UNIT-V NOISE

Noise is any unwanted random disturbance or variation that interferes with the transmission, reception, or processing of signals.

It reduces the signal-to-noise ratio (SNR) and can distort or mask the desired information.

Mathematically, noise is often modeled as a random process with specific statistical properties (e.g., Gaussian distribution).

Major Sources of Noise

1. Thermal Noise

- Caused by random motion of electrons in resistors and conductive materials.
- Present in all electronic devices.
- Power: $P_n = kTB$, where k= Boltzmann constant, T= temperature, B= bandwidth.

2. Shot Noise

- Originates from discrete charge carriers crossing junctions (e.g., diodes, transistors).
- Current noise PSD: $2qI$, where q= electron charge, I= average current.

3. Flicker Noise

- Also called **1/f noise**.
- Dominant at low frequencies in semiconductors.
- Caused by impurities and defects in materials.

4. Transit-Time Noise

- Occurs in high-frequency devices when carrier transit time becomes comparable to signal period.
- Limits performance of microwave transistors.

5.Intermodulation Noise

- Generated when signals of different frequencies mix in nonlinear devices.
- Produces unwanted spurious frequencies.

6. Atmospheric Noise

- Natural noise from lightning and other atmospheric disturbances.
- Strong in HF (shortwave) bands.

7. Industrial Noise

- Produced by motors, machines, fluorescent lights, switching circuits.
- Often impulsive and broadband.

8. Extraterrestrial Noise

- Cosmic background radiation, solar noise, galactic noise.
- Important in radio astronomy and satellite communication.

Noise Source	Cause	Key Feature
Thermal noise	**Electron motion**	**White spectrum**
Shot noise	**Discrete charge carriers**	**Proportional to current**
Flicker noise	**Material defects**	**Dominant at low freq**
Transit-time noise	**Carrier transit delay**	**High-frequency limit**
Intermodulation noise	**Nonlinear mixing**	**Spurious signals**
Atmospheric noise	**Lightning, storms**	**HF band interference**
Industrial noise	**Machines, circuits**	**Impulsive**
Extraterrestrial noise	**Sun, galaxy, cosmic**	**Radio astronomy impact**

Thermal (Resistive) Noise

- **Thermal noise** (Johnson-Nyquist noise) arises from random electron motion in resistors and lossy components.
- Origin: Random thermal agitation of electrons in resistive materials.
- Power spectral density (PSD): Flat across frequency (white noise).
- Noise power:

$$P_n = k \cdot T \cdot B$$

where $k = 1.38 \times 10^{-23}\, J/K$, T= absolute temperature, B= bandwidth.

- Noise voltage across R:

$V_n = \sqrt{4kTRB}$(rms).

Arbitrary Noise Sources

- **Arbitrary noise** can include:
  - Shot noise (due to discrete charge carriers).
  - Flicker noise (1/f noise in semiconductors).
  - Phase noise (oscillators).
- These sources are modeled as equivalent resistive noise or added PSD contributions.

Effective Noise Temperature

- **Effective noise temperature** (T_e) represents the equivalent temperature of a noisy device.
- Relation: $T_e = T_0(F-1)$, where $F$is noise factor and $T_0 = 290K$.
- Lower $T_e \rightarrow$ better low-noise performance (e.g., cryogenic LNAs).

Noise Equivalent Bandwidth

- **Noise equivalent bandwidth** is the bandwidth of an ideal rectangular filter that passes the same noise power as the actual filter.
- Important for calculating noise power in non-ideal filters.

Noise Figure

- **Noise figure** (NF) quantifies SNR degradation.

$$F = \frac{SNR_{in}}{SNR_{out}}$$

- **Noise figure (NF):**

$$NF = 10\log_{10}(F)$$

(in dB).

- Represents degradation of SNR by a device.
- **Average noise figure** is used when considering multiple measurements or varying operating conditions.
- **Noise figure** is a key metric in RF design.

Step 1: Define Noise Factor
Noise factor is the ratio of input SNR to output SNR:

$$F = \frac{SNR_{in}}{SNR_{out}}$$

Step 2: Input Noise Power
For a source resistance at reference temperature T_0, the input noise power is:

$$N_{in} = kT_0B$$

where $k$is Boltzmann's constant and $B$is bandwidth.

Step 3: Output Noise Power
At the output of a real device, the total noise power is:

$$N_{out} = G \cdot N_{in} + N_{added}$$

where:

- G= gain of the device,
- N_{added}= extra noise contributed by the device itself.

Step 4: Equivalent Noise Temperature
We define an **effective noise temperature** $T_e$such that the device's added noise looks like it came from an equivalent resistor at temperature T_e:

$$N_{added} = G \cdot kT_eB$$

So the total output noise becomes:

$$N_{out} = G \cdot k(T_0 + T_e)B$$

Step 5: Relating Noise Factor to T_e
Now, compute the output SNR:

$$SNR_{out} = \frac{G \cdot S_{in}}{N_{out}} = \frac{G \cdot S_{in}}{G \cdot k(T_0 + T_e)B} = \frac{S_{in}}{k(T_0 + T_e)B}$$

Input SNR is:

$$SNR_{in} = \frac{S_{in}}{kT_0B}$$

Thus, noise factor:

$$F = \frac{SNR_{in}}{SNR_{out}} = \frac{S_{in}/(kT_0B)}{S_{in}/(k(T_0 + T_e)B)} = \frac{T_0 + T_e}{T_0}$$

Step 6: Solve for T_e

$$F = 1 + \frac{T_e}{T_0}$$

$$T_e = T_0(F - 1)$$

or cascaded stages:

$$F_{total} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots$$

where:

- F_i= noise factor of stage i,
- G_i= gain of stage i.

Step 2: Express Each Stage in Terms of Effective Noise Temperature

For a single stage:

$$F_i = 1 + \frac{T_{e,i}}{T_0}$$

So:

$$T_{e,i} = T_0(F_i - 1)$$

Step 3: Substitute into Friis Formula

$$F_{total} = 1 + \frac{T_{e,total}}{T_0}$$

and

$$F_{total} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots$$

Replace each $F_i - 1$with $\frac{T_{e,i}}{T_0}$:

$$F_{total} = 1 + \frac{T_{e,1}}{T_0} + \frac{T_{e,2}}{T_0 G_1} + \frac{T_{e,3}}{T_0 G_1 G_2} + \cdots$$

Step 4: Rearrange to Find $T_{e,total}$

$$1 + \frac{T_{e,total}}{T_0} = 1 + \frac{T_{e,1}}{T_0} + \frac{T_{e,2}}{T_0 G_1} + \frac{T_{e,3}}{T_0 G_1 G_2} + \cdots$$

Cancel the 1's:

$$\frac{T_{e,total}}{T_0} = \frac{T_{e,1}}{T_0} + \frac{T_{e,2}}{T_0 G_1} + \frac{T_{e,3}}{T_0 G_1 G_2} + \cdots$$

Multiply through by T_0:

$$T_{e,total} = T_{e,1} + \frac{T_{e,2}}{G_1} + \frac{T_{e,3}}{G_1 G_2} + \cdots$$

Concept	**Formula / Definition**	**Key Point**
Thermal noise	$P_n = kTB$	**Sets fundamental noise floor**
Effective noise temp	$T_e = T_0(F - 1)$	**Equivalent device temperature**
Noise figure	$NF = 10\log_{10}(F)$	**SNR degradation measure**

Concept	Formula / Definition	Key Point
Friis cascaded NF	$F_{total} = F_1 + \frac{F_2 - 1}{G_1} + \cdots$	**First stage dominates**
Narrowband noise	**Quadrature form**	**In-phase & quadrature components**

Cascaded Networks

- **Friis formula:**

$$F_{total} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \cdots$$

- First stage NF dominates overall system performance.
- Example: A low-noise amplifier (LNA) at the front end reduces total NF significantly.

Noise Equivalent Bandwidth

- Real filters are not perfectly rectangular.
- **Definition:** Bandwidth of an ideal rectangular filter that passes the same noise power as the actual filter.
- **Formula:**

$$B_{eq} = \frac{1}{H_{max}^2} \int_0^\infty |H(f)|^2 \, df$$

where $H(f)$= filter transfer function.

- Important in practical systems for accurate noise power estimation.
- **Noise equivalent bandwidth** ensures fair comparison between filters.

Quadrature Representation of Narrowband Noise

When noise is concentrated around a carrier frequency ω_c, it can be expressed in terms of two **low-pass Gaussian processes**:

$$n(t) = n_I(t)\cos(\omega_c t) - n_Q(t)\sin(\omega_c t)$$

- $n_I(t)$: **In-phase component** (I-channel).
- $n_Q(t)$: **Quadrature component** (Q-channel).

This representation is extremely useful in communication systems because it allows us to treat narrowband noise as if it were a baseband signal with two orthogonal components.

Properties of Quadrature Noise Representation

- **Gaussian nature:** Both $n_I(t)$and $n_Q(t)$are Gaussian random processes.
- **Uncorrelated components:** $n_I(t)$and $n_Q(t)$are statistically independent (uncorrelated).
- **Equal variance:** Each component has the same variance, equal to half the total noise power.
- **Stationarity:** Both processes are wide-sense stationary.
- **Symmetry:** The power spectral density (PSD) of narrowband noise is symmetric around the carrier frequency.
- **Envelope representation:** The noise envelope can be expressed as:

$$A(t) = \sqrt{n_I^2(t) + n_Q^2(t)}$$

which follows a Rayleigh distribution.

- **Phase representation:** The instantaneous phase:

$$\phi(t) = \tan^{-1}\left(\frac{n_Q(t)}{n_I(t)}\right)$$