Chapter IX: Fluctuation Overview and Electrical Noise

II.1. Introduction

In any electronic or semiconductor device, current and voltage signals are never perfectly steady. They are accompanied by random, unpredictable fluctuations known as **electrical noise**. Understanding these noise sources is essential for designing low-noise systems, especially in sensitive applications like communication, sensing, and precision measurements. This chapter explores the main types of noise encountered in electronic systems.

II.2. Shot noise

Shot noise arises from the discrete nature of electric charge. It becomes significant whenever current flows due to the movement of individual charge carriers, such as electrons or holes, across a potential barrier or junction — for example, in diodes or vacuum tubes.

- **Origin**: Caused by the statistical variation in the arrival times of charge carriers. Since electrons are discrete particles, their flow is not continuous but consists of a stream of individual events.
- **Characteristics**:
    - Random and has a white (frequency-independent) spectrum.
    - The power spectral density (in units of **A^2/Hz** for current noise) is given by:

$$S_I(f) = 2qI$$

where :

- $\boldsymbol{q}$ is the elementary charge;
- $\boldsymbol{I}$ is the average current.

Important Notes:

- Shot noise is independent of temperature.
- It appears in components where current flows due to thermionic emission, tunneling, or carrier injection.

II.3. Thermal Noise (Nyquist or Johnson Noise)

Thermal noise is a fundamental noise present in all resistive elements, even in the absence of a current. It originates from the random thermal motion of electrons within a conductor due to its temperature.

- **Origin**: Caused by the agitation of charge carriers due to thermal energy.
- **Characteristics**:
  - White noise: constant spectral density across a wide range of frequencies.
  - Present even when no external current is applied.
- **Power Spectral Density**:

$$S_V(f) = 4KTR$$

where:

- $\boldsymbol{K}$ is Boltzmann's constant,
- $\boldsymbol{T}$ is the absolute temperature (in kelvin),
- $\boldsymbol{R}$ is the resistance in ohms.

Thermal noise is:

- Directly proportional to temperature and resistance.
- Also called **Johnson noise**, named after John B. Johnson who first observed it, and **Nyquist noise**, after Harry Nyquist who explained it theoretically.

II.4. Generation – recombination (GR) noise

Generation-recombination noise is specific to semiconductors and arises from fluctuations in the rate of generation and recombination of charge carriers.

- **Origin**: Due to the random nature of electron-hole pair generation and their recombination processes, which result in temporal changes in carrier density.
- **Behavior**:
  - Exhibits a Lorentzian power spectral density:

$$S(f) = \frac{S_0}{1 + (2\pi f \tau)^2}$$

Where:

- $\boldsymbol{\tau}$ is the carrier lifetime ;
- $\boldsymbol{f}$ is the frequency.
- $\boldsymbol{S_0}$ represents the maximum power spectral density (value of $\boldsymbol{S(f)}$ when the frequency $\boldsymbol{f = 0}$.

- The spectrum is flat at low frequencies and rolls off at higher frequencies.

Relevance :

- Often seen in photodetectors, transistors, and other devices where charge generation and recombination are significant.
- Dominates at mid frequencies, where shot and ***1/f*** noise are not predominant.

II.5. 1/f noise (Flicker or Scintillation noise)

This noise, also known as flicker noise or pink noise, is characterized by its power spectral density decreasing with frequency.

- **Origin**: Not fully understood, but often linked to defects, traps, or impurities in materials that cause long-term memory effects in charge transport.
- **Spectral Characteristic**:

$$S(f) \propto \frac{1}{f^{\gamma}}$$

Where $\gamma \approx 1$

This means the noise increases as frequency decreases.

- **Features**:

- Becomes significant at low frequencies (typically below a few kHz).
- Present in many devices including MOSFETs, bipolar transistors, and resistors.

Impact:

- Particularly problematic in precision analog circuits and low-frequency applications.
- Unlike thermal or shot noise, 1/f noise cannot be filtered out easily due to its dominance at low frequencies.

Electrical noise is an intrinsic part of electronic systems and can limit the performance of sensitive devices. By recognizing the different types of noise — **shot noise**, **thermal noise**, **generation-recombination noise**, and **1/f noise** — engineers can design systems with better noise immunity. Understanding their origins, spectral characteristics, and conditions under which each becomes dominant is essential for optimizing circuit performance, especially in communication, measurement, and low-signal environments.