- Noise & Noise Figure
- Circuit insight
- Transmission lines
- CIM Workshop

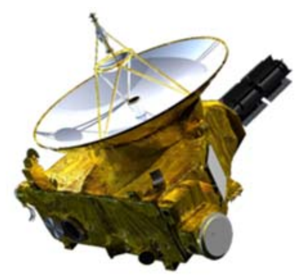
Quiz Thu 2:30-6:30p

- Develop understanding without equations, google.
- Knowledge of key finger tip facts and ability to estimate results.
- Break down the big problem into smaller ones
- In algebra inversion frequently will solve problems which nothing else will solve
- Learn to think through problems backwards as well as forward

Understanding Noise

- Many applications deal with very small signals:
  - EEG (ElectroEncephaloGraphy): electrical activity of the brain 10uv -100uv
  - EMG (ElectroMyoGraphy): electrical activity by skeletal muscles 50uv – 30mv
  - ECG (ElectroCardioGraphy): electrical activity of the heart 2mv
  - New Horizon probe – even lower amplitude signal

New Horizon Signal



- Transmitter power 12 watts
- Transit time to earth 4.5 hours from Pluto
- Received signal strength ~ 10^{-19} watts!

https://upload.wikimedia.org/wikipedia/commons/thumb/4/4f/New_Horizons_Transparent.png/257px-New_Horizons_Transparent.png

Noise vs Interference

- Interference
  - 60 Hz AC pickup
  - RF pick up (cell phones, cell phones, radio stations, WiFi, etc…)
  - Laptop, cell phone chargers
  - Power supply emissions, variation
- Noise
  - Characterized by density: rms noise in 1 Hz band. Units: $e_n = \frac{nv}{\sqrt{hz}}$
  - Noise spectra
    - white noise: e_n constant over frequency
    - flicker or pink (1/f) noise: spectral density is inversely proportional to the frequency

Sources of Noise

- Johnson Noise
- Shot noise
- Flicker noise
- Burst noise

Johnson Noise

- Cause: thermal fluctuations generating noise voltage in a resistor.
  $v_n = \sqrt{4kTRB}$
- Flat frequency spectrum (white noise)
- 10k resistor has a 1.3uV open circuit noise with a 10kHz bandwidth at room temperature

k Boltzmann's constant
T temperature in Kelvin
R resistance
B bandwidth

Sets a lower limit on noise voltage in circuits

Table: Art of Electronics, page 475

	Johnson noise, at T=25°C			
	open circuit		short circuit	
R	e_n (nV/√Hz)	$e_n\sqrt{B}$ B=10 kHz (μV)	i_n (pA/√Hz)	$i_n\sqrt{B}$ B=10 kHz (pA)
100 Ω	1.28	0.128	12.8	1280
1k	4.06	0.406	4.06	406
10k	12.8	1.28	1.28	128
100k	40.6	4.06	0.406	40.6
1M	128	12.8	0.128	12.8
10M	406	40.6	0.041	4.06
100M	1280	128	0.0128	1.28

Shot Noise

- Shot noise: fluctuations created by discrete nature of charges in steady current
  $i_n = \sqrt{2qI_{dc}}\ \ A/\sqrt{Hz}$

  At 1ma, 1.8nA at 10kHz bandwidth

q electron charge
B bandwidth

- White noise – same as Johnson noise

1/f Noise

- AKA pink noise or flicker noise
- Present in real devices; for resistors caused by fluctuations in resistance
- Apply 1V across different resistor types over 1 decade of frequency

Carbon composition	0.10μV to 3.0μV
Carbon film	0.05μV to 0.3μV
Metal film	0.02μV to 0.2μV
Wire wound	0.01μV to 0.2μV

Burst Noise

- A sudden random jumps in base current for BJT or steps in threshold voltage for MOSFETS
- AKA popcorn noise or random telegraph signal noise.
- Caused microscopic defects in semiconductor material. Less prevalent current technology.
- Popcorn noise occurs at low frequency (<1 kHZ)

Analysis and Measurement of Intrinsic Noise in Op Amp Circuits
Part VIII: Popcorn Noise TI.com

SNR, Noise Figure, LNA

- Signal to noise ratio SNR = $10\log_{10}\left(\frac{V_s^2}{V_n^2}\right)$
- Amplifier Noise Figure (in dB) : ratio in dB, of the output of the real amplifier to the output of perfect noiseless amplifier of the same gain with a resistor value Rs connect across the input.
- For RF signals, Rs=50 ohms.
- LNA: Low Noise Amplifier

Measured noise voltage spectra for MOSFETS, JETs, BJT

2SD786 used in serious audio amplifiers

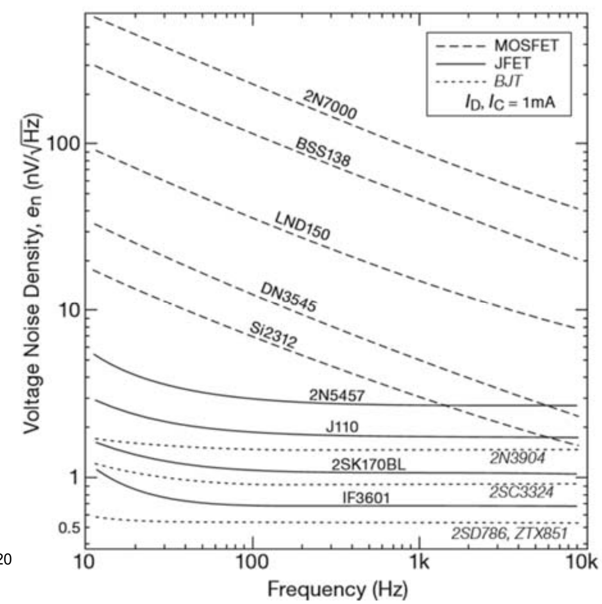
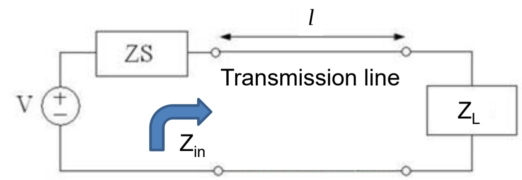


Table: Art of Electronics, Figure 8.54 p520

Eliminating Noise

- Ensure clean power supply; use a battery
- Use bypass capacitors - lots!
- Use shielded lines to avoid capacitive coupling
- Use twisted pair to reduce magnetic pickup
- Be aware of protoboards and cables. Protoboard capacitance between ~1pf
- Use ground plane for high frequencies
- Understand power supply and signal grounds
  - Within circuit
  - Between instruments
- Avoid long wires particularly with small signals

Transmission lines



Z_0: characteristic impedance

At low frequency:

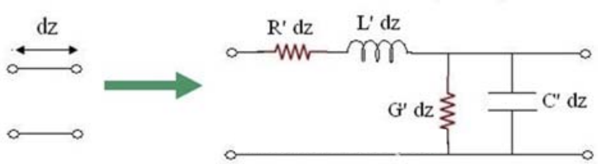
$$I = \frac{V}{Z} \rightarrow I = \frac{V}{ZS + Z_L}$$

At higher frequencies, the transmission line would matter!

$$Z_{IN} = Z_0 \left[\frac{Z_L + j Z_0 \tan(\beta\ell)}{Z_0 + j Z_L \tan(\beta\ell)} \right]$$

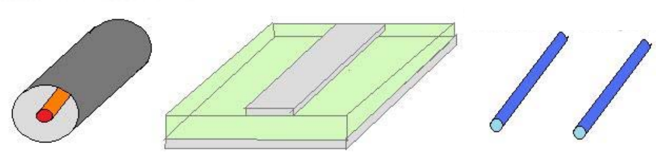
- *Z_L is the termination impedance*
- *ℓ is line length.*
- *$\beta = 2\pi f / (V_P)$* V_P: Wave propagation speed in the transmission line

Lumped Equivalent Model of a Transmission Line



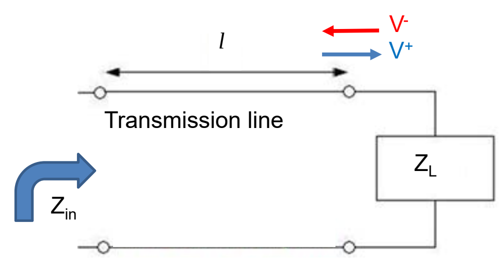
$$Z_0 = \sqrt{\frac{R' + j\omega L'}{G' + j\omega C'}}$$

If losses are negligible: $Z_0 = \sqrt{\frac{L'}{C'}}$ (Lossless Line) $R' = G' = 0$



Coaxial Cable Microstrip Line Two-Wire Line

Reflection and VSWR



Z_0: characteristic impedance

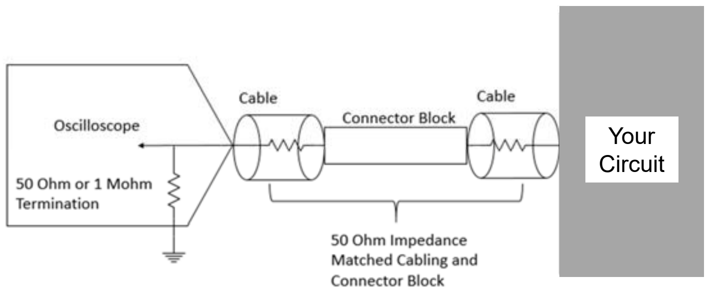
Reflection coefficient $\Gamma = \frac{V^-}{V^+} = \frac{Z_L - Z_0}{Z_L + Z_0}$

A measure of how much a wave would be reflected back at the interface of the transmission line and the load.

Voltage Standing Wave Ratio

$$VSWR = \frac{V_{max}}{V_{min}} = \frac{1 + |\Gamma|}{1 - |\Gamma|}$$

Matching in Instruments

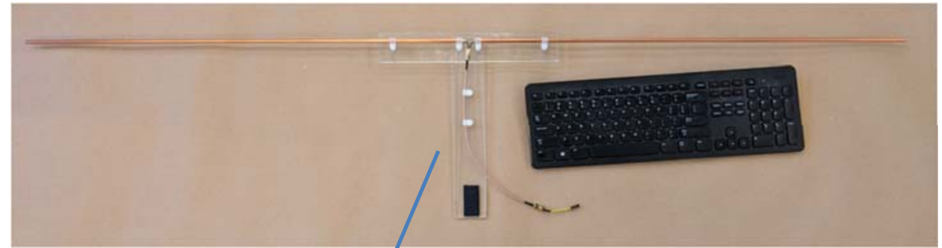


50Ω Is the standard termination load selected for equipment, or in general in analog and RF electronics.

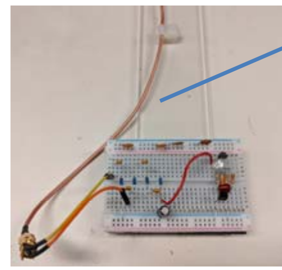
The **maximum power transfer theorem** states that, to obtain *maximum* external power from a source with a finite internal resistance, the resistance of the load must equal the resistance of the source as viewed from its output terminals.

- Be mindful of your circuit's output load and instrument's input load!

50Ω Matching in Antenna Lab



SMA connector/coax cables used in the antenna lab have 50Ω impedance.



- Follow on classes – Fall 2020
  - 2.75/2.750/6.025/6.525J Medical Device Design
  - 6.111 Introductory Digital Systems Laboratory
  - 6.131 Power Electronics Laboratory
  - 6.301 Solid-State Circuits