NOISE CALCULATIONS

Noise can be defined as any undesired disturbance, be it man-made or natural, in any dynamic electrical or electronic system. It may take the form of atmospheric noise caused by the immense energy of the sun or it may be something as trivial as the thermal noise associated with a carbon resistor. Whatever the source, noise is an obstacle that man has been trying to overcome since time began.

The purpose of this appendix is to simply pinpoint a few of the many sources of noise in the electronic systems of today. We will examine noise in its relationship with amplifier design and receiver systems design. The emphasis of this appendix will be placed on the practical aspects of noise rather than on its probabilistic nature.

TYPES OF NOISE

Basically, we are concerned with two types of noise —thermal noise and shot noise.

Thermal Noise

In any conducting medium whose temperature is above absolute zero (0 Kelvin), the *random* motion of charge carriers within the conductor produces random voltages and currents. These voltages and currents produce noise. As the temperature of the conductor increases, the random motion and the velocity of the charge carriers increase; hence, the noise voltage increases.

The open-circuit noise voltage across the terminals of any conductor is given by:

$$V = \sqrt{4kTRB} \qquad \text{(Eq. B-1)}$$

where,

V = the rms noise voltage in volts,
k = Boltzmann's constant (1.38×10^{-23} j/Kelvin),
T = the absolute temperature in Kelvin (°C + 273),
R = the resistance of the conductor in ohms,
B = the bandwidth in hertz.

Notice that the amount of noise voltage present in the conductor is dependent upon the system bandwidth. The narrower the system bandwidth, the less thermal noise that is introduced. Consequently, for optimum noise performance, the bandwidth of any circuit should never be wider than that required to transmit the desired signal.

> **EXAMPLE B-1**
>
> What noise voltage is produced in a 10K resistor at room temperature (293 Kelvin) over an effective bandwidth of 10 MHz?
>
> *Solution*
>
> Using Equation B-1, we find that:
>
> $$\begin{aligned} V &= \sqrt{4kTRB} \\ &= \sqrt{4(1.38 \times 10^{-23})(293)(10{,}000)(10 \times 10^{6})} \\ &= 40.22 \text{ microvolts} \end{aligned}$$

Thermal noise is also known as *Johnson noise* and *white noise.*

Shot Noise

Shot noise is a type of noise that is common to the particle-like nature of the charge carriers. It is often thought that a dc current flow in any semiconductor material is constant at every instant. In fact, however, since the current flow is made up of individual electrons and holes, it is only the time-average flow of these charge carriers that is seen as a constant current. Any fluctuation in the number of charge carriers at any instant produces a random current change at that instant. This random current change is known as noise.

Shot noise is also often called *Schottky noise* and is found by the formula:

$$I_n^2 = 2qI_{dc}B \qquad \text{(Eq. B-2)}$$

where,

I_n^2 = the mean square noise current,
q = the electron charge (1.6×10^{-19} coulombs),
I_{dc} = the direct current in amperes,
B = the bandwidth in hertz.

NOISE FIGURE

The *noise figure,* or NF, of a network is a quantity used as a "figure-of-merit" to compare the noise in a network with the noise in an ideal or noiseless network. It is a measure of the degradation in signal-to-noise ratio (SNR) between the input and output ports of the network. *Noise factor* (F) is the numerical ratio of NF, where NF is expressed in dB. Thus,

$$NF = 10 \log_{10} F \qquad \text{(Eq. B-3)}$$

and,

$$F = \frac{\text{Input SNR}}{\text{Output SNR}} \qquad \text{(Eq. B-4)}$$

Cascaded Devices

Often, it is necessary to calculate the noise figure of a group of amplifiers that are connected in cascade (Example B-2). This is easily done if the noise figure of each individual amplifier in the cascade configuration is known.

$$F_{TOTAL} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \frac{F_4 - 1}{G_1 G_2 G_3} \cdots \qquad \text{(Eq. B-5)}$$

where,

F_n = the noise factor of each stage,
G_n = the numerical gain of each stage (not in dB).

EXAMPLE B-2

What is the noise figure of the three cascade-connected amplifiers diagrammed in Fig. B-1?

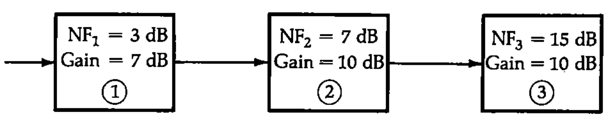

Fig. B-1. Block diagram for Example B-2.

Solution

Since the gains and noise figures of each stage are given in dB, they must first be changed to numerical ratios.

$$F_1 = 2, F_2 = 5, F_3 = 31.6$$
$$G_1 = 5, G_2 = 10, G_3 = 10$$

The overall noise factor is then given by:

$$F_{TOTAL} = 2 + \frac{5-1}{5} + \frac{31.6-1}{(5)(10)}$$
$$= 3.4$$
$$NF = 10 \log_{10} 3.4$$
$$= 5.3 \text{ dB}$$

Another look at Equation B-5 will reveal a very interesting point. If the gain of the first stage is sufficiently high, the denominators of the second and succeeding terms will force those terms to very small values leaving only F_1 in the equation. Hence, the NF of the first stage will typically determine the NF of the cascade configuration (Example B-3).

Lossy Networks

The NF of a lossy network is equal to the loss of the network in dB. For example, a mixer with a conversion

EXAMPLE B-3

If the gain of the first stage in Example B-2 were 25 dB, what would be the NF of the entire cascade?

Solution

We know that 25 dB is a numerical ratio of 316. Therefore, using Equation B-5:

$$F_{TOTAL} = 2 + \frac{5-1}{316} + \frac{31.6-1}{(316)(10)}$$
$$= 2.022$$
$$NF = 10 \log_{10} 2.022$$
$$= 3.06 \text{ dB}$$

Note that the NF of the entire cascade is approximately equal to the NF of the first stage.

EXAMPLE B-4

Find the NF of the receiver whose block diagram is shown in Fig. B-2.

Solution

For analysis purposes, the last three blocks of Fig. B-2 may be replaced with a single block having a noise figure of:

$$NF_c = 10 \text{ dB} + 7 \text{ dB} + 4 \text{ dB}$$
$$= 21 \text{ dB}$$

or,

$$F_c = 126$$

The noise factor looking into the preamplifier is, therefore, equal to:

$$F_{preamp} = F_p + \frac{F_c - 1}{G_{preamp}}$$
$$= 2 + \frac{126-1}{10}$$
$$= 2 + 12.5$$
$$= 14.5$$

Therefore, the NF at the preamplifier is equal to:

$$NF_{preamp} = 10 \log_{10} 14.5$$
$$= 11.6 \text{ dB}$$

The noise figure of the entire receiver is, thus, equal to the sum of 11.6 dB and the noise figure of the two-pole filter.

$$NF_{rcvr} = 11.6 \text{ dB} + 6 \text{ dB}$$
$$= 17.6 \text{ dB}$$

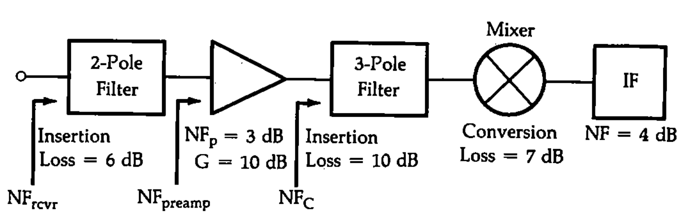

Fig. B-2. Receiver block diagram for Examples B-3 and B-4.

loss of 10 dB has an NF of 10 dB. Similarly, a filter with an insertion loss of 5 dB has an NF of 5 dB.

The NF of two or more cascaded lossy networks can be found simply by adding the losses (in dB) of each network. Thus, if a mixer with a conversion loss of 10 dB is followed by a filter with an insertion loss of 3.5 dB, the combined noise figure of the cascaded network is equal to 13.5 dB (Example B-4).

RECEIVER SYSTEMS CALCULATIONS

The thermal noise that is added to a signal while passing through a system can be calculated as:

$$n_o = kTB \qquad \text{(Eq. B-6)}$$

where,

n_o = the noise power in watts,
k = Boltzmann's constant,
T = the temperature in Kelvins,
B = the noise bandwidth of the system.

Expressed as noise power in dBm, we have:

$$n_o = 10 \log_{10} \frac{kTB}{1 \times 10^{-3}} \qquad \text{(Eq. B-7)}$$

If n_o and the NF of a receiver are known (or can be calculated), the required input signal level to the receiver for a given output signal-to-noise ratio can then be calculated (Example B-5).

$$S_i = NF + n_o + S/N \qquad \text{(Eq. B-8)}$$

where,

S_i = the required input signal level in dBm,
NF = the noise figure of the receiver,
n_o = the thermal noise power of the receiver in dBm,
S/N = the required output signal-to-noise ratio in dB.

EXAMPLE B-5

Using the block diagram shown in Fig. B-2, calculate the required input signal level for a 10-dB signal-to-noise ratio at the output of the if stage. The noise bandwidth (B) is 1.25 MHz.

Solution

The NF of the receiver was determined in Example B-4 to be 17.6 dB.

Calculate n_o using Equation B-7. (Assume a room temperature of 293 K.)

$$n_o = 10 \log_{10} \frac{(1.38 \times 10^{-23})(293)(1.25 \times 10^{6})}{1 \times 10^{-3}}$$
$$= -113 \text{ dBm}$$

Therefore, the required input signal level is calculated as:

$$S_i = NF + n_o + S/N$$
$$= 17.6 - 113 + 10$$
$$= -85.4 \text{ dBm}$$