Chapter 5: Noise

5.1 Noise – Representation, Types and Sources

*Electrical noise is defined as any undesirable electrical energy that falls within the passband of the signal.*

Figure 5.1 shows the effect that noise has on the electrical signal:

![Figure 5.1: Effects of noise on a signal: (a) without noise; (b) with noise](image)

Noise can be divided into two general categories: *correlated* and *uncorrelated*. Correlation implies a relationship between the signal and the noise. Therefore, correlated noise exists only when a signal is present. Uncorrelated noise is present all the time whether there is a signal or not.

5.1.1 Uncorrelated Noise

Uncorrelated noise can be further subdivided into two general categories: external and internal.

External noise (generated outside the device or circuit)

a. Atmospheric noise

- Naturally occurring electrical disturbances that originate within Earth’s atmosphere such as lightning
- Also known as *static electricity*

b. Extraterrestrial noise

- Consists of electrical signals that originate from outside Earth’s atmosphere and therefore also known as *deep-space noise*
- Subdivided into two categories

  - Solar noise that is generated directly from the sun’s heat
  - Cosmic noise/black-body noise that is distributed throughout the galaxies
c. *Man-made noise*

- Noise that is produced by mankind
- The predominant sources of this noise are spark-producing mechanism, such as commutators in electric motors, automobile ignition systems, ac power-generating and switching equipment and fluorescent lights
- Sometimes known as *industrial noise*

**Internal noise (generated within a device or circuit)**

a. *Shot noise*

- Caused by the random arrival of carriers (holes and electrons) at the output element of an electronic device
- Shot noise is randomly varying and is superimposed onto any signal present

b. *Transit-time noise*

- Irregular, random variation due to any modification to a stream of carriers as they pass from the input to the output of a device
- This noise become noticeable when the time delay takes for a carrier to propagate through a device is excessive

c. *Thermal/random noise*

- Associated with the rapid and random movement of electrons within a conductor due to thermal agitation
- Also known as *Brownian noise, Johnson noise* and *white noise*
- Uniformly distributed across the entire electromagnetic spectrum
- A form of additive noise, meaning that it cannot be eliminated, and it increases in intensity with the number of devices and with circuit length
- The most significant of all noise sources
- Thermal noise power

\[
N = KTB
\]  \hspace{1cm} (5.1)

\[
N = \text{noise power (watts)}, \ B = \text{bandwidth (hertz)}, \ T = \text{absolute temperature (kelvin)}
\]

\[
K = \text{Boltzmann’s constant (}1.38 \times 10^{-23} \ \text{joules/kelvin)}
\]

Note: \( T = ^{0}C + 273^0 \)

The following figure shows the equivalent circuit for a thermal noise source when the internal resistance of the source \( R_t \) is in series with the rms noise voltage \( V_n \)
For worst-case condition and maximum transfer of noise power, the load resistance $R$ is made equal to internal resistance. Thus the noise power developed across the load resistor:

$$N = KTB = \frac{(V_N/2)^2}{R} = \frac{V_N^2}{4R}$$

Thus

$$V_N = \sqrt{4RKTB}$$ (5.2)

5.1.2 Correlated Noise

Correlated noise is a form of internal noise that is correlated to the signal and cannot be present in a circuit unless there is a signal. It is produced by nonlinear amplification resulting in nonlinear distortion. There are two types of nonlinear distortion that create unwanted frequencies that interfere with the signal and degrade performance:

a. Harmonic distortion

- Occurs when unwanted harmonics of a signal are produced through nonlinear amplification
- Harmonics are integer multiples of the original signal. The original signal is the first harmonic (fundamental frequency). A frequency two times the fundamental frequency is the second harmonic, three times is the third harmonic, and so on
- Distortion measurements
  - Nth harmonic distortion = ratio of the rms amplitude of Nth harmonic to the rms amplitude of the fundamental
  - Total harmonic distortion (THD)

$$\% \text{ THD} = \frac{v_{\text{higher}}}{v_{\text{fundamental}}} \times 100$$ (5.3)

Notes: $v_{\text{higher}} = \sqrt{v_2^2 + v_3^2 + v_4^2 + \ldots + v_n^2}$ and all in rms values
b. Intermodulation distortion

- Intermodulation distortion is the generation of unwanted sum and difference frequencies produced when two or more signal mix in a nonlinear device (called **cross products**)
- The emphasis here is on the word *unwanted* because in communication circuits it is often desirable to produce harmonics or to mix two or more signals to produce sum and difference frequencies

Figure 5.3 shows both forms of correlated noise

![Figure 5.3: Correlated noise: (a) Harmonic distortion; (b) Intermodulation distortion](image)

5.1.3 Other Noise Types

a. Impulse noise

- Characterized by high-amplitude peaks of short duration (sudden burst of irregularly shaped pulses) in the total noise spectrum
- Common sources of impulse noise: transients produced from electromechanical switches (relays and solenoids), electric motors, appliances, electric lights, power lines, poor-quality solder joints and lightning

b. Interference

- Electrical interference occurs when information signals from one source produce frequencies that fall outside their allocated bandwidth and interfere with information signals from another source
- Most occurs in the radio-frequency spectrum
5.2 Noise Parameters

5.2.1 Signal-to-Noise Power Ratio

Signal-to-noise power ratio (S/N) is the ratio of the signal power level to the noise power level and can be expressed as

\[
\frac{S}{N} = \frac{P_s}{P_n}
\]  

(5.4)

In logarithmic function

\[
\frac{S}{N} \text{(dB)} = 10 \log \frac{P_s}{P_n}
\]  

(5.5)

It can also be expressed in terms of voltages and resistance

\[
\frac{S}{N} \text{(dB)} = 10 \log \left( \frac{V_s^2 / R_{in}}{V_n^2 / R_{out}} \right)
\]  

(5.6)

If the input and output resistances are equal, Equation (5.6) can be reduced to

\[
\frac{S}{N} \text{(dB)} = 20 \log \frac{V_i}{V_n}
\]  

(5.7)

5.2.2 Noise Factor and Noise Figure

Noise factor is the ratio of input signal-to-noise ratio to output signal-to-noise ratio

\[
F = \frac{(S / N)_{in}}{(S / N)_{out}}
\]  

(5.8)

Noise figure is the noise factor stated in dB and is a parameter to indicate the quality of a receiver

\[
NF = 10 \log F = 10 \log \left( \frac{(S / N)_{in}}{(S / N)_{out}} \right)
\]  

(5.9)

Noise Figure in Ideal and Nonideal Amplifiers

An electronic circuit amplifies signals and noise within its passband equally well. Therefore, if the amplifier is ideal and noiseless, the input signal and noise are amplified the same and the signal-to-noise ratio at the output will equal the signal-to-noise ratio at the input. In reality, amplifiers are not ideal. Therefore, the amplifier adds internally generated noise to the waveform, reducing the overall signal-to-noise ratio.

The figure on the next page shows the noise figure for both ideal and nonideal amplifier.
Figure 5.4: Noise figure: (a) ideal, noiseless amplifier; (b) nonideal amplifier

- For Figure 5.4 (a), the input and output S/N ratios are equal
- For Figure 5.4 (b), the circuit adds the internally generated noise $N_d$ to the waveform. Consequently, the output signal-to-noise ratio is less than the ratio at the input

**Noise Figure in Cascaded Amplifiers**

When two or more amplifiers are cascaded as shown below, the total noise factor is the accumulation of the individual noise factors.

- Friiss’ formula is use to calculate total noise factor of several cascaded amplifiers

$$F_T = F_1 + \frac{F_2 - 1}{A_1} + \frac{F_3 - 1}{A_1 A_2} + \ldots + \frac{F_N - 1}{A_1 A_2 \ldots A_N}$$  

(5.10)

- The total noise figure

$$NF_T = 10 \log F_T$$  

(5.11)

Figure 5.5: Noise figure of cascaded amplifiers

Note: To use Friiss’ formula, the noise figures must be converted to noise factors
5.3 Noise and Angle Modulation

When thermal noise with constant spectral density is added to an angle-modulated signal, it produces an unwanted deviation of the carrier frequency. The magnitude of this deviation depends on the relative amplitude of the noise with respect to the carrier. Consider one interfering noise signal with amplitude $V_n$ and frequency $f_n$.

- For PM, the unwanted peak phase deviation due to this interfering noise signal is given by
  \[ \Delta \theta_{\text{peak}} \approx \frac{V_n}{V_c} \text{ rad} \quad (5.12) \]

- For FM, when $V_c > V_n$, the unwanted instantaneous phase deviation is approximately
  \[ \theta(t) = \frac{V_n}{V_c} \sin(\omega_n t + \theta_n) \text{ rad} \quad (5.13) \]

  Taking derivative, we obtain
  \[ \Delta \omega(t) = \frac{V_n}{V_c} \omega_n \cos(\omega_n t + \theta_n) \text{ rad/s} \]

  Therefore, the unwanted peak frequency deviation is
  \[ \Delta \omega_{\text{peak}} = \frac{V_n}{V_c} \omega_n \text{ rad/s}, \quad \Delta f_{\text{peak}} = \frac{V_n}{V_c} f_n \text{ Hz} \quad (5.14) \]

When this unwanted carrier deviation is demodulated, it becomes noise.

- The frequency of the demodulated noise signal is equal to the difference between the carrier frequency and the interfering signal frequency $(f_c - f_n)$
- The signal-to-noise ratio at the output demodulator due to unwanted frequency deviation from an interfering signal is the ratio of the peak frequency deviation due to the information signal to the peak frequency deviation due to the interfering signal
  \[ \frac{S}{N} = \frac{\Delta f_{\text{signal}}}{\Delta f_{\text{noise}}} \quad (5.15) \]

The spectral shape of the demodulated noise depends on whether an FM or a PM demodulator is used as shown in Figure 5.6

- The noise voltage at the output of PM demodulator is constant with frequency
- The noise voltage at the output of FM demodulator increases linearly with frequency
5.4 Preemphasis and Deemphasis

From Figure 5.6, there is nonuniform distribution of noise in FM. Noise at the higher-modulating signal frequency is greater than noise at lower frequencies. Therefore, for information signal with a uniform signal level, a nonuniform signal-to-noise ratio is produced as shown below.

- S/N ratio is lower at the high-frequency ends of the triangle (Figure 5.7 (a))
- To compensate for this, the high-frequency modulating signals are emphasized or boosted in amplitude prior to performing modulation (Figure 5.7 (b))
- At the receiver, to compensate this boost, the high frequency signals are deemphasized or attenuated after the demodulation is performed

In essence, the preemphasis network allows the high-frequency modulating signal to modulate the carrier at a higher level while the deemphasis network restores the original amplitude-versus-frequency characteristics to the information signals.

- A preemphasis network is a high pass filter (i.e. a differentiator)
- A deemphasis network is a low pass filter (i.e. a integrator)

The following figure shows the schematic diagrams for preemphasis and deemphasis and their corresponding frequency response curves.
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Figure 5.8: Preemphasis and deemphasis: (a) schematic diagrams, (b) frequency-response

- The break frequency (the frequency where pre- and deemphasis begins) is determined by the $RC$ or $L/R$ time constant of the network

$$ f_b = \frac{1}{2\pi RC} = \frac{1}{2\pi L/R} \tag{5.16} $$

- The networks shown are for the FM broadcast band, which uses a 75-µs time constant. Therefore the break frequency is approximately 2.12 kHz

From the preceding explanation and Figure 5.8, it can be seen that the output amplitude from a preemphasis network increases with frequency for frequencies above break frequency

- From Equation (4.13), if changes in $f_m$ produce corresponding changes in $V_m$, the modulation index $m$ remains constant

  o This is the characteristic of phase modulation (modulation index independent of frequency)
  o I.e. for frequencies below 2.12 kHz produces FM, and frequencies above 2.12 kHz produce PM