EE 240B – Spring 2018

Advanced Analog Integrated Circuits
Lecture 4: Electronic Noise

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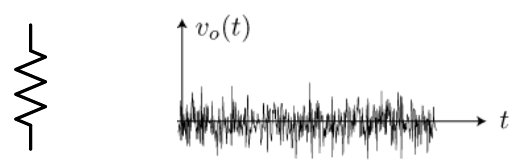
Electronic Noise

- **Why is noise important?**
  - Sets minimum signals we can deal with
  - Ensuring sufficiently low noise will be another "active constraint" that we will develop a design methodology around
- **Most often care about "signal-to-noise ratio"**
  - How do you make the signal larger?
  - Will see today and next time how to make noise smaller, but can you guess what it takes?

Types of "Noise"

- **Interference**
  - Not actually "noise" – deterministic
  - Signal coupling
    - Capacitive, inductive, substrate, etc.
  - Supply variations
- **Device noise**
  - Caused by discreteness of charge
  - "Fundamental physics" related – thermal and shot noise
  - "Technology" related – flicker noise

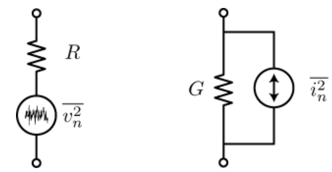
Noise in Electrical Circuits



- **Noise is random**
  - Has to be treated statistically – can't predict actual value
- **Deal with mean (average), variance, spectrum**

Origin and Properties of Thermal Noise

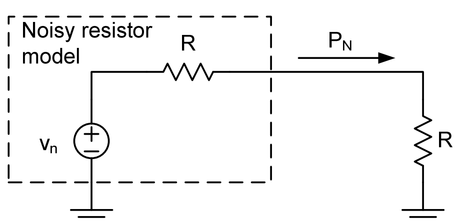
- **Origin: Brownian Motion**
  - Thermally agitated particles
  - (Everything that can generate heat has this type of noise)



- **Independent of DC current flow**
- **Zero mean, Gaussian PDF, i.i.d.**
- **Available noise power:** $P_N = k_B T \Delta f$
  - Noise power in bandwidth Δf delivered to a matched load
  - Power spectral density is "white" up to ~THz frequencies
  - kbT = 4e-21 J (T = 290K)

J.B. Johnson, "Thermal Agitation of Electricity in conductors," Phys. Rev., July 1928

Resistor Noise Model



$$P_N = k_B T \Delta f = \frac{\overline{v_n^2}}{4R}$$

Mean square noise voltage:

$$\overline{v_n^2} = 4 k_B T R \Delta f$$

Resistor Noise Model (current)

Thermal Noise in Capacitors?

Noise Power Spectral Density (PSD)

Noise Calculations

- Noise calculations
  - Instantaneous voltages add
  - Power spectral densities add
  - RMS voltages do NOT add
- Example: R_1+R_2 in series

Calculating Noise in Passive Networks

- Capacitors and inductors only shape spectrum:

$$\overline{v_{on,T}^2(f)} = \sum_x |H_x(s)|^2_{s=2\pi jf} \overline{v_x^2(f)}$$

Side Note on Shot Noise (Diodes)

- Shot noise
  - Zero mean, Gaussian pdf, white
  - Proportional to current
  - Independent of temperature

$$\overline{i_n^2} = 2qI_D\Delta f$$

- Example:
  I_D = 1mA → <u>17.9pA/rt-Hz</u>
  1MHz bandwidth → σ = <u>17.9nA</u>

- Shot noise versus thermal noise
  - $g_{diode} = I_d/(k_b T/q)$
  - Thermal noise density: $4k_b T g_{diode} = 4qI_d$
  - Shot noise half of this (current flow in 1 direction)

Simplified FET Noise Model

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Simplified FET Noise Model

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Word of Caution

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Flicker Noise

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1/f Noise Modeling

$$\overline{i^2_{1/f}} = \frac{K_f I_D}{L^2 C_{ox}} \frac{\Delta f}{f}$$

- **Flicker noise**
  - **$K_{f,NMOS}$ = 6 x 10^{-29} A*F**
    $K_{f,PMOS}$ = 3 x 10^{-29} A*F
  - **Strongly process dependent**

- **<u>Example</u>: I_D = 10μA, L = 1μm,**
  - **C_{ox} = 15fF/μm², f_{hi} = 1MHz**

    f_{lo} = 1Hz → σ = 0.74nA
    f_{lo} = 1/year → σ = 1.11nA

$$\overline{i^2_{1/f,total}} = \int_{f_{lo}}^{f_{hi}} \frac{K_f I_D}{L^2 C_{ox}} \frac{df}{f} = \frac{K_f I_D}{L^2 C_{ox}} \ln \frac{f_{hi}}{f_{lo}}$$

Modified FET Noise PSD

1/f Noise Corner Frequency

- **Definition (MOS)**

$$\frac{K_f I_D}{L^2 C_{ox}} \frac{\Delta f}{f_{co}} = 4k_B T_r \gamma g_m \Delta f \qquad f_{co} = \frac{K_f I_D}{L^2 C_{ox}} \frac{1}{4k_B T_r \gamma g_m}$$

$$= \frac{K_f}{4k_B T_r \gamma C_{ox}} \frac{1}{L^2} \frac{1}{g_m/I_D}$$

$$= \frac{K_f}{8k_B T_r \gamma C_{ox}} \frac{V^*}{L^2}$$

- **Example:**
  - **V* = 100mV, γ = 1.16**

		NMOS	***PMOS***
L = 100nm	→	**2MHz**	**233kHz**
L = 300nm	→	**222kHz**	**25.9kHz**

Noise PSD Calculation in an Amplifier