Unit-5

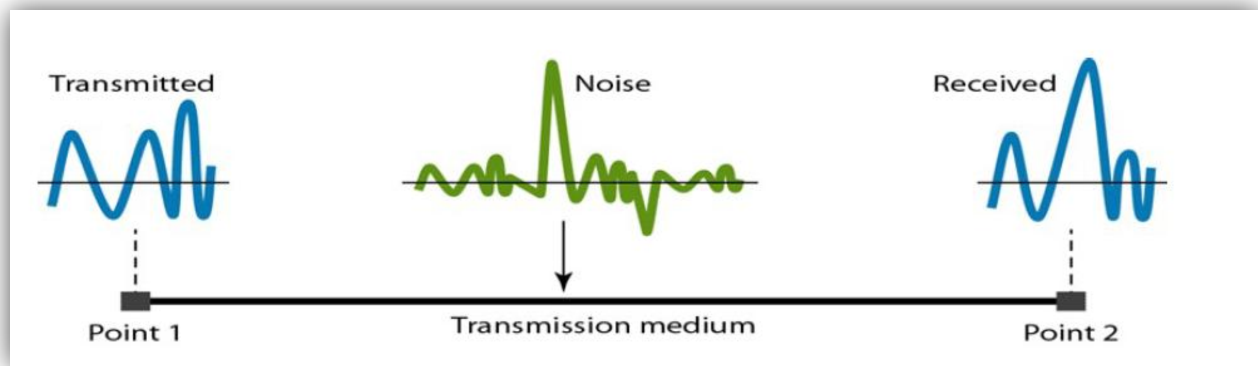
Noise

Introduction:

Communication and control system engineers deal with noise which is random. When a signal containing noise is applied to a communication system, it is necessary to know the effect of noise on the performance of the system

Definition

1) Noise is defined as an undesired or unwanted electrical signal which accompanies the desired signal



2) Noise is an unintentional fluctuation that tends to disturb transmission and reproduction of transmitted signals

About Noise

- Many disturbances of electrical nature reduce noise in communication systems.
- Noise signals may or may not be predictable.
- The presence of noise increases system complexity.
- Noise is present at all frequencies
- Predictable noise has known values and can be eliminated easily.
- Unpredictable noise is random in nature and is called Random Noise. We can eliminate or minimize the effect by finding its statistical behavior.

Some Examples

- Power Supply fluctuations produce hum noise

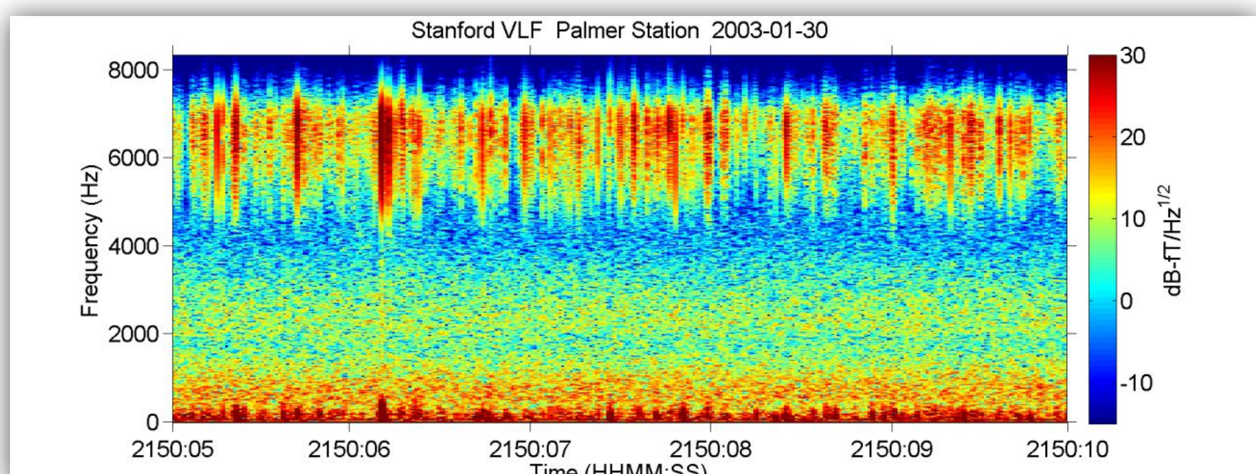
What Does an Electrical Humming Noise Mean?

Some electrical buzzing noises are irritating but ultimately harmless. Others can be the byproducts of bad wiring or electrical failure and can be very dangerous. If you're ever in doubt about whether the source of the noise is a safety concern, shut down the device or circuit making the hum and call an electrician for a safety inspection.

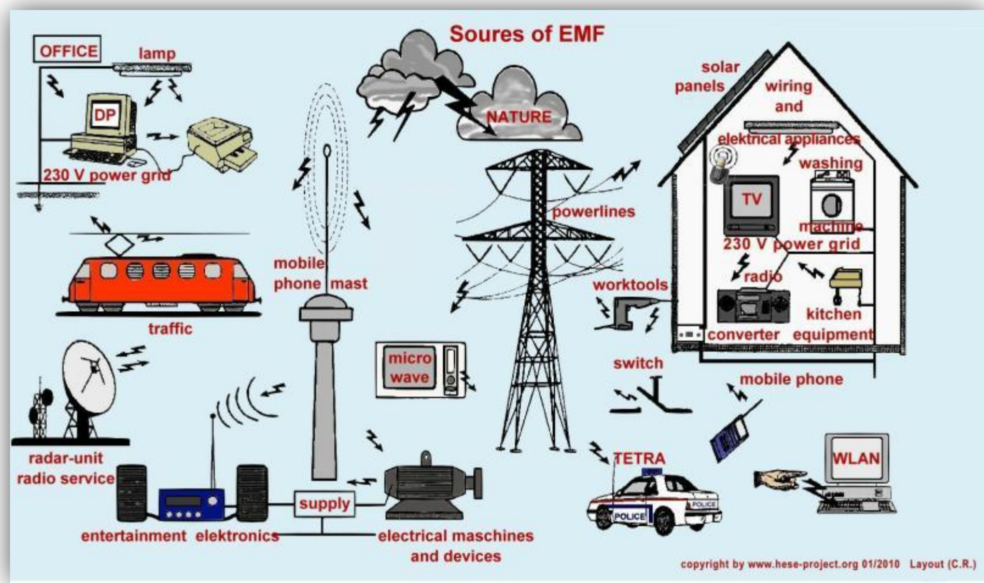
Here are some common sources of electrical humming sounds in the home, along with their likely causes:

- **Light bulbs and fixtures**: Many fluorescent light fixtures make a humming sound. You may need to switch to a different fixture type to get rid of it. Sometimes the sound can come from the bulb itself, especially if it's a cheaper bulb or if it's being used on a dimmer. Upgrade to a high-quality LED bulb to see if that quiets things down.
- **Electric or gas meters**: Newer digital meters are almost always silent, but older meters that have moving parts may emit a noise you can hear inside your home. If you find this is the case, contact your utility provider to inquire about meter replacement or planned upgrades.
- **"Mains hum":** This is something of a catch-all term to refer to the audible sound of alternating current. You may hear this sound coming from appliances that contain electric motors, such as dryers and refrigerators, or from electrical transformers outside your home. Unless the hum becomes a loud buzzing sound, the mains hum is normal and harmless.
- **Wiring and outlets:** These elements can hum for a variety of reasons, many of which signify danger. If an outlet is not grounded properly or if wiring is transferring voltage above the level for which it's rated, they may make a humming noise and could eventually spark a fire. Call an electrician to investigate these electrical buzzing sounds.
- **Circuit breakers:** These are designed to trip when there's too much voltage coursing through a circuit, but some defects or malfunctions can prevent this from happening. This can keep the circuit in an overloaded state, which will produce noise from the breaker box

- In Radio receivers, noise may produce a Hiss in the loud speaker output



- Radiation Generated by electrical / electronic devices

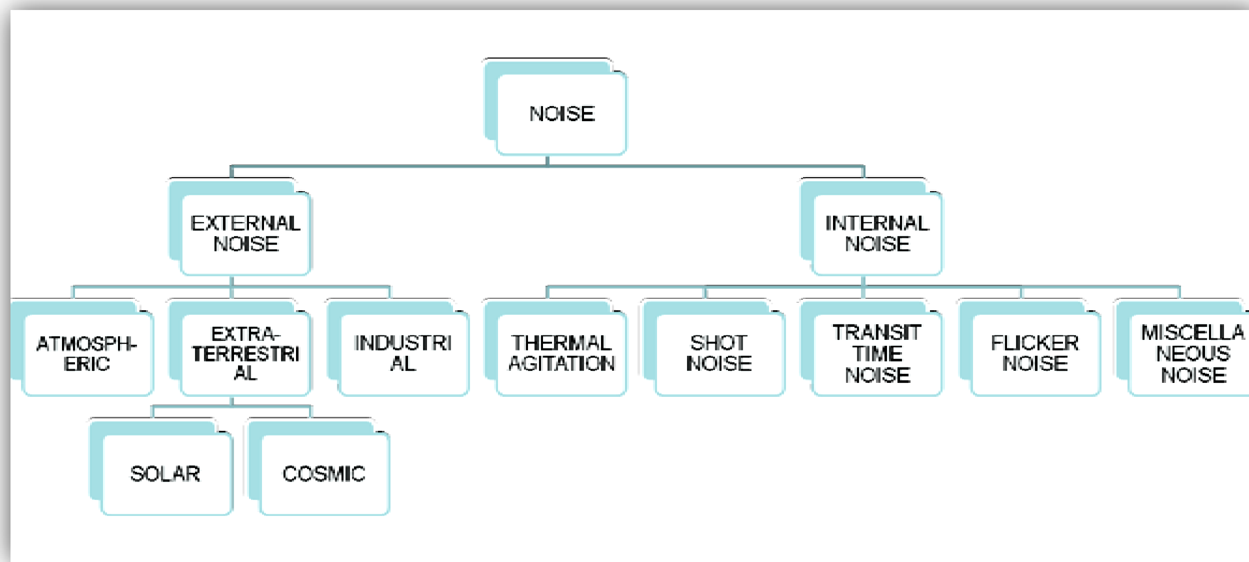


- In TV receivers, noise appear as White Snow on the screen

Effects of Noise

- Produce unwanted signals or may cancel desired values in communication systems
- Cause serious Mathematical errors in computation
- Limit the range of systems for a given transmitted power
- Effects the sensitivity of receivers and may reduce the bandwidth of the system

Classification



External Noise

- Noise whose sources are external to the receiver / system

1) ***Atmospheric Noise***

Impulses caused by Lightning discharges in thunder storms and other natural disturbances

2) ***Extra-terrestrial Noise***

a) Solar Noise

Sun, being at very high temperature(over 6000^{o}C on the surface)

Radiates electrical energy in the form of noise spread over most of the RF spectrum normally used for communications

b) Cosmic Noise

Noise received from Distant stars, Our galaxy (The Milky Way), Other Galaxies, Pulsars

3) Industrial Noise (Man-made Noise)

Electrical disturbances in

- Automobiles and aircraft ignition,
- Electric motors,
- Switching equipment,
- Leakage from high voltage lines and a
- Cross-talk between channels

Internal Noise

- Noise created within a device or a system is called internal noise
- This can be generated by any of the active or passive devices found in receivers.

1) Shot Noise

- This noise occurs mainly due to
  - Random drift of current carriers across the junctions (semiconductor)
  - Random generation and recombination of electron-hole pairs
- This shot noise follows (Discreteness) – Poisson’s Distribution
- This noise occurs in solid-state devices like
  - Tunnel junctions
  - Schottky diodes
  - Vacuum tubes etc

2) Transit Time Noise

At VHF & EHF the time taken by charge carriers to travel from emitter to the collector of a transistor becomes significant during the process of amplification producing random noise.

3) Flicker Noise

- Trapping and release of charge carriers in unsatisfied valence bonds on an immobilized atom produces this noise.
- This noise occurs at low frequencies more often and is called "*1/f" noise*
- It is seen in CRO Screens and TV Screens

4) Resistive / Thermal Noise (Johnson Noise)

- The free electrons within an electrical conductor possess kinetic energy as a result of heat exchange between the conductor and its surroundings.
- This motion is randomized through collisions with imperfections in the structure of the conductor.
- This noise due to this thermal agitation is called Thermal noise / Resistive noise
- Temperature increases in any conducting material the free electrons move more randomly and hence noise increases.
- More noise is generated for a high resistive path.
- Thermal Noise Power is proportional to the temperature in degree Kelvin and the Bandwidth (Hz) of the system

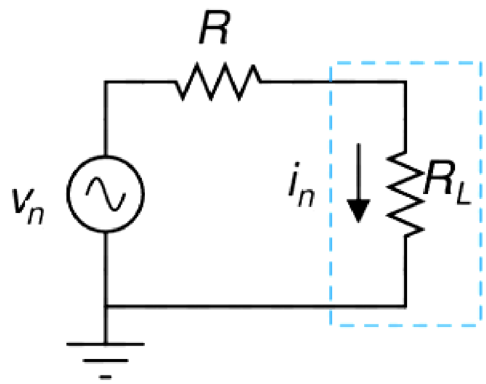
$$P_n \propto TB$$

Noise Power is

$$P_n = kTB \text{ ---------(1)}$$

Where k=Boltzman's constant $=1.38\times10^{-23}$ J/^oK

- The noisy resistor (R) can be modelled as a noise source $V_n(t)$ in series with a resistor R. (Just like Thevinen's equivalent)



- Let the noisy resistor R is driving a load R_L as shown in the circuit.

- The noise current $i_n = \frac{v_n}{R+R_L}$

- According to maximum power transfer theorem, the circuit delivers maximum power when $R = R_L$

- Therefore $i_n = \frac{v_n}{2R}$

- Maximum Noise power delivered to Load is

$$P_n = {i_n}^2 R_L$$

  - Therefore

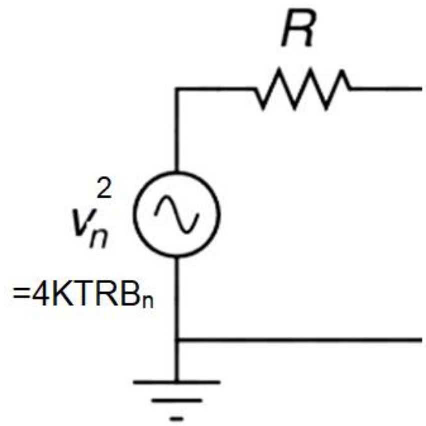
$$P_n = \frac{v_n^2}{4R^2} R_L = \frac{v_n^2}{4R} \text{----------(2)}$$

Equating (1) and (2)

$$\frac{v_n^2}{4R} = KTB_n$$

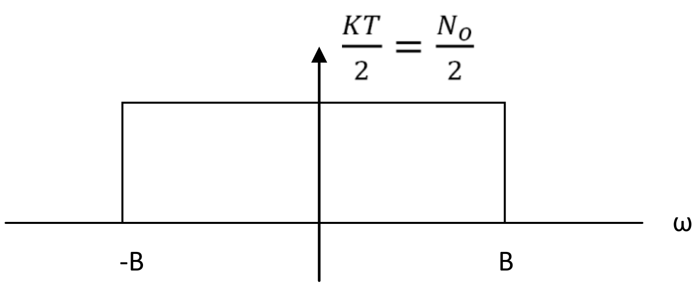
$$v_n^2 = 4KTRB_n \text{--------(3)}$$

  - Hence a noisy resistor R can be represented as a noise-free resistor R in series with noise voltage $v_n(t)$ with mean square value $v_n^2 = 4KTRB_n$



Note:

1. Noise PSD $S_{NN}(\omega)$ is a two sided function (Even function)
2. The Area under PSD is average power in watts
   We know that from (1)
   P_n = kTB = $\frac{KT}{2}.2B$
   That can be represented as Area under the $S_{NN}(\omega)$



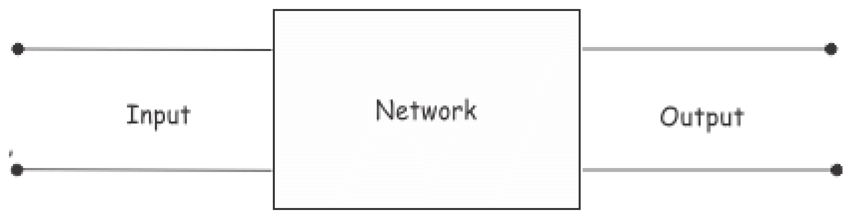
SIGNAL TO NOISE RATIO (SNR)

The ratio of the signal power to the accompanying noise power is called signal to noise ratio (SNR).

$$\frac{S}{N} = \frac{Signal\ Power}{Noise\ Power} = \frac{V_s^2}{V_n^2}$$

(or)

$$\frac{S}{N} = \frac{Signal\ PSD}{Noise\ PSD} = \frac{S_s(\omega)}{S_n(\omega)}$$



Two Part Network

For a two port network

→Input signal to noise ratio

$$\left[\frac{S}{N}\right]_i = \frac{S_{si}(\omega)}{S_{ni}(\omega)}$$

→Output signal to noise ratio

$$\left[\frac{S}{N}\right]_o = \frac{S_{so}(\omega)}{S_{no}(\omega)}$$

Where

$$S_{si}(\omega) = Input\ Signal\ PSD$$
$$S_{ni}(\omega) = Input\ Noise\ PSD$$
$$S_{so}(\omega) = Output\ Signal\ PSD$$
$$S_{no}(\omega) = Output\ Noise\ PSD$$

Available Power Gain

It is defined as

$$G_a(\omega) = \frac{Maximum\ PSD\ of\ Signal\ at\ Output}{Maximum\ PSD\ of\ Signal\ at\ Input} = \frac{S_{so}(\omega)}{S_{si}(\omega)}$$

Equivalent Noise Bandwidth

The equivalent noise bandwidth of a system is defined as the bandwidth of the ideal system which has the same output power as the actual system with infinite Bandwidth.

$$W_N = \frac{\int_0^{\infty} |H(\omega)|^2 d\omega}{|H(0)|^2}$$

And

$$W_N = 2\pi B_N$$

Proof:

The output Noise PSD (from the concept of systems)

$$S_{no}(\omega) = |H(\omega)|^2 S_{ni}(\omega) \text{ ------(0)}$$

Consider a low pass filter as shown in Fig.1 and assume that a white noise is applied at the input of the filter.

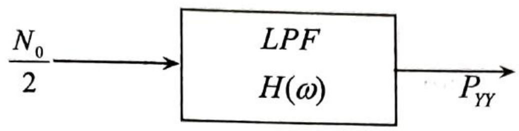


Fig. 1 *Low pass filter*

The output power is $\quad P_{YY} = \frac{1}{2\pi}\int_{-\infty}^{\infty} S_{no}(\omega)d\omega$

$$= \frac{1}{2\pi}\int_{-\infty}^{\infty} \frac{N_0}{2}|H(\omega)|^2\, d\omega$$

$$P_{YY} = \frac{N_0}{2\pi}\int_{0}^{\infty} |H(\omega)|^2\, d\omega \quad \text{-----------} \quad (1)$$

Now consider an ideal system with bandwidth $2W_N$,
The transfer function is

$$H(\omega) = \begin{cases} H(0) & |\omega| < W_N \\ 0 & \text{otherwise} \end{cases}$$

The output power is

$$P_{\text{ideal}} = \frac{1}{2\pi}\int_{-\infty}^{\infty} \frac{N_0}{2}|H(\omega)|^2\, d\omega$$

$$= \frac{N_o}{4\pi}\int_{-W_N}^{W_N} |H(0)|^2\, d\omega$$

$$P_{\text{ideal}} = \frac{N_0}{4\pi}|H(0)|^2 \int_{-W_N}^{W_N} d\omega = \frac{N_0}{4\pi}|H(0)|^2\, 2W_N \text{ ---------(2)}$$

Equating eq. (1) and eq.(2),

$$\frac{N_o}{2\pi}\int_0^\infty |H(\omega)|^2\, d\omega = \frac{N_0}{2\pi}|H(0)|^2 W_N$$

$$\therefore \qquad W_N = \frac{\int_0^\infty |H(\omega)|^2\, d\omega}{|H(0)|^2}$$

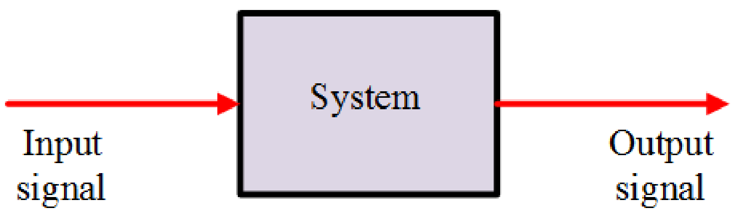
Similarly, for a band pass filter, the equivalent noise bandwidth is the bandwidth of the ideal band pass filter which produces the same output power as the actual system with infinite bandwidth.

$$\therefore \qquad W_N = \frac{\int_0^\infty |H(\omega)|^2\, d\omega}{|H(\omega_0)|^2}$$

where ω_0 is the resonant frequency.

Effective Input Noise Temperature

The total input noise spectral density is equal to the spectral density of the input noise plus the spectral density of the noise generated internally by the system



i.e., $$S_{ni}(\omega) = S'_{ni}(\omega) + S''_{ni}(\omega)$$

where $S'_{ni}(\omega) = \frac{kT}{2}$ is the power spectral density of the input noise

and $S''_{ni}(\omega) = \frac{kT_e}{2}$ is the power spectral density of the noise generated internally by the system. The output power spectral density is

$$S_{no}(\omega) = G_a(\omega)\, S_{ni}(\omega)$$

$$S_{no}(\omega) = G_a(\omega)\left(\frac{kT}{2} + \frac{kT_e}{2}\right)$$

$$S_{no}(\omega) = \frac{kG_a(\omega)(T + T_e)}{2}$$

Note: For a noiseless system, the effective input noise temperature, $T_e = 0$.

Then the output power spectral density is

$$S_{no}(\omega) = \frac{kTG_a(\omega)}{2}$$

NOISE FIGURE

- Noise figure is defined as the ratio of PSD of total noise available at the output of a (2-port) network to the PSD available at the output only due to input noise source.
- Noise figure gives a measure of the system performance of the noise
- It is mathematically expressed as

$$F = \frac{S_{no}(\omega)}{S'_{no}(\omega)} = \frac{S'_{no}(\omega) + S''_{no}(\omega)}{S'_{no}(\omega)} = 1 + \frac{S''_{no}(\omega)}{S'_{no}(\omega)}$$

where $S_{no}(\omega) =$ the total noise power spectral density at the output, $S'_{no}(\omega)$ is the noise power spectral density at the output due to input noise and $S''_{no}(\omega) =$ noise power spectral density at the output due to the noise generated internally by the system.

and If $S_{no}(\omega) = S_{no}'(\omega)$

then $F = 1$

Note: If $F > 1$, the system is said to be a noisy system.

The range of F is $1 < F < \infty$. As F increases, the system becomes noisy.

NOISE FIGURE IN TERMS OF AVAILABLE POWER GAIN

$$F = \frac{S_{no}(\omega)}{S_{no}'(\omega)}$$

$$S'_{no}(\omega) = G_a(\omega)S'_{ni}(\omega)$$

$$= G_a(\omega)kT/2$$

$$\therefore \quad F = \frac{S_{no}(\omega)}{G_a(\omega)kT/2}$$

or $$S_{no}(\omega) = G_a(\omega)FkT/2 \quad \text{---------(1)}$$

where $G_a(\omega)$ = available power gain.

NOISE FIGURE IN TERMS OF INPUT NOISE TEMPERATURE

$$\begin{aligned} S_{no}(\omega) &= G_a(\omega)S_{ni}(\omega) \\ &= G_a(\omega)(S'_{ni}(\omega) + S''_{ni}(\omega)) \\ &= G_a(\omega)(kT/2 + kT_e/2) \end{aligned}$$

$$S_{no}(\omega) = G_a(\omega)k(T + T_e)/2 \quad \text{--------(2)}$$

Comparing eq. (1) and eq. (2),

$$F = (T + T_e)/T = 1 + \frac{T_e}{T}$$

or $$T_e = T(F-1)$$

Note: Noise figure, F in dB $= 10 \log_{10}(F)$ dB.

For a noiseless system, noise figure is $F = 0$ dB.

NOISE FIGURE IN TERMS OF SIGNAL-TO-NOISE RATIO

We know that the signal power spectral density at the output

$$S_{so}(\omega) = G_a(\omega)S_{si}(\omega)$$

$$S'_{no}(\omega) = G_a(\omega)S'_{ni}(\omega)$$

and $$S_{no}(\omega) = F\,S'_{no}(\omega)$$

$$= G_a(\omega)F\,S'_{ni}(\omega)$$

$$S_{no}(\omega) = \frac{S_{so}(\omega)}{S_{si}(\omega)} F S'_{ni}(\omega)$$

$$\therefore \quad F = \frac{S_{si}(\omega)/S'_{ni}(\omega)}{S_{so}(\omega)/S_{no}(\omega)}$$

$$F = \frac{(S/N)_i}{(S/N)_0}$$

where $\quad (S/N)_i = \dfrac{S_{si}(\omega)}{S'_{ni}(\omega)} =$ Input signal-power-to-noise ratio

and $\quad (S/N)_0 = \dfrac{S_{so}(\omega)}{S_{no}(\omega)} =$ Output signal-power-to-noise ratio

Therefore, noise figure is also defined as the signal-power-to-noise ratio of the input to the signal-power-to-noise ratio of the output.

Note

If $(S/N)_i = (S/N)_o$, then $F = 1$ represents an ideal system.

For real systems, $(S/N)_i$ is always greater than $(S/N)_o$. $\therefore$ F is always greater than 1.

AVERAGE NOISE FIGURE

The average operating noise figure $\overline{F}$ is defined as the ratio of the total output available noise power N_o to the total output available noise power N_{so} due to the source alone. It can be expressed as

$$\overline{F} = \frac{N_o}{N_{so}}$$

where $\quad N_o = N_{so} + N_{sys}$

$$N_{so} = \frac{1}{\pi}\int_0^\infty G_a S'_{ni}(\omega)d\omega$$

$$\therefore \quad N_{so} = \frac{k}{2\pi}\int_0^\infty T G_a d\omega$$

and $\quad N_o = \dfrac{k}{2\pi}\displaystyle\int_0^\infty F T G_a d\omega$

$$\therefore \qquad \overline{F} = \frac{\frac{k}{2\pi}\int_0^\infty FT\,G_a d\omega}{\frac{k}{2\pi}\int_0^\infty T\,G_a d\omega}$$

$$\therefore \qquad \overline{F} = \frac{\int_0^\infty FTG_a d\omega}{\int_0^\infty TG_a d\omega}$$

If T is constant, then average noise figure is

$$\overline{F} = \frac{\int_0^\infty F\,G_a d\omega}{\int_0^\infty G_a d\omega}$$

AVERAGE NOISE FIGURE IN CASCADE AMPLIFIERS

Consider two amplifiers that are cascaded.

G_{a_1} : Power gain of amplifier 1

G_{a_2} : Power gain of amplifier 2

T_{e_1} : Equivalent input noise temperature of amplifier 1

T_{e_2} : Equivalent input noise temperature of amplifier 2

F_1 : Noise figure of amplifier 1

F_2 : Noise figure of amplifier 2

The overall gain is

$$G_a = G_{a_1} \times G_{a_2} \qquad \text{----------(1)}$$

The total output noise power available is

$$N_o = N_{o_1} + N_{o_2} + N_{o_3}$$

where N_{o1} = output noise power due to input noise power N_i.

$$\therefore \; N_{o_1} = G_{a_1} G_{a_2} N_i = G_a N_i \qquad \text{-----------(2)}$$

N_{o_2} = output noise power due to noise power generated internally by the first amplifier.

From eq. (1),

$$N_{o_2} = N_{sys1} = G_{a_1} N_i (F_1 - 1)\, G_{a_2}$$

$$\therefore \qquad N_{o_2} = G_a N_i (F_1 - 1) \qquad \text{-----------(3)}$$

N_{o_3} = output noise power due to noise power generated by the second amplifier

$$N_{o_3} = G_{a_2} N_i (F_2 - 1) \qquad \text{-----------(4)}$$

We know that the overall noise figure is

$$F = \frac{N_o}{G_a N_i}$$

or

$$N_o = G_a N_i F$$

Now

$$N_o = N_{o_1} + N_{o2} + N_{o3}$$

$$G_a N_i F = G_a N_i + G_a N_i (F_1 - 1) + G_{a_2} N_i (F_2 - 1) \qquad \text{------(5)}$$

$$F = 1 + F_1 - 1 + \frac{(F_2 - 1) G_{a_2}}{G_{a_1} G_{a_2}}$$

or

$$F = F_1 + \frac{F_2 - 1}{G_{a_1}}$$

Similarly, for three amplifiers cascaded,

$$F = F_1 + \frac{F_2 - 1}{G_{a1}} + \frac{F_3 - 1}{G_{a1} G_{a2}}$$

For N amplifiers cascaded as shown in Fig. 2,

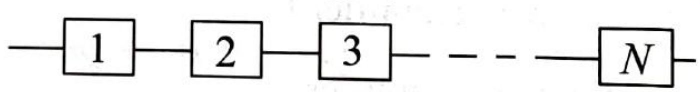


Fig. 2. *Cascaded networks*

the overall noise figure is

$$F = F_1 + \frac{F_2 - 1}{G_{a_1}} + \frac{F_3 - 1}{G_{a_1} G_{a_2}} + \ldots\ldots + \frac{F_n - 1}{G_{a_1} G_{a_2} \ldots. G_{a_{n-1}}} \quad \text{------(6)}$$

This equation is called Fris's formula. It shows that the contribution to overall noise figure is mainly at the first stage.

Equivalent noise temperature

We know that, $F = 1 + T_e / T$

$$F_1 = 1 + T_{e_1} / T$$

$$F_2 = 1 + T_{e_2} / T$$

The overall noise figure for two amplifiers cascaded is $F = F_1 + \frac{F_2 - 1}{G_{a_1}}$

$$\therefore \qquad 1 + \frac{T_e}{T} = 1 + \frac{T_{e_1}}{T} + \frac{T_{e_2}}{G_{a_1} T}$$

$\therefore$ The equivalent noise temperature is

$$T_e = T_{e_1} + \frac{T_{e_2}}{G_{a_1}} \quad \text{----------(7)}$$

For N amplifiers cascaded, the equivalent noise temperature is

$$T_e = T_{e_1} + \frac{T_{e_2}}{G_{a_1}} + \frac{T_{e_3}}{G_{a_1} G_{a_2}} + \ldots\ldots. + \frac{T_{e_n}}{G_{a_1} G_{a_2} \ldots.. G_{a_{n-1}}} \quad \text{----------(8)}$$

support.

o/p Noise power and system noise power

$$N_o = G_a(\omega) . N_i + N_{sys} \quad \text{— (i)}$$

$$F = (S_i/N_i) / (S_o/N_o) = \frac{N_o}{\left(\frac{S_o}{S_i}\right) \cdot N_i} = \frac{N_o}{G_a(\omega) \cdot N_i} \quad \text{— (ii)}$$

from (i) & (ii) $G_a(\omega) \cdot N_i + N_{sys} = F . N_i \, G_a(\omega)$

$$N_{sys} = N_i \, G_a(\omega)(F - 1) \quad \text{— (iii)}$$

SOLVED PROBLEMS

Example -1

The bandwidth of a system is 10 MHz. Find the thermal noise voltage across an 800Ω resistor at room temperature.

Solution

Given $B_N = 10$ MHz, $R = 800\ \Omega$, $T = 300$ K.

The mean square value of noise is

$$v_n^2 = 4kTRB_N$$

$$v_n^2 = 4\times1.3810^{-23}\times300\times800\times10\times10^6$$

$$v_n^2 = 132.48\times10^{-12}$$

rms noise voltage $\quad v_n = \sqrt{132.48\times10^{-12}} = 11.5\ \mu\text{volts}$

Example 2

An amplifier has 3 dB noise figure. Find the equivalent i/p noise temperature at 30ºC.

Solution

Given $\quad F = 3\text{dB}$ or $F = 10^{0.3} = 2$

$$T = 30^\circ\text{C} = 30 + 273 = 303\,^\circ\text{K}$$

Now $\quad T_e = T(F-1)$

$$= 303(2-1) = 303\,^\circ\text{K}.$$

Example -3

An amplifier has 3 stages for which $T_{e_1} = 200^\circ$ K (first stage), $T_{e_2} = 450^\circ$ K and $T_{e_3} = 1000^\circ$ K (last stage). If the available power gain of the second stage is 5, what gain must the first stage have to guarantee an effective input noise temperature of 250°K?

Solution

Given $\quad T_{e_1} = 200\text{K};\quad T_{e_2} = 450\text{K};\quad T_{e_3} = 1000\text{K}$

$$G_2 = 5, \qquad T_e = 250\text{K}$$

we know that effective input temperature,

$$T_e = T_{e_1} + \frac{T_{e_2}}{G_1} + \frac{T_{e_3}}{G_1 G_2}$$

$$T_e = 200 + \frac{450}{G_1} + \frac{1000}{5G_1}$$

$$\text{given} \quad T_e = 200 + \frac{1}{G_1}(450 + 200) = 250$$

$$\therefore \quad G_1 = \frac{650}{50} = 13$$

Example 4

The noise present at the input of a two port network is 5 μW. The noise figure is 0.5 dB. The gain is 10^6. Calculate

(a) the available noise power contributed by the two port system.

(b) O/P available noise power.

Solution

Given watts $N_i = 5\mu\text{W} = 5\times10^{-6}$ watts

$$F = 0.5\,\text{dB} \text{ or } F = 10^{0.05} = 1.122$$

$$G = 10^6$$

(a) Available noise power contributed by the two port system is

$$N_{SYS} = G(F-1)N_i$$

$$N_{SYS} = 10^6(1.122-1)\times5\times10^{-6} = 0.61 \text{ watts}$$

(b) Noise power available at the output

$$N_o = GFN_i$$

$$= 10^6 \times 1.122 \times 5 \times 10^{-6} = 5.61 \text{ watts}$$

EXERCISE PROBLEMS

1. An amplifier with $G_a = 40\,\text{dB}$ and $B_N = 20$ KHz is found to have $T_e = 10^\circ$ K. Find noise figure.

2. The noise figure of an amplifier is 0.2 dB. Find the equivalent temperature T_e.
3. An amplifier has a standard spot noise figure $F_0 = 6.31(8.0\,\text{dB})$. An engineer uses the amplifier to amplify the output of an antenna that is known to have antenna temperature of $T_a = 180^\circ\text{K}$.
   (a) What is the effective input noise temperature of the amplifier?
   (b) What is the operating spot noise figure?

4. A satellite receiver has the following specifications

   $T_e = 4\,\text{K}, \quad F_2 = 3\,\text{dB}, \quad F_3 = 10\,\text{dB}$

   $G_1 = 20\,\text{dB}, \quad G_2 = 40\,\text{dB}, \quad G_3 = 60\,\text{dB}$

   $T_0 = 290\,\text{K}, \quad B_N = 1\,\text{GHz}$

   Find the available noise power at the receiver output.