EEEN3006J

Wireless Systems

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Noise in Radio-Frequency Systems

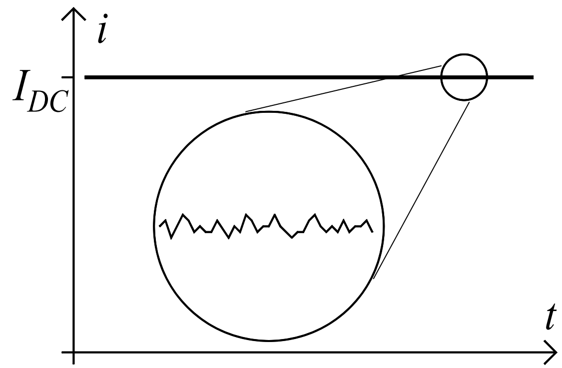
- Noise: a random disturbance
  - Present in all electronic circuits and systems.
  - Noise power is usually very small: significant when dealing with small signals, e.g. radio.
  - Often limits system performance.
- We consider:
  - sources of noise
  - noise analysis
  - system design for low noise.

INTERNAL NOISE SOURCES

Thermal noise

- Some of the noise in a radio receiver is generated within the electronic circuits – often called *internal noise*, *intrinsic noise* or *circuit noise*.
- **Thermal noise (or Johnson noise)**
  - Produced by random motion of electrons in resistive elements. E.g. resistors, MOSFET channels, lossy inductors and capacitors, etc.
  - Zero mean Gaussian p.d.f.
- Constant power spectral density up to > 1THz $\Rightarrow$ *white noise* at RF.

Shot noise

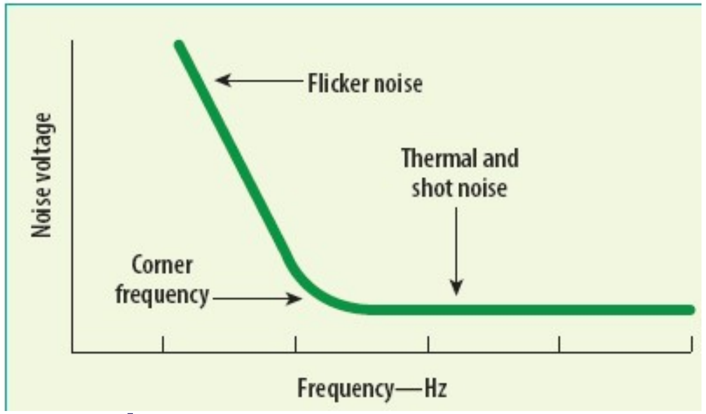


- **Shot noise**
  - Arises when current flows across a junction, as in a diode or transistor.
  - What looks like a steady flow of charge is actually many charge carriers, each with $\pm 1.6 \times 10^{-19}$ C, moving across the junction.
  - The number crossing in any small time interval is random, hence small random current fluctuations (around).
  - Zero mean Gaussian PDF.
- Typically very small, so get effectively white noise into GHz region.

Avalanche noise

- **Avalanche noise**
  - Occurs in Zener diodes and other avalanche-breakdown in *pn* junctions.
    - Sometimes diodes like this are used for noise generation, e.g. random number generators.
  - Similar in principle to shot noise, but larger.
  - Electrons rapidly gain momentum (large reverse bias) and may hit the crystal lattice with such energy that they can dislodge other charge carriers creating hole electron pairs. In turn these carriers are accelerated and may similarly hit the lattice and dislodge further carriers.

Flicker noise



- **Flicker noise**
  - Occurs in active devices, when current is flowing.
  - Imperfections in the semiconductor can produce *traps*, which can *capture* a charge carrier, and later release it.
  - Relatively long time constants, so mainly a low-frequency phenomenon: power spectral density $\propto 1/f$ - “pink noise”.
- Not normally relevant at RF (but can be important in some receiver types).

EXTERNAL NOISE SOURCES

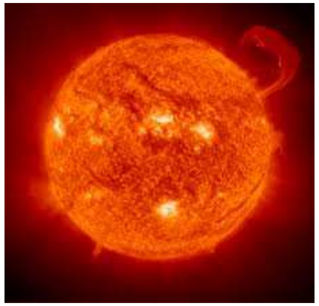
External noise sources

- In principle, all external noise could be kept out of system by screening – surround the system with an earthed metal box – ideally with thick walls of high permeability.
- Perfect screening is very difficult – signals and power supplies must pass through the screen.
- Also, radio receivers have an antenna, which is *designed* to collect electromagnetic radiation and bring it into the system.

Atmospheric noise

- For receivers on Earth
- Electromagnetic radiation due to lightning and other electrical discharges occurring in the atmosphere.
- Most significant below ~30 MHz.

Extra-terrestrial noise



- Electromagnetic radiation from all objects in the universe (also called cosmic noise, galactic noise).
- Stars are high-temperature black-body radiators, radiating over wide range of frequencies
  - Sun is particularly significant.
  - Also pulsars, quasars, etc.
- Background radiation from universe (temperature ~3 K). Most significant above ~20 MHz.

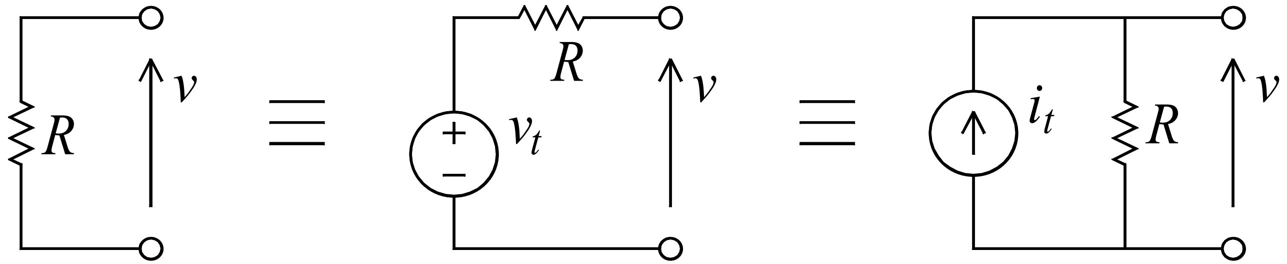
Industrial noise

- Electromagnetic radiation due to human activity – mainly discharges in industrial processes, power line insulators, etc.
- Also high-frequency or high-speed switching in electronic equipment.
- Strongest in urban areas.
- Most significant below a few GHz.
- May have a periodic content.

Interference

- This term is usually used for intended emissions from other systems, which are unwanted in the system being analysed or designed. It may also be applied to unintended emissions (industrial noise?).
- EMI = electromagnetic interference – unwanted emissions.
- EMC = electromagnetic compatibility – regulations controlling unwanted emissions by electronic equipment and susceptibility of electronic equipment to interference.

Noise in 1-port networks: resistor

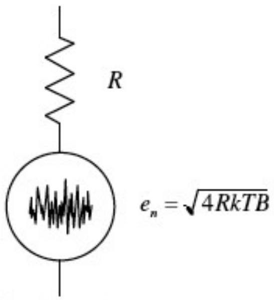


- Thermal noise only. Model as noise voltage source with ideal series resistance.

- Gaussian thermal noise voltage, with $E[v_t] = 0$ mean, and variance $E[v_t^2] = 4kTRB$ (V^2)
  - k = Boltzmann's constant ($1.38\text{x}10^{-23}$ J/K),
  - T = absolute temperature (K),
  - R = resistance (Ω),
  - B = measurement bandwidth (Hz)

  (or the equivalent noise bandwidth of the system; see later).

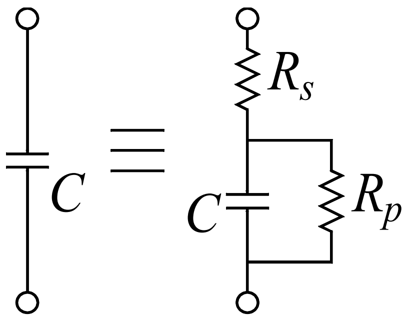
- Dividing by bandwidth, get *mean-squared voltage spectral density* $W_V(\mathrm{f}) = 4kTR$ (V^2/Hz).
- To get power, must connect load resistance.
  - Maximum power transfer for a matched load.
  - Available noise power (max. available power; matched load) is *kTB* W.
  - Divide by bandwidth, available noise power spectral density: $kT = 4 \times 10^{-21}$ W/Hz @ 290K.
- **Note** no <u>net</u> power transfer to load at same temperature: would violate thermodynamics.

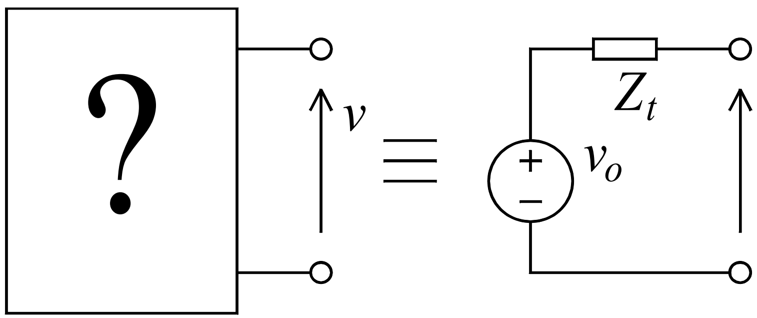


Thermal Noise Source
under matched load conditions

Other passive components

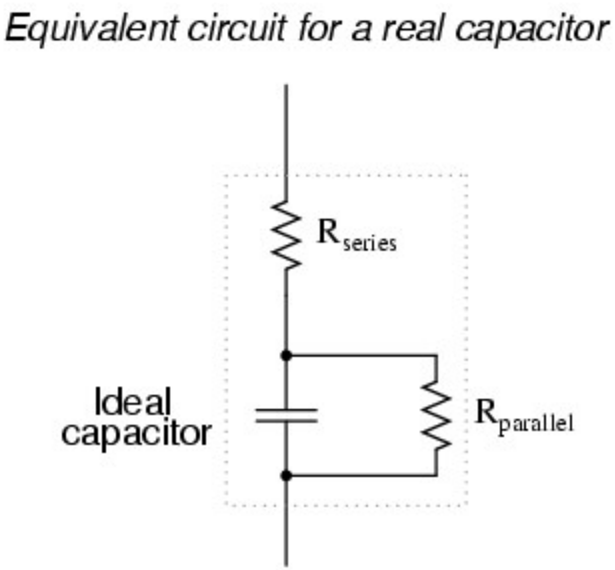
- Ideal capacitors, inductors, transformers, etc. produce no noise (from thermodynamics again).
- Real components have losses, modelled as resistances. These must produce thermal noise just like any other resistance.





Thévenin equivalent

- Any 1-port network can be modelled as Thévenin (or Norton) equivalent circuit, consisting of source and impedance: $z(f) = r(f) + jx(f)$.



Passive network

- A circuit with no power supply (typically R, L, C) gives thermal noise only, so noise output same as noise from resistance R_t at temperature of the network components, T_a. Thus $W_V(\mathrm{f}) = 4kTaRt(f)$ (V^2/Hz).
  - **Note:** Around room temperature, small changes in temperature make little difference (~0.34 %/K), so a standard temperature T_0 = 290 K (~17°C) is usually used for systems which are not specifically cooled or heated.

Active network

- Circuits with power supply, e.g. semiconductor devices.
- Find from small-signal equivalent circuit. May have noise from many sources.
- Can model the total noise **as if** it were all from one source – usually model as thermal noise.
- Need a simple way of expressing how noisy the network is.

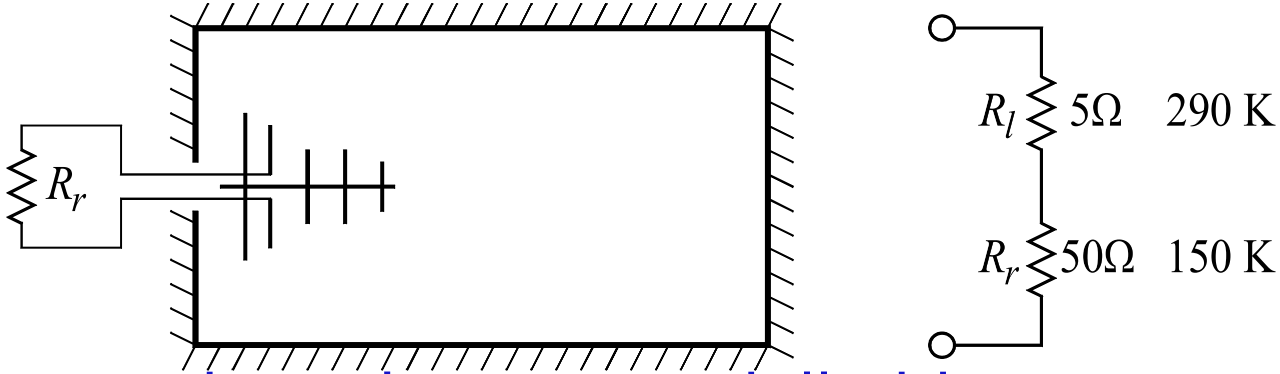
Active network

- **Method 1:** define *equivalent noise resistance*, R_{eq}, which, at the true temperature T_0, would generate noise equal to the noise actually produced by the network: $W_V(\mathrm{f}) = 4kT_0R_{eq}(f)$ (V²/Hz).
- **Method 2:** define *equivalent noise temperature*, T_{eq}, at which the true resistance, R_t, would generate thermal noise equal to the noise actually produced by the network: $W_V(\mathrm{f}) = 4kTeqRt(f)$ (V²/Hz).

Antenna

- Equivalent to 1-port network. At resonance, an ideal antenna appears resistive, with *radiation resistance*, R_r. Power delivered to this resistance will be radiated and absorbed by objects in its environment. These objects also radiate (thermodynamics).
- Radiation resistance is not real, so does not generate thermal noise, but it does have an equivalent noise temperature – accounts for noise power collected by the antenna, so temperature of objects "seen" by antenna.

Antenna

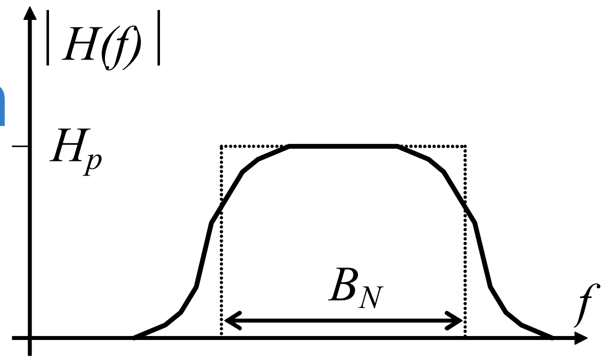


- Real antennas have losses, modelled by a loss resistance R_l (usually small) at the actual temperature of the antenna.
  - Overall equivalent noise temperature of antenna is combination of both.
- Ideal directional antenna, pointed vertically, could have T < 20 K at 10 GHz (clear day).
  - Atmosphere absorbs power, hence also emits noise, so $T \to \sim$ 100 K at lower angles, or higher if the earth included in antenna beam.
- An indoor antenna, or a non-directional antenna in a city, has $T \sim T_0$.

Frequency dependent noise

- Sometimes quote noise at a specific frequency, giving PSD or noise temperature, at that frequency: *spot-frequency* values.
- For relatively narrow-band RF system, can assume noise PSD or noise temperature constant over the bandwidth of the system.
- Or may want total noise power over some B
  - Integrate power spectral density over bandwidth: *broadband* noise power.
  - Modelled as thermal noise ($\propto$ temperature), so total can be expressed as broadband noise temperature. Must specify relevant bandwidth.

Equivalent noise bandwidth



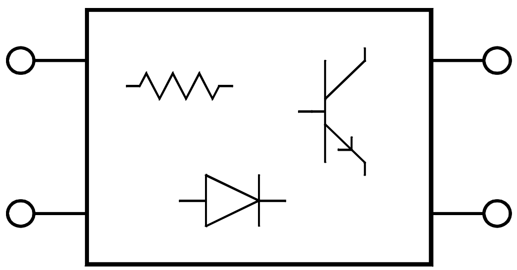
- Consider a system with transfer function as shown.
  - Input white noise, get output noise power spectral density.
  - Integrate over *f* for total output noise power.
- Consider an ideal filter, with the same pass-band gain, with bandwidth so total output noise power is same - same white noise input.
  - That bandwidth is the *equivalent noise bandwidth* of the original system.
  - Easy way to calculate noise power.

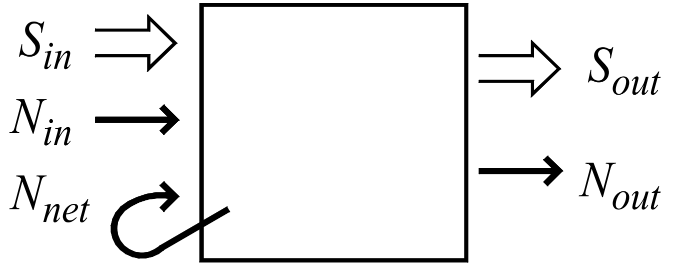
Matched systems

- In most RF systems, all sub-systems are matched, so output impedance of each is matched to input impedance of next (conjugate match). Common values 50 Ω, 75 Ω (esp. TV) – values used for co-axial cables.
- Power gain of amplifier or other 2-port network depends on load and perhaps on source output impedance. We will assume all sub-systems are matched, unless otherwise stated. This simplifies analysis.

Noise in 2-port networks

- This includes many sub-systems of interest: amplifiers, attenuators, filters, transmission lines, etc. All are intended to transport or process the signal in some way, but will also transport or process the noise which arrives with the signal **and** generate additional noise.

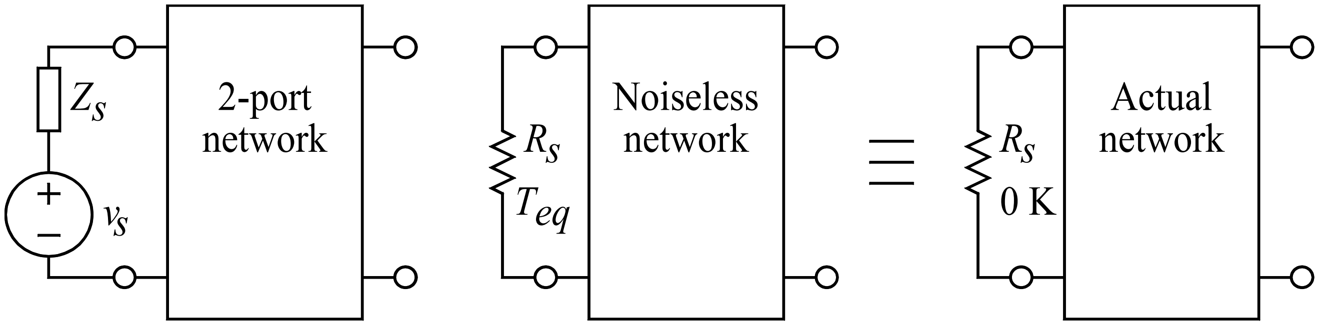




- The network may contain many noise sources – from a system viewpoint, want to model it as if all the noise produced at one point – usually input or output terminals.
- **Example:** Network is amplifier, power gain 10. 10 pW of noise produced by circuit near output terminals can be modelled as 1 pW at input.
- Modelling noise at the input terminals is often convenient – can calculate S/N directly if input signal known.

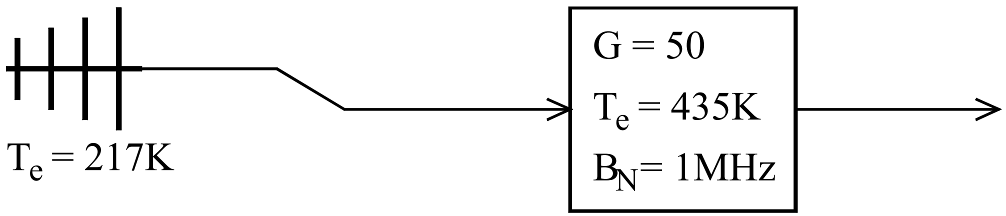
Network noise temperature

- As with all noise temperature, model all noise as if it were thermal noise.
  Express noise power in terms of temperature, since thermal noise power proportional to temperature. Need to know resistance.
- For 2-port network, use the source resistance, or resistive part of source impedance. Model all noise as if produced by at same temperature, called *(equivalent) noise temperature* of network.



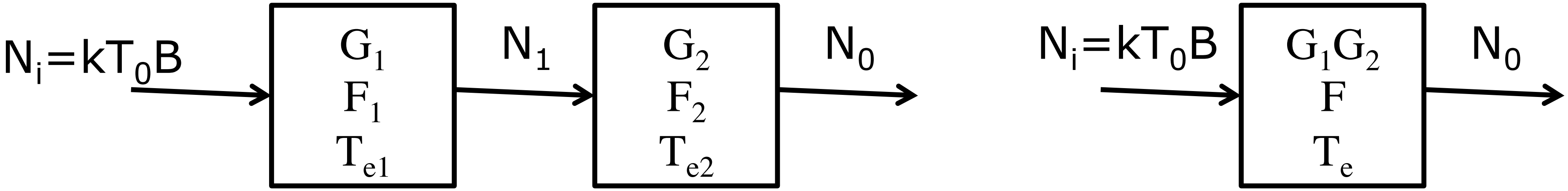
- **Definition:** Noise temperature of a 2-port network is temperature at which the thermal noise from the source resistance, passed through a noiseless version of the network, would produce the same noise at the output as the real network, with noiseless input.
- **Note**: "noise at the output" can be p.s.d. into specified load, total available noise power, open-circuit r.m.s. noise voltage, etc.
- **Note:** Most RF sub-systems matched.

- **Example:** Antenna, noise temp. 217 K, delivers 9 pW of signal to matched amplifier, power gain 50, noise temp 435 K, equivalent noise bandwidth 1 MHz, centred on signal. Find S/N at output, to matched load.



  - Available noise power from antenna: 3 fW.
  - Total noise power "at input" 9 fW.
  - S/N "at input" = 1000, or 30 dB.
  - S/N at output same.

Cascading Components



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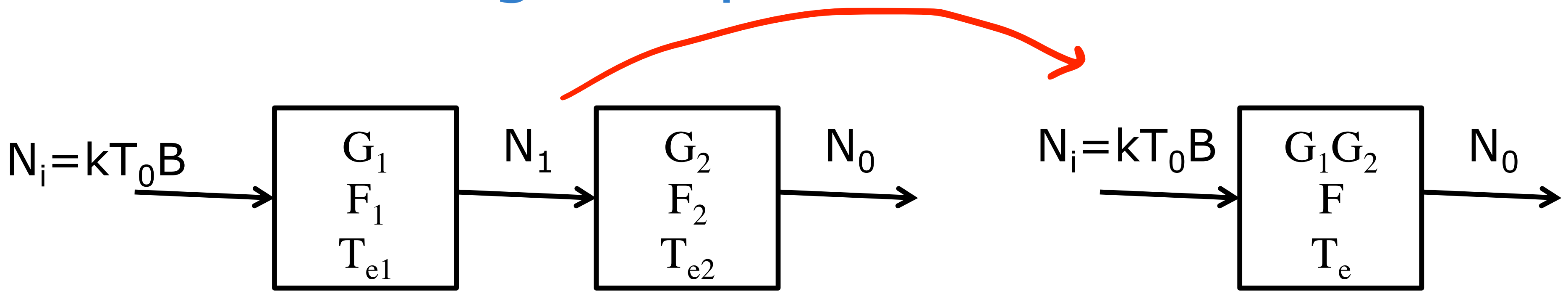

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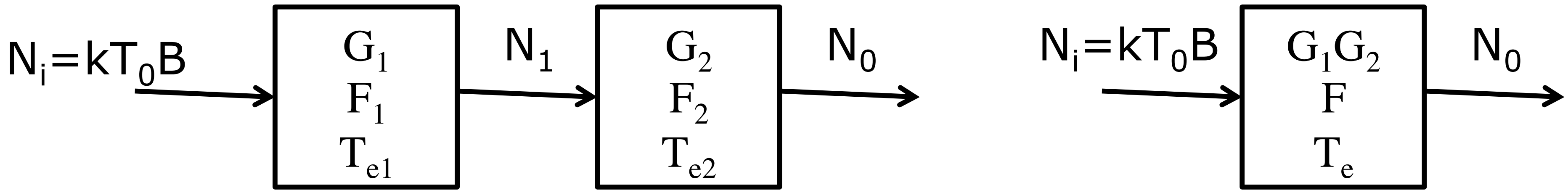
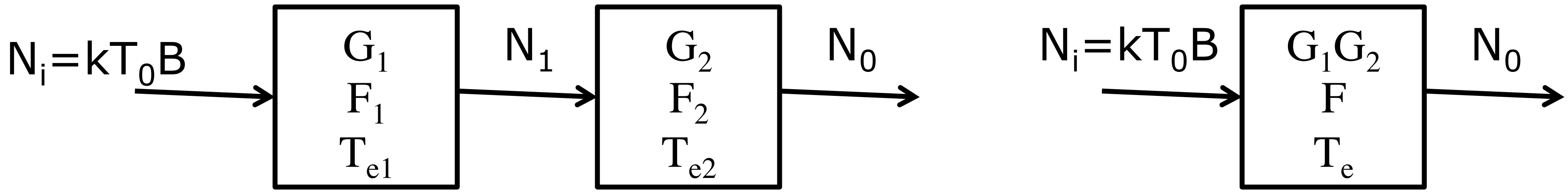


- $N_1 = G_1kT_0B + G_1kT_{e1}B$
- $N_0 = G_2N_1 + G_2kT_{e2}B$

Cascading Components



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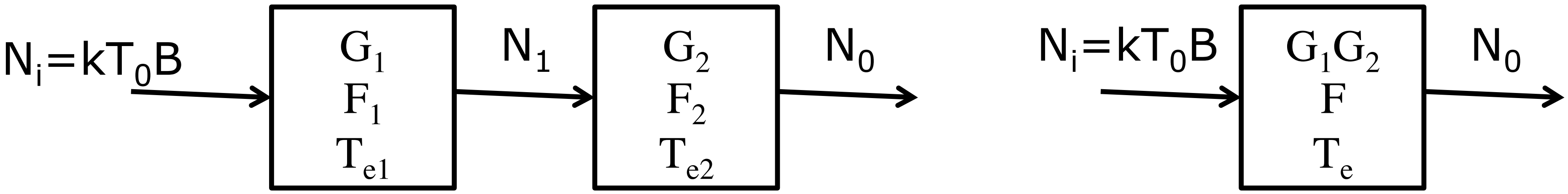
$$\underline{N_0 = G_1G_2kB(T_e+T_0)}$$

Cascading Components



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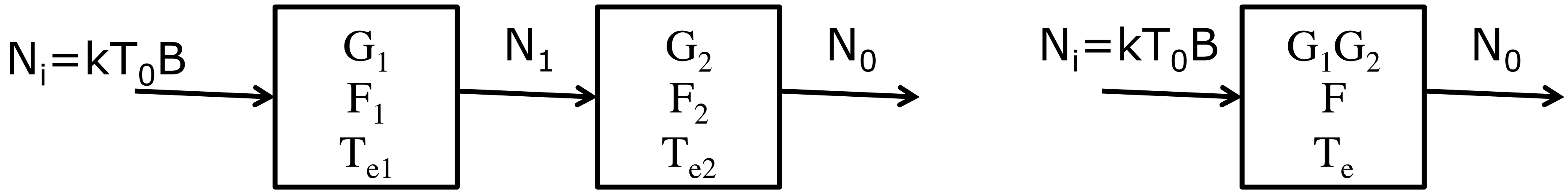
$$\underline{N_0 = G_1G_2kB(T_e+T_0)}$$

- $T_e = T_{e1} + T_{e2}/G_1 + T_{e3}/G_1G_2 + \ldots..$

Cascading Components



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  $\underline{N_0= G_1G_2kB(T_e+T_0)}$

- $T_e = T_{e1} + T_{e2}/G_1 + T_{e3}/G_1G_2 + ...$
- $F = F_1 + (F_2\text{-}1)/G_1 + (F_3\text{-}1)/G_1G_2 + ...$
  – Gain(G) and Noise Factor (F) as linear (not dB)!

Cascading Components

- The best way to compute the output noise power is through noise temperature.
  - Find T_e
  - Find overall gain in the system - G
  - $N_0 = kB(T_e + T_{in})G$
- Noise of the first component in the cascade has the largest effect on cascade noise
  - What design choice can we make from this?

Noise Figure and Noise Temperature

- Noise Figure of of a component:
  - $F = SNR_{in}/SNR_{out}$
- The noise temperature of a component can have a reference to the noise figure:
  - $T_e = (F - 1)T_0$ $\quad$ *$T_0 = 290$ - assume real system temp*

Example

- In satellite TV receiver, usually place first low-noise amplifier at focus of receive antenna – often combined with feed horn – minimal loss before.

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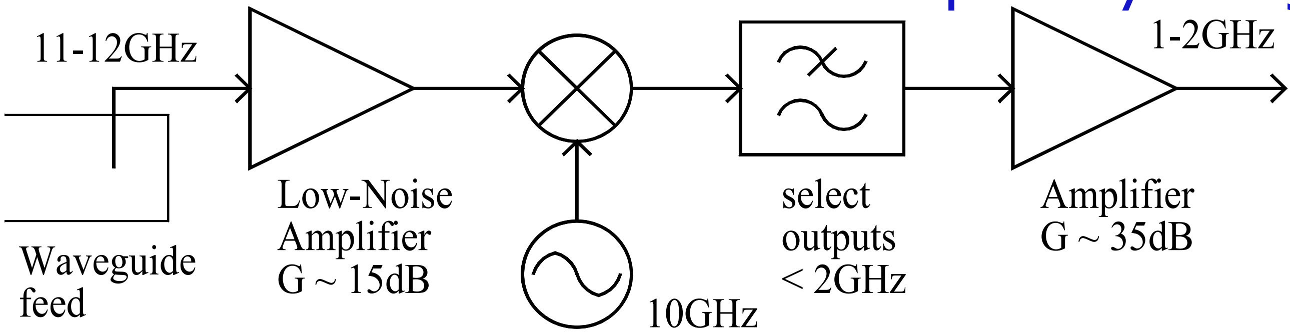
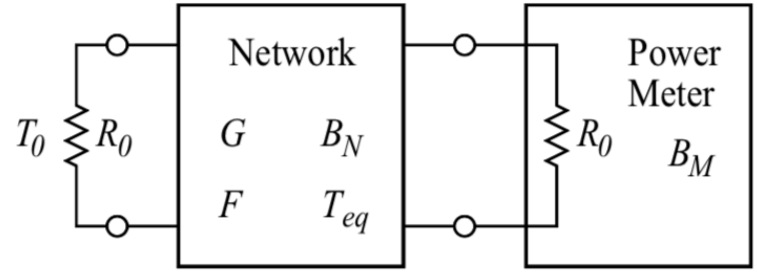
- In satellite TV receiver, usually place first low-noise amplifier at focus of receive antenna – often combined with feed horn – minimal loss before.
- LNB = low-noise block-converter – combines antenna feed, low-noise amplifier, and *block* down-conversion to lower frequency range.



Noise measurement



- How to measure noise temperature or noise factor of 2-port network?
- In principle, connect a matched resistor at input, measure output noise power using matched power meter.
- Difficult to measure noise directly
  - Very small levels of noise.
  - Must have very sensitive equip.

Noise measurement

- Y-Factor method
  - Ratio technique to measure noise of a device.

- Use 2 different matched loads at different temperatures.
  - Hot load, T_1
  - Cold load, T_2
- Test both loads to get
  - $N_1 = GkT_1B + GkT_eB$
  - $N_2 = GkT_2B + GkT_eB$

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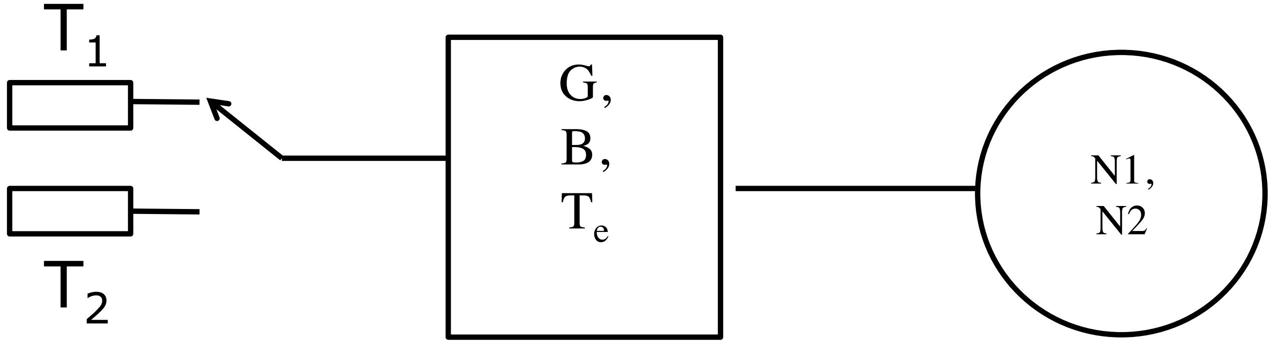

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Noise measurement

- Y-Factor method
  - Ratio technique to measure noise of a device.

$$Y = \frac{N1}{N2} = \frac{T1 + Te}{T2 + Te} \geq 1$$

$$Te = \frac{T1 - YT2}{Y - 1}$$

Antenna noise measurement

- In principle, connect a matched power meter, measure the noise power directly. This would need a very sensitive power meter (since noise power very low), with known equivalent noise bandwidth.
- Easier to measure by comparison. Often use the receiver (which is to be used with the antenna) to amplify the noise – allows measurement to be made at a higher power level, can also define measurement bandwidth, *B*.