}} \times \frac{N_o}{S_{in}G}$$

$$F = \frac{N_o}{kTBG} = \frac{N_{in}G + N_{int}G}{kTBG}$$

$$F\left(kTB\right) = kTB + N_{int}$$

$$N_{int} = \left(F-1\right)kTB$$

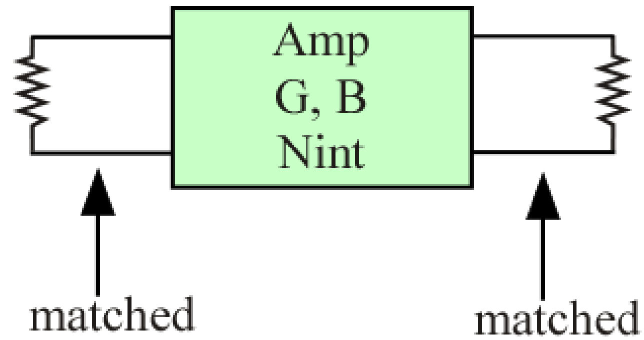
The *Noise Figure* is the noise factor expressed in decibels

$$NF = 10\log(F)$$

Noise Figure

$$F = \frac{S_{in}/N_{in}}{S_o/N_o} = \frac{S_{in}}{S_o} \times \frac{N_o}{N_{in}} = \frac{1}{G} \times \left[\frac{(N_{in} + N_{int})G}{N_{in}} \right]$$

$$F = \frac{1}{G} \times \left[\frac{(kTB + N_{int})G}{kTB} \right]$$



$N_{in} = kTB$ **if matched**

To have a standard value for F, we use $T = 290^o$ for the temperature of the resistor giving the N_{in}

$$F(G)kTB = (kTB + N_{int})G$$

$$(F-1)kTB = N_{int}$$

Noise Figure - Example

Receiver

NF=9 dB, BW=3 kHz, R_o = 500 Ω, R_{in} = 50 Ω, G = 10^8

$$NF = 10\, log_{10} \frac{S_{in} / N_{in}}{S_o / N_o}$$

What input signal voltage do we need to get S_o/N_o = 10?

$$S_o = GS_{in} \qquad N_o = G\,N_o\big|_{in}$$

$$N_o = kTBG + N_{int}G = kTBG + \left(F-1\right)kTBG$$

$$N_o\big|_{in} = F\left(kTB\right) = 8\times 1.38\times 10^{-23}\times 290\times 3\times 10^3 = 9.936\times 10^{-17}\ watts$$

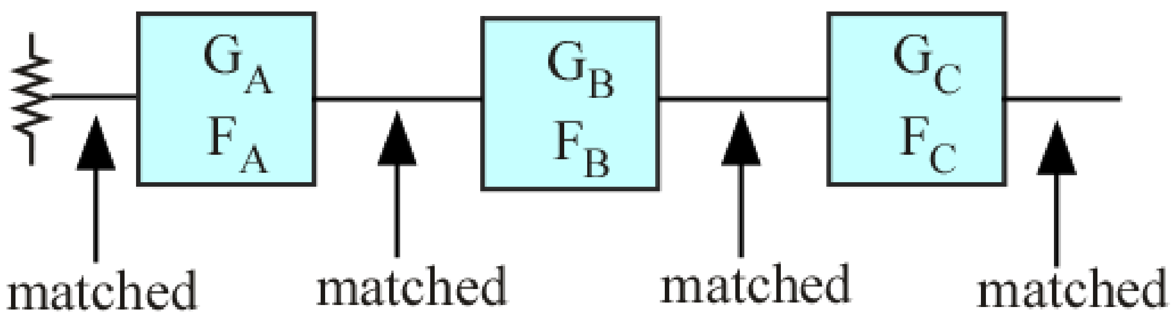
Noise Figure - Example

For $S_o/N_o = 10$, we need

$$S_{in} = 10N_o\Big|_{in} = \frac{V_{in}^2}{R_{in}} = \frac{V_{in}^2}{50\Omega} = 10\times 9.93\times 10^{-17}\ watts$$

$V_{in} = 0.223\ \mu V$

Cascaded Stages



What is the overall Noise Factor?

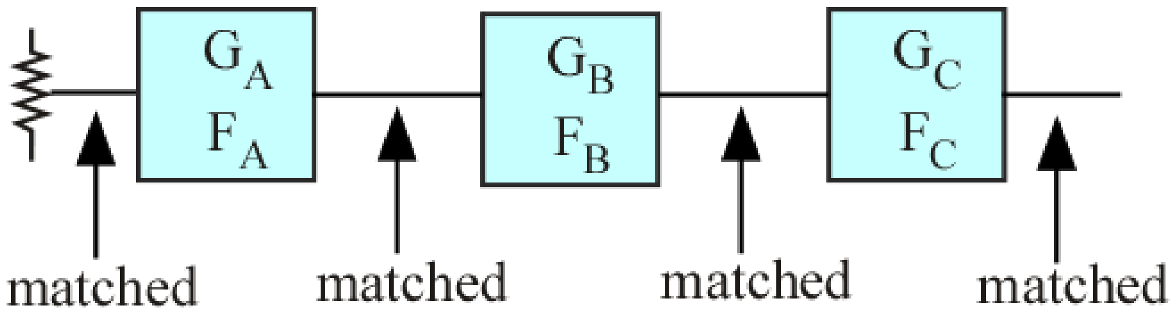
$$N_{output} = kTBG_A G_B G_C + (F_A - 1)kTBG_A G_B G_C$$
$$+ (F_B - 1)kTBG_B G_C + (F_C - 1)kTBG_C$$

F of 3 stages

$$F = \frac{N_o}{GN_{in}} = \frac{N_o}{kTBG_A G_B G_C}$$

$$= 1 + (F_A - 1) + \frac{(F_B - 1)}{G_A} + \frac{(F_C - 1)}{G_A G_B}$$

Cascaded Stages



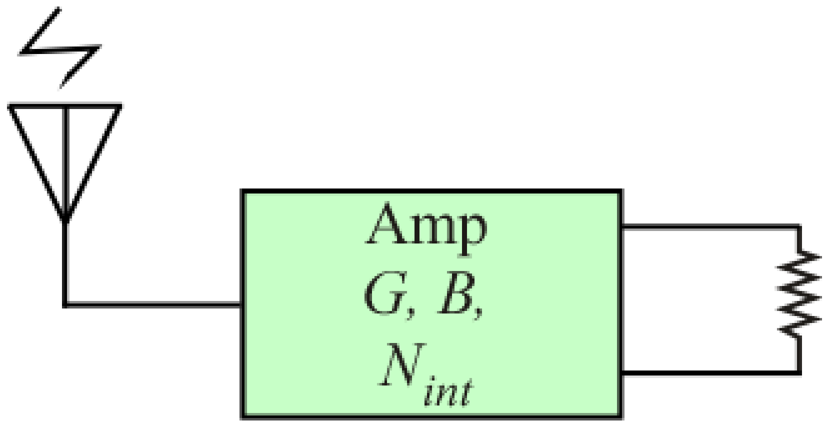
Noise Factor of 3 stages

$$F = F_A + \frac{(F_B - 1)}{G_A} + \frac{(F_C - 1)}{G_A G_B}$$

Frii's formula for *m* cascaded stages

$$F^T = F_1 + \sum_{n=2}^{m} \frac{F_n - 1}{\prod_{i=2}^{n} G_{i-1}}$$

Antenna



Two noise sources

- Thermal noise from ohmic resistance
- External sources

$$N_o = N_{int}G + N_A G$$

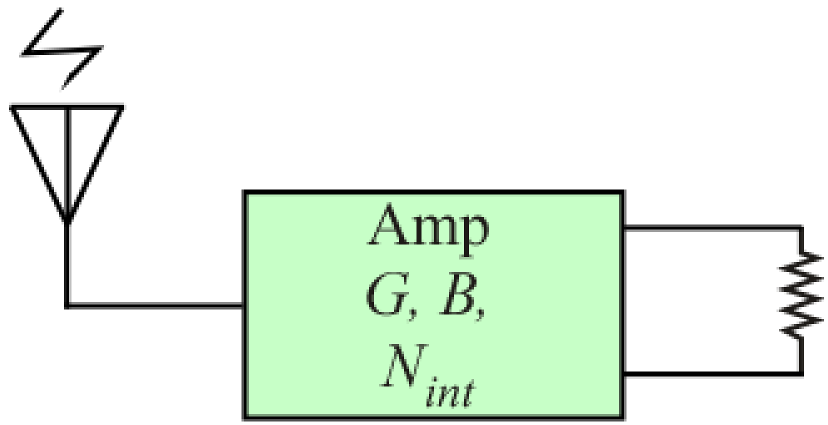
noise from antenna

We can write:

$$N_A = kT_A B$$

T_A = equivalent temperature of the antenna

Antenna



200-Ω antenna exhibiting an rms noise voltage of 0.1 μV with B=10^4 Hz

$$V^2 = 4kT_A RB$$

$$T_A = \frac{V^2}{4kRB} = \frac{10^{-14}}{1.38\times10^{-23}\times200\times10^4} = 90.6K$$

Noise equivalent to that of a 200-Ω resistor at temperature of 90.6K

Antenna

Antenna temperatures

- T_A looking at earth = 300 K
- T_A looking at the moon = 450 K
- T_A looking at the sun = 3000 K

$$N_o = kT_{eq}BG$$

where T_{eq} is the temperature of the system referred to the input of the amplifier

$$N_o = kT_A BG + N_{int}G$$

$$kT_{eq}BG = kT_A BG + (F-1)kT_{stan}BG$$

Antenna

$$T_{eq} = T_A + \underbrace{(NF - 1)T_{290}BG}_{T_{rec}}$$

$$F = \frac{S_{in} / N_{int}}{S_o / N_o}$$

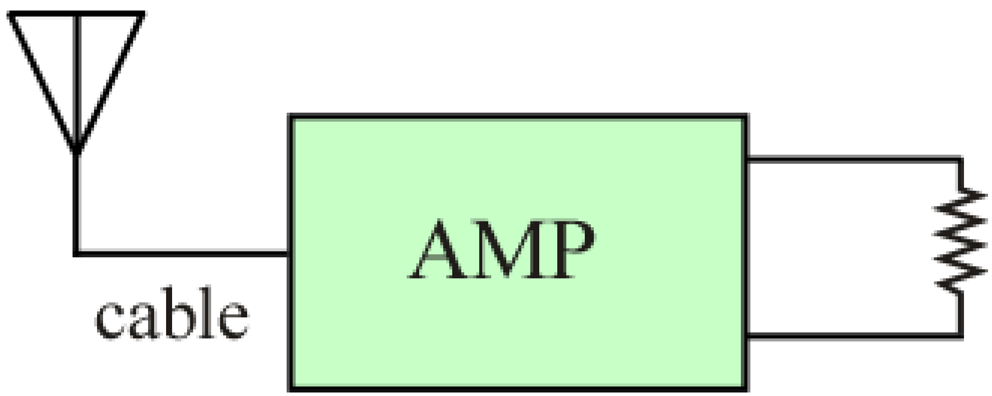
For $F = 1$, the amplifier is noiseless and $T_{rec} = 0$

Cable

RG8v cable given 3dB loss per 100 ft at 200 MHz

Cable

- Attenuates signal
- Attenuates noise from antenna
- Generates noise



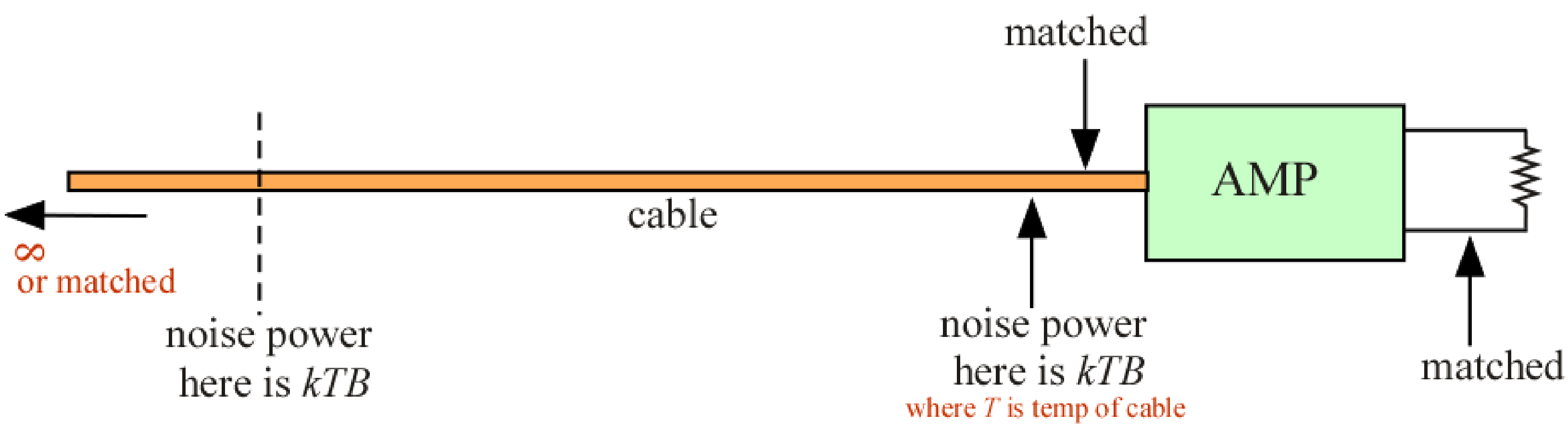
Cable

Let L = loss factor of cable $\quad L = \frac{P_{in}}{P_{out}}$

For 6-dB loss $L = 4$

N into the amplifier $= kT_{cable}B$

Also, N into the amplifier $= \frac{kT_{cable}B}{L} +$ Noise generated in the finite length of cable



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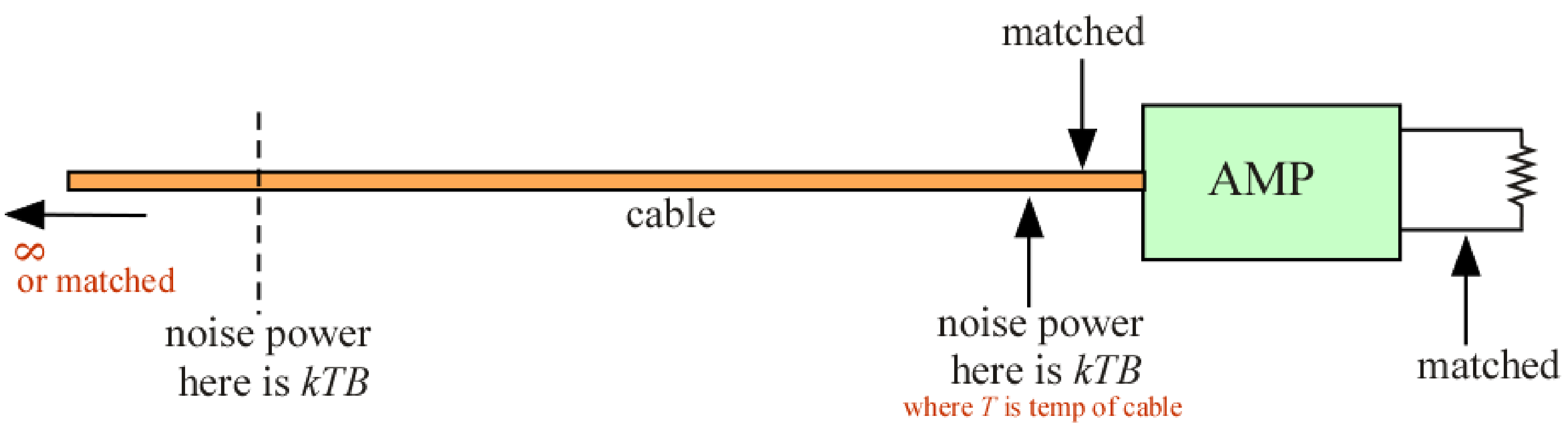

Cable

Noise generated in the finite length of cable $= kT_{cable}B - \dfrac{kT_{cable}B}{L} = kT_{cable}\left[1 - \dfrac{1}{L}\right]B$

The equivalent noise temperature of a finite length of cable = $T_{cable}\left[1 - \dfrac{1}{L}\right]$

- For a short cable $L = 1$ and T_{eq} of cable =0
- For a very long cable $L \rightarrow inf$ and T_{eq} of cable = T_{cable}

$$\underbrace{T_{system}}_{\text{referred to amp input}} = \frac{T_A}{L} + T_{cable}\left[1 - \frac{1}{L}\right] + T_{amp}$$

$$N_o\Big|_{input} = kT_{system}B$$