CHAPTER 6
Noise

6.1 Real versus Ideal:

When we process an electrical signal which contains information, we find that at the output of the system there exist other signals in addition to the processed information. Those spurious signals may be classified as: interference, distortion and noise.

Interference refers to signals other than the desired channel - as we saw in the case of radio receiver - due to error in tracking or local oscillator instability. It could also appear as pick up in the wires due to a strong nearby transmitter or power lines. Both electromagnetic and electrostatic induction or coupling can cause interference pickup.

Distortion refers to a non - ideal treatment of an input signal by a real system. There are 3 types of distortion. Amplitude distortion means that the system does not deal with all frequency components of the input signal on the same footing, i.e., some components are favored in gain at the expense of others. As a result, the output is not a faithful reproduction of the input. For the output to be a faithful reproduction of the input, all frequency components must be augmented by the same amount, i.e, the gain is a constant independent of frequency.

There is also frequency distortion. This originates from the nonlinearity of the output / input characteristic. Frequency components that do not exist in the input now appear as cross modulation. We saw before that this property was the premise of the operation of the mixer.

The third type of distortion is phase distortion. An ideal system (in which there is no phase distortion) must have a constant time delay for all frequency components. If the phase shift is $\Phi = \omega\tau$, then the phase relation must be truly linear. This way, the output frequency components appear shifted in time with respect to those at the input. This constant shift in time scale does not degrade the desired quality of the system needed for a faithful reproduction of the signal, usually referred to as a high fidelity (Hi Fi) system.

The third type of unwanted signals is noise. A Hi Fi system is the one that is designed to be immune as much as possible to interference, distortion and noise. All tricks in the book are used to achieve such a system. This becomes costly. But this is the price we have to pay for trying to achieve an ideal result through a non - ideal and imperfect system in a non - ideal and real world.

6.2 What is Noise?

Noise is defined as a random electrical signal. Sometimes, it is introduced intentionally for the purpose of jamming in such military applications known as Electronic Counter Measures (ECM), meant to jam enemy bases of communication, such as radar, planes and missiles. But most of the time, noise is unintentional unwanted electrical fluctuations that exist, regardless of whether there is information or not. These fluctuations represent unwanted signals. If there is no information, these unwanted signals give a measurable random output. In the presence of information, these fluctuations marr the intelligent signal. We can understand the origin of these fluctuations or noise by remembering that an electron-which is a negative charge has three types of motion, a drift motion due to the electric field, diffusion due to concentration gradient and thermal motion due to its kinetic energy.

The second and third types are statistical phenomena. In thermal motion, the electron moves at a high speed (10^5 m/s at room temperature). A moving charge generates a current impulse. Due to collisions and the random nature of this motion, an electron does not maintain a consistent path as it does in drift motion. Therefore, the current impulses generated by this thermal motion average out to zero. (Fig. 6.1).

Fig. 6.1 Noise in time domain

However, the average current is not really what counts. We know, for example, that the average of a sine wave is zero, but the rms (root mean square) is non - zero. Similarly, in noise, what is important is the rms. The rms represents the total energy in the time domain of the signal. So, what we are really saying is that noise represents the thermal energy contained in the electron. Hence, noise is associated with any randomness in the motion of the electron.

There are usually two types of noise; internal noise and external noise. Internal noise is generated in components and in systems involving electron motion. External noise is generated in the medium over which a signal is transmitted. There is very little that can be done to this type of noise. But the designer is always challenged to control the internal noise as much as possible, and to cope with the external noise as the technology serves him.

6.3 Thermal Noise (Johnson Noise):

Thermal agitation cannot be eliminated, but can be reduced by cooling. Nyquist showed that the available thermal noise power P_n is given, for $T >> O\ ^oK$, by

$$P_n = kTB \qquad J/Hz, \qquad (6-1)$$

Where k = Boltzmann's constant = 1.38 X 10^{-23} $J/{}^0K$

T = Absolute temperature in Kelvin ${}^0K$

B = Bandwidth in Hz.

A noisy resistor R can, thus, be represented - using Thevenin's equivalent circuit - by an open circuit rms voltage source $\bar{\bar{v}}_n$ in series with an ideal noiseless resistor R (Fig. 6.2). See Appendix I.

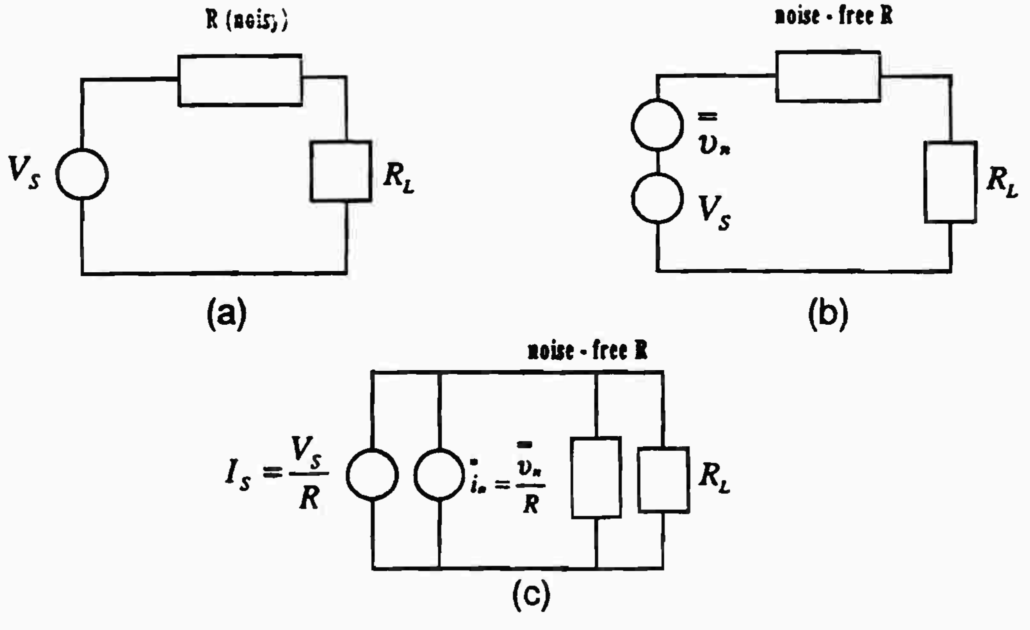

Fig. 6.2 Equivalent representation of a noisy resistor

a) real system b) Thevenin's equivalence c) Norton's equivalence

By the principle of superposition, - forgetting about the intelligent signal V_S for now - we can replace the noisy resistor R by its Thevenin's equivalence (Fig 6-2b). We shall assume that R_L is noise - free and that it is equal to R for matched condition. The rms noise current becomes

$$\bar{\bar{i}}_n = \sqrt{\frac{1}{T}\int_o^T i_n^2(t)\,dt} \qquad (6 \quad 2)$$

We can relate the rms noise voltage $\bar{\bar{v}}_n$ to the rms noise current $\bar{i}_n$ (Fig 6-2c) - using Norton's theorem - by

$$\bar{\bar{i}}_n = \bar{\bar{v}}_n / R \qquad (6 \quad 3)$$

The maximum available power from the noise source becomes

$$P_{n_{max}} = \frac{\overline{\overline{v_n}}^2}{4R} \qquad (6-4)$$

From eqn. (6 1),

$$kTB = \frac{\overline{\overline{v_n}}^2}{4R}$$

or

$$\overline{\overline{v_n}}^2 = 4kTBR \qquad (6-5)$$

Thus, the mean square noise voltage is proportional to temperature, bandwidth, and the value of the noisy resistor R.

6.4 White Noise:

We notice from eqn. (6 1) that Johnson noise power is proportional to B. If we define the spectral noise power $P_n(f)$ as the noise power between $f + df$ and f per unit frequency, so that

$$P_n = \int_{f_1}^{f_2} P_n(f)df \qquad (6-6)$$

Then, from eqn. (6 1):

$$P_n(f) = kT \qquad (6-7)$$

We see that the spectral noise power for $T >> O\ ^oK$ is constant or flat (Fig 6.3). This is called white noise.

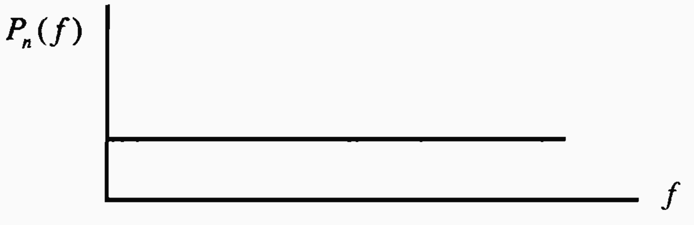

Fig. 6.3 White noise

It is found that the flat response extends up to 10^{13} Hz, after which it starts rolling off according to the quantum theory. We see that for an extended bandwidth, the amount of noise power becomes infinite. Therefore, most practical systems deal with narrowband circuits to limit the amount of noise, by limiting the bandwidth of the circuit to the minimum needed to process the information. If we unduly increase the bandwidth, we do not gain any advantage in the signal quality. On the contrary, the noise of the system increases, thus, degrading the quality of the signal at the output.

There are a number of cases which possess such a flat noise spectrum. Thermal (Johnson) noise is one. Another type (called shot noise) is caused by the fluctuation of free electrons flowing in semiconductors, such as in PN junctions and transistors. The name (shot) refers to the stochastic arrival of electrons at the collector (or plate in vacuum tubes) as shots. See Appendix J. Also, the division of emitter current to base and collector currents in transistors gives rise to partition noise. Also, short breaks in transmission due to bad contacts give noise impulses. All these types of noise are white noise.

In contrast to flat spectrum, there is 1/ noise, which occurs due to fluctuations in the conductivity of semiconductor. It is usually negligible above 1–10 kHz.

The effect of internal noise though cannot be eliminated yet can be controlled by the proper use of components, cooling and screening. However, a transmitted signal will be subject to external noise. This includes atmospheric conditions, tropospheric noise (fluctuations of electrons in the ionosphere), cosmic radiation and sunspots (fluctuations at the surface of the sun emitting random electromagnetic radiation which might blind communication links on the Earth).

6.5 Signal to Noise Ratio:

An important figure of merit is the signal to noise ratio (S/N or SNR). It is defined as

$$SNR = \frac{S}{N} = \frac{Wanted\ signal\ power}{Unwanted\ noise\ power} \qquad (6-7)$$

Hi Fi systems have high S/N. The objective of a good design is to maximize S/N, which is usually expressed in decibels.

6.6 Noise Figure:

The common problem in communication is dealing with weak signals. A signal which is stronger than noise background can be detected by the receiver. The challenge is to detect a signal so weak that it is buried in noise. In such a case, if we use an amplifier it will not help the situation, because the amplifier will amplify both input signal and input noise. In fact, because the amplifier itself has electronic components, it will contribute additional noise of its own. We call this noise excess noise, In other words, S/N at the output of the amplifier is less than S/N at the input, due to this excess noise. Thus, the amplifier does not improve S/N. On the contrary, it degrades it. The amount of degradation is called noise figure F

$$F = \frac{(S/N)_{input}}{(S/N)_{output}} = \frac{S_i/N_i}{S_o/N_o} \qquad (6-9)$$

$$S_o = GS_i \qquad (6-10)$$

$$N_o = GS_i + N_e \;, \qquad (6-11)$$

where N_i is the noise at the input and N_e is the excess noise, G is the power gain. Thus,

$$F = \frac{S_i / N_i}{GS_i /(GN_i + N_e)} = \frac{N_i + (N_e / G)}{N_i} = 1 + \frac{(N_e / G)}{N_i}$$

$$F = 1 + \frac{N_{ei}}{N_i}, \qquad (6-12)$$

where

$$N_{ei} = \frac{N_e}{G}, \qquad (6-13)$$

N_{ei} is the excess noise referred to the input side (Fig 6.4). We notice that $F > 1$. The best situation we can aspire for is $F = 1$, which occurs when we have an ideal amplifier ($N_e = O$). Alternatively, we can obtain an expression for N_e in terms of noise figure as follows:

$$F = \frac{S_i}{N_i}\frac{G(N_i + N_{ei})}{GS_i} \qquad (6-14)$$

Since

$$N_o = G(N_i + N_{ei}) \qquad (6-15)$$

$$F = \frac{S_i}{N_i}\frac{N_o}{GS_i} = \frac{N_o}{GN_i} \qquad (6-16)$$

Or

$$N_o = GN_i F = GN_i + GN_{ei} \qquad (6-17)$$

But

$$GN_{ei} = N_e$$

Thus,

$$N_o = GN_i + N_e$$

$$F = \frac{S_i}{N_i}\frac{GN_i + GN_{ei}}{GS_i} = \frac{GN_i + N_e}{GN_i}$$

$$GFN_i = GN_i + N_e$$

$$N_e = GN_i(F-1) = GN_{ei} \qquad (6-18)$$

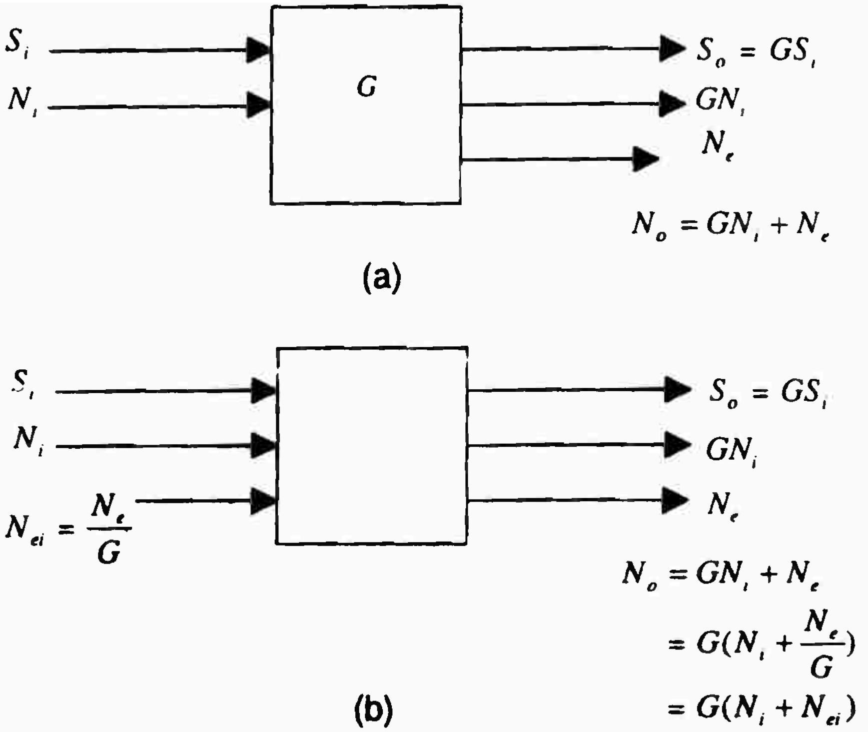

Fig. 6.4 Noise input and output
a) with excess noise at the output side.
b) with excess noise referred to the input side.

Ex. 4.1:

If a system is composed of several stages (Fig. 6.5), find the noise figure for the cascaded system.

Solution:

$$N_o = G_t N_i (F_t - 1), \tag{6 - 19}$$

Where G_t is the overall gain, and F_t is the overall noise figure,

Then,

$$F_t = \frac{N_{ot}}{G_t N_i} = \frac{N_{ot}}{N_i G_1 G_2 G_3} \tag{6 - 20}$$

$$N_{o_t} = G_1 G_2 G_3 N_i + G_2 G_3 N_{e_1} + G_3 N_{e_2} + N_{e_3} \tag{6 - 21}$$

From eqn. (6 – 18),

$$N_{o_t} = G_1 G_2 G_3 N_i + G_2 G_3 G_1 (F_1 - 1) N_i + G_3 G_2 (F_2 - 1) N_i + G_3 (F_3 - 1) N_i$$

From eqn. (6 – 20),

$$F_t = 1 + (F_1 - 1) + \frac{1}{G_1}(F_2 - 1) + \frac{1}{G_1 G_2}(F_3 - 1)$$

$$= F_1 + \frac{(F_2 - 1)}{G_1} + \frac{(F_3 - 1)}{G_1 G_2} \qquad (6-22)$$

Thus, the first stage contributes most to the noise figure. It is also seen that F_t increases as we increase the number of stages. It is important to design the first stage with low noise characteristics. Sometimes, cooling is used for the first stage. The first amplifier should have the lowest noise figure and the lowest gain, while the last amplifier should have the highest gain and the highest noise figure.

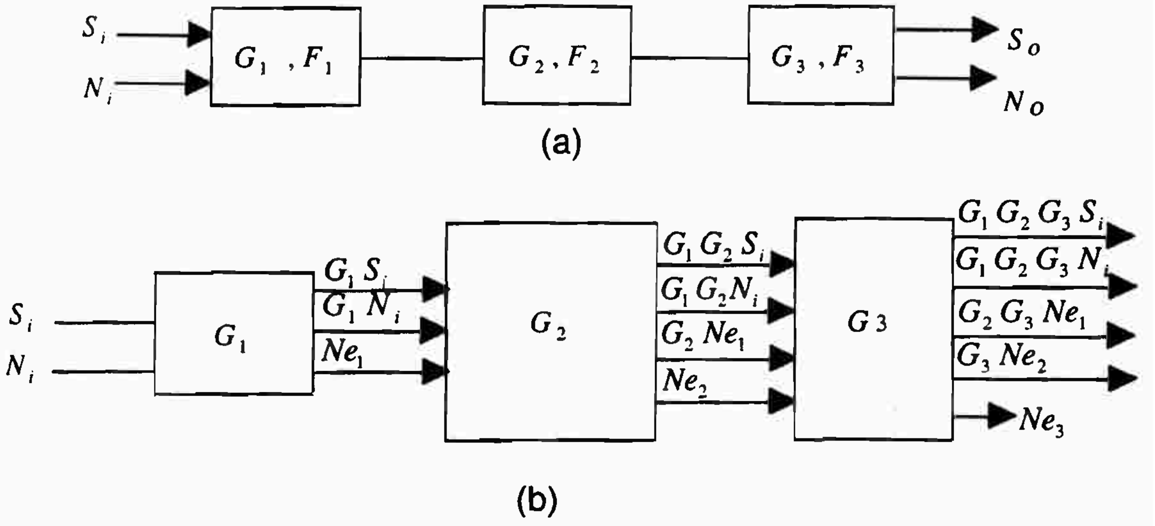

Fig. 6.5 Noise in a cascaded system
a) system block diagram. b) noise calculations.

6.7 Effective Noise Temperature:

We note from eqn. (6-18),

$$N_{e_t} = (F - 1)N_i \qquad (6-23)$$

If we replace

$$N_i = kT_o B \qquad (6-24)$$

$$N_{e_t} = kT_e B \qquad (6-25)$$

Then

$$T_e = (F - 1)T_o \qquad (6-26)$$

$$F = 1 + \frac{T_e}{T_o} \qquad (6-27)$$

Since

$$F_t = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \dots\dots\dots + \frac{F_n - 1}{G_1 G_2 \dots . G_{n-1}} \tag{6 - 28}$$

$$1 + \frac{T_{e_t}}{T_o} = 1 + \frac{T_{e_1}}{T_o} + \frac{T_{e_2}}{G_1 T_o} + \frac{T_{e_3}}{G_1 G_2 T_o} + \dots\dots + \frac{T_{e_n}}{G_1 G_2 \dots - G_{n-1}\ T_o}$$

Or

$$T_{e_t} = T_{e_1} + \frac{T_{e_2}}{G_1} + \frac{T_{e_3}}{G_1 G_2} + \dots\dots \frac{T_{e_n}}{G_1 G_2 \dots\dots G_{n-1}\ T_o} \tag{6 - 29}$$

The effective noise temperature gives a measure for the noise activity in each component and is an overall average noise temperature. We see that increasing the cascade stages does not improve the signal quality. On the contrary, it makes things worse, as far as noise is concerned. Why then do we need amplifiers, single or cascaded, evil as they are? The answer is this. When the signal is very weak, we try to bring it up to a level which allows us to detect it. But the quality gets worse. If the signal is too weak to the point of being buried in the noise at the input, then there is no way to make S/N any better at the output using just an amplifier. In fact, amplification augments the degradation in the signal, which might appear as a hiss in audio signals, or salt and pepper in black and white TV, or colored snow (confetti) in color TV. This situation is similar to problems in photography. When a picture is magnified, we do not make it look any better. In fact, faults in the picture become more visible, not only because we are making these faults bigger, but also because additional distortion due to optics are added, and hence, faults in the picture stand out.

Problems:

1- Determine the values of noise voltage developed in 10kΩ resistor for 6kHz bandwidth at 20°C.

2- 3 amplifiers which have G_1 = 12dB, F_1=2, G_2= 6dB, F_2= 1.7, G_3= 20dB, F_3= 4. Put them in the best order, and calculate the overall noise figure.

3 An amplifier has a power gain of 12dB and has 0.118nw of internal noise referred to the input. Determine the noise figure for the amplifier when the input signal level to the amplifier is 38dBm (dBm is decibels of power referred to 1mw). Calculate S/N at the input and the output, and noise at the output of each stage.

4- Determine the effective noise temperature for each stage and the overall effective noise temperature for problem (2)

5- Determine the noise voltage in a 1k Ω resistor at 25°C for frequency range 50kHz 100kHz.

6- Determine S/N at the output of an amplifier that causes an rms output current of 2mA to flow in a matched load of impedance 1k Ω. The input rms node voltage is 2mV. The amplifier has a gain of 20dB.

7- Find the overall lowest noise figure for the cascaded system, the effective noise temperature for each amplifier and the overall effective noise temperature.

G_1 = 40dB, F_1 = 2

G_2 = 20dB, F_2 = 1.6

G_3 = 10dB, F_3 = 1.3

8- The received input signal level is - 20dBm. Determine the noise figure for a 3 - stage amplifier, which must have S/N = 38dB. Find the best order, lowest noise figure, effective noise temperature for each stage and the overall noise temperature.

G_1 = 16dB	G_2 = 13dB	G_3 = 20dB
F_1 = 2.3	N_{ei} = 80pW (80×10^{-12} W)	F_3 = 1.3

References:

1- "Digital and Analogue Communication Systems," L. Couch, 6th ed., Prentice Hall, Upper Saddle River, N.J, 2001.

2- "Modern Digital and Analogue Communication Systems," B. Lathi, 3rd ed., Oxford University Press, N.Y., 1998.

3- "Analogue and Digital Communication Techniques," G. Smillie, Arnold, London, 1999.

4- "Noise," F.R. Connor, 2nd ed. Arnold, London, 1982.

5- "Electronic Communication Systems.," G.Kennedy, Mc Graw Hill, N.Y., 1986.