Transmission Lines - Why is it important?

- The study of Transmission Lines (T-lines) is part of the larger field of Signal Integrity ($I$)

- Signal Integrity consists of:
  - T-Lines: getting signals from source to destination while preserving their important characteristics.
  - Electromagnetic Interference (EMI): keeping other signals from effecting my signals and keeping my signals from effecting others. (minor focus)
As an Engineer using T-lines, you want to be able to:

- Launch a signal from source to destination AND
  - do so in an acceptable time frame OR
  - with an acceptable waveshape OR
  - with a maximum power transfer to the load AND
  - while not interfering with or being interfered by other signals AND
  - doing so with the given design constraints
You should be able to: (eventually!)

- Identify situations where conductor pairs behave as T-lines
- Be able to develop mathematical or circuit models of
  - T-lines
  - drivers, receivers
  - discontinuities (R, L, C, Zo)
- Be able to design an interconnect that provides correct operation via
  - termination schemes
  - conductor topology
  - impedance matching
- Be able to confirm by simulation or computation that your solution works
  - spice, matlab, smith chart

ECE391 is focused on the design and use of electrical structures that deliver electrical waveforms to electrically distant loads.

I, V, P

edge rate, wavelength
component size
Some definitions + terminology

- **Signals**
  - Digital ("1" or "0") voltage waveforms
  - Analog (continuous) voltage and current waveforms

- **Driver**
  - A *driver* is the entity that "launches" or signals
  - A digital *driver* is usually a CMOS inverter output
    - regardless of gate type
  - e.g., $\text{digital driver} = \begin{cases} \text{high} & \text{Zin} \\ \text{low} & \text{Zout} \end{cases}$

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**Spice Model:**

- `vin` to `output`
- Pulses to IV
- 2ns delay
- Ins tr
- Ins tf
- Pulse width
- Period

**Netlist**

```
Vin Vin 0 Pulse(0 1.0 2n 1n 1n 40n 80n)
```

```
R1 vin output 10
```

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- **Diagrams:**
  - Circuit diagrams showing waveforms and connections.
  - Annotations for waveforms and circuit components.
Some definitions + terminology

Driver (cont.)

- A analog driver could be an analog amplifier, discrete or integrated
- An antenna... it drives a T-line to a receiver
- A T-line... it could drive another T-line or low noise amplifier
- Spice model of a 50 Ohm output resistance amplifier

\[ \text{netlist } \text{Vin} \text{ vin } \Phi \text{ AC (Sin } \Phi \text{ 1.0 29.6M)} \]
\[ R_1 \text{ vin output 50} \]
Some Definitions & Terminology

- Receiver
  - A receiver is where the launched signal is sensed (voltage, current, power)

- A digital receiver is usually a CMOS inverter

\[
\frac{\text{Vpp}}{\text{Vdd}} \Rightarrow \text{spice model?} \ldots
\]

- An analog receiver could be a discrete or integrated amplifier typically exhibiting a specified input impedance that is mostly (but not always) resistive. \( \Rightarrow \) spice model?

- An analog receiver could also be an antenna or another T-line. \( \Rightarrow \) spice model?
- Analog receiver (cont)
  - Could be a resistor "-AM-

\[ \text{RL can be a model for another piece of T-line!} \]

One representation of a T-line,
A piece of coaxial cable.

Why would you want to do this?!

Although we sometimes model T-lines as a resistive load, they **DO NOT** exhibit a DC resistance equal to their stated impedance.

In other words, a 50Ω coax cable does not exhibit a 50Ω DC resistance. Likewise, a T-line may exhibit an "apparent impedance of X" ohms, it does not dissipate any power for lossless lines, but
Some definitions + terminology

"lightly loaded", "heavily loaded"

- Consider

\[ \begin{align*}
\text{What } R_L \text{ makes } V_L \text{ begin to approach } V_S \text{?} \\
\text{Ans: An } R_L \text{ that "lightly loads" the Thevenin source}
\end{align*} \]

\[ \begin{align*}
U_1 \text{ is lightly loaded} \\
U_2 \text{ is heavily loaded}
\end{align*} \]
Definitions + Terminology (cont)

Switching Threshold - the voltage level at which a digital logic gate decides if an input is logic "1" or "0".
- Usually about \( V_{DD}/2 \)
- Guaranteed levels: \( \text{logic 1} \geq 0.7 \text{V}_{DD} \)
\( \text{logic 0} \leq 0.3 \text{V}_{DD} \)

Termination - typically, a resistor placed at the driver or receiver. The resistor helps create the conditions for the proper operation of a T-line.
- Can also be a diode, inductor, capacitor, an active device or even another T-line.

"Looking Into" - An anthropomorphism that describes the "apparent impedance" experienced by an incoming or outgoing wavefront.
Definitions & Terminology

"Ringing"

Another representation of a T-line... ground return is understood.

VDD      VDD
\[ \text{we start with this...} \]
\[ \text{receiver sees this} \]

"Ringing" is the damped sinusoid at the edges of signals that oscillates around the supply rails.

"Overshoot", "Undershoot"

VDD      VDD
\[ \text{overshoot} \]
\[ \text{undershoot} \]
Problems caused by T-line phenomena

Ringing can be a source of EMI at unexpected frequencies.

Mistimed T-lines often "ring," especially with fast edges.

The ringing frequency depends on parasitic L+C, and is not necessarily related to the driving frequency.

Ringing (damped high-frequency sinusoids)
Problems caused by T-line phenomena.

Reliability Issues with Overshoot/Undershoot

CMOS Input:

EσDiodes

ESD diodes are very fast, very small diodes. Easily damaged.
Driven repeatedly from a 50Ω or less source will quickly kill them.
Another Problem

Timing Issues

IF the switching thresholds of G0, G1, G2 are 0.7VDD + 0.2VDD
For guaranteed VIL and VIH, who switches first, G1 or G2?

G2 switches first!

MUST OBEY KCL HERE, HOW?

Voltage divider right plane

Apparent resistance from low value resistor

not consider a logic 1 until

VDD not considered logic 0 until

VSS 0.3VDD

0.7VDD
More Problems

Maximum Power Transfer

Receiver "Front End"

\[ \begin{align*}
& \text{Antenna is the 50Ω source. It is driving the LNA thru a} \\
& \text{T-line. For maximum power transfer, the antenna should} \\
& \text{"look into" a 50Ω impedance.}
\end{align*} \]

At the LNA, the T-line is the source and should present
a 50Ω driving point impedance to the LNA for max
power xfer.

\[ \begin{align*}
\text{Max power is delivered when } R_L &= R_{TH}
\end{align*} \]
Special Uses of Transmission Lines

Impedance Transformation

![Diagram of a T-line circuit with impedance transformation]

Depending on the T-lines electrical length and the frequency of operation, the antenna may or may not be "looking into" 80Ω. The apparent input impedance at the T-line may vary widely.

With continuous waveforms, depending on line length, frequency and line loss, a 50Ω coax may look like anything from 0Ω to 100Ω.

This is actually good news! We can transform impedances.

In steady state AC condition apparent impedance looking into a T-line is defined by the terminal Vin/In condition.
Special Uses Curt.

- Under correct conditions, T-lines appear to be a very high quality LC resonator.

- At multiples of $\frac{\lambda}{4}$, T-lines look like a pure inductor or capacitor.

- At $\frac{\lambda}{4}$ multiples, T-lines may also be used to transform impedances like a transformer.
Transmission Line Examples

- coaxial line
- two-wire line (also twisted-pair)
- microstrip
- stripline
- coplanar strip (CPS)
- coplanar waveguide (CPW)
- A conductor pair is or is not a transmission line because of the:
  - Frequency or wavelength of the signal
  - Velocity of propagation on the line
  - Rise time of the signals (fall time too) on the line
  - Physical length of the line

not just the physical configuration.

- A 50Ω coaxial line is not always a T-line.
- We want to know when we have a T-line scenario.