Transmission Lines - Why is it important?

- The study of Transmission Lines (T-lines) is part of the larger field of Signal Integrity (SI)
- Signal Integrity consists of:
  - T-Lines: getting signals from source to destination while <u>preserving their important characteristics</u>.
  - 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 <u>AND</u>
    - do so in an acceptable time frame <u>OR</u>
    - with an acceptable waveshape <u>OR</u>
    - with a maximum power transfer to the load <u>AND</u>
    - while not interfering with or being interfered by other signals AND
    - doing so with the given design constraints

You should be able to: (eventually!)

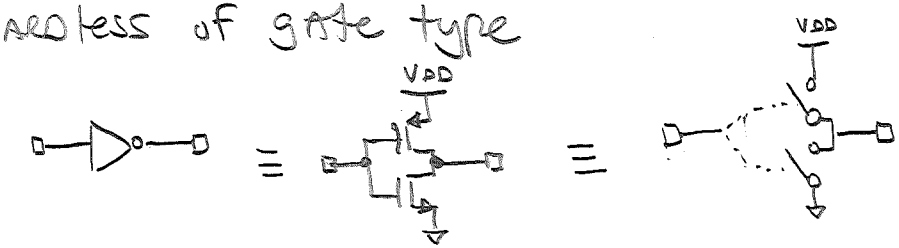
- Identify situations where conductor pairs behave as T-lines
- Be able to develop mathematical $\frac{\text{and}}{\text{or}}$ circuit models of
  - T-lines
  - drivers, receivers
  - discontinuities (R, L, C, Z_0)
- Be able to design an interconnect that provides correct operation via
  - termination 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 $\overbrace{\text{electrical structures}}^{\text{T-lines, terminations, matching networks}}$ that deliver $\underbrace{\text{electrical waveforms}}_{I, V, P}$ to $\underbrace{\text{electrically distant}}_{\substack{\text{edge rate, wavelength} \\ \text{component size}}}$ loads.

Some definitions + terminology

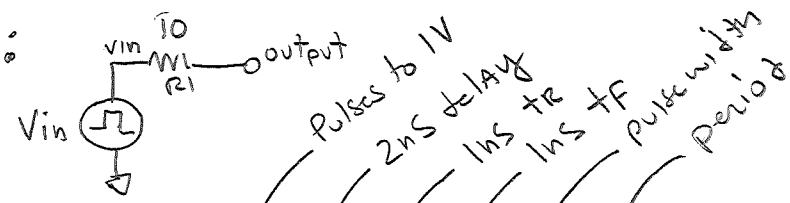
- Signals
  - digital ("1" or "Ø") voltage waveforms
  - Analog (continuous) voltage and current waveforms

- "Driver"
  - A <u>driver</u> is the entity that "launches" or signal
  - A <u>digital driver</u> is usually a CMOS inverter output regardless of gate type
  - e.g.

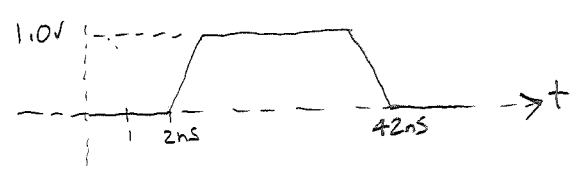


characteristics:
$Z_{in} \Rightarrow$ high
$Z_{out} \Rightarrow$ low

spice model:

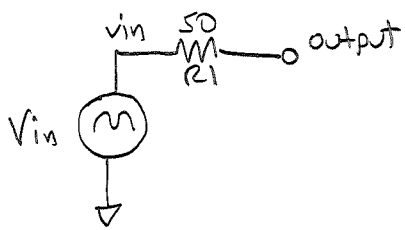


netlist
```
Vin vin 0 Pulse(0 1.0 2n 1n 1n 40n 80n)
R1 vin output 10
```



Some definitions + terminology

- Driver (cont.)
  - A <u>analog driver</u> 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 50Ω output resistance amplifier

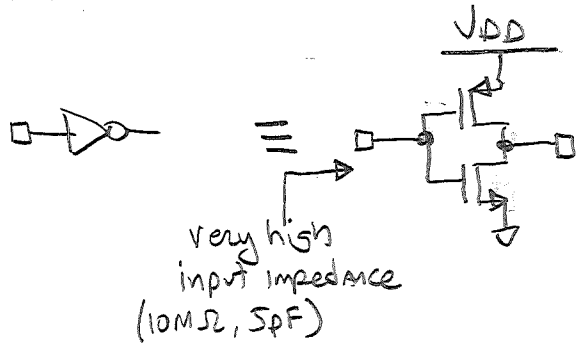


type of waveform
DC offset
Amplitude Vpp
frequency

netlist Vin vin Ø AC (sin Ø 1.0 29.6m)
R1 vin output 50

Some Definitions + Terminology

- Receiver
  - A receiver is where the launched signal is sensed (voltage, current, power)
  - A <u>digital receiver</u> is usually a CMOS inverter

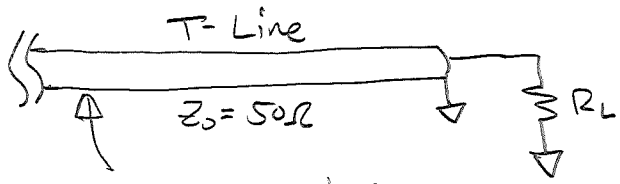


⇒ spice model ??...

  - An <u>Analog receiver</u> could be a discrete or integrated amplifier typically exhibiting a specified input impedance that is mostly (but not always) resistive. ⇒ spice model?
  - An analog receiver could also be an antenna or another T-line. ⇒ spice model?

— Analog receiver (cont)

- Could be a resistor "—ᴍ—"



R_L 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?!

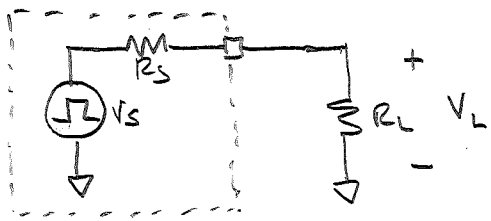
Although we sometimes model T-lines as a resistive load, <u>they DO NOT exhibit a DC resistance equal to their stated impedance.</u>

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 but it does not dissipate any power for lossless lines.

Some definitions + terminology

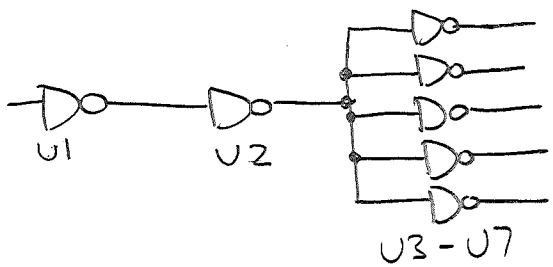
- "lightly loaded", "heavily loaded"

- consider



What R_L makes V_L begin to approach V_S ?

Ans: An R_L that "lightly loads" the Thevenin source



U1 is lightly loaded

U2 is heavily loaded

Definitions + Terminology (cont)

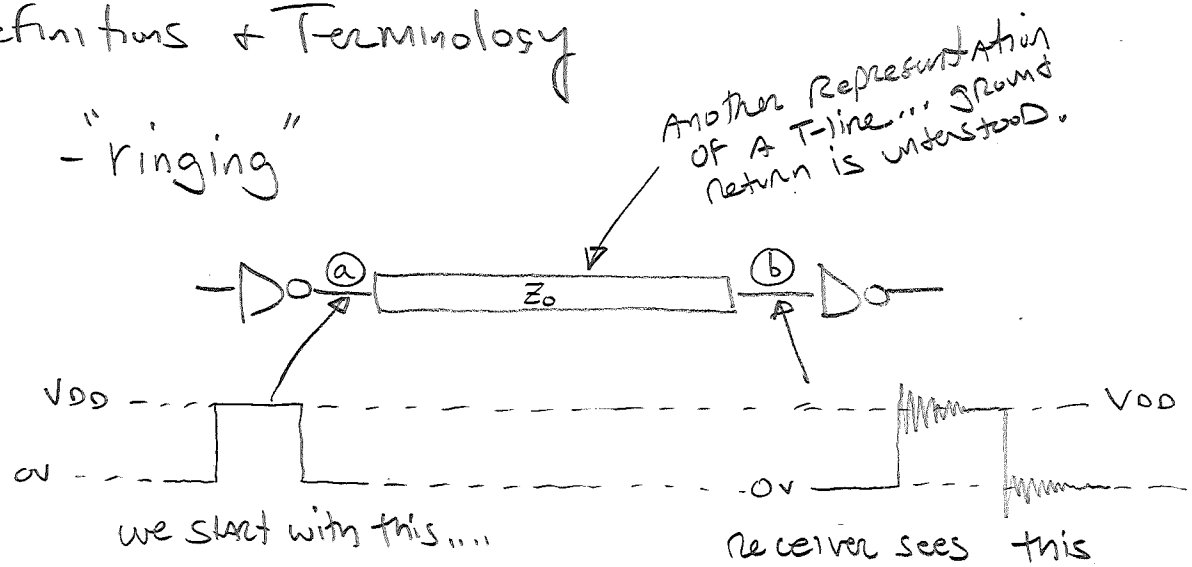
Switching Threshold - the voltage level at which a digital logic gate decides if an input is logic "1" or "0".
- usually about $V_{DD}/2$
- guarnteed levels : logic 1 $\geq 0.7 V_{DD}$
  logic 0 $\leq 0.3 V_{DD}$

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 a incoming or outgoing wavefront.

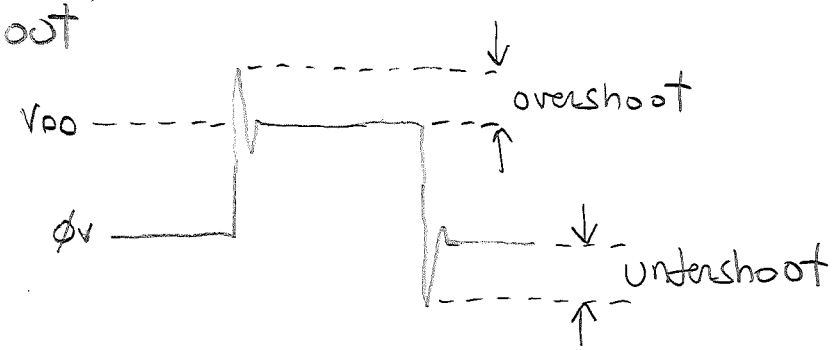
Definitions + Terminology

- "ringing"



"ringing" is the dampened sinusoid at the edges of signals that oscillates around the supply rails

- "overshoot", "undershoot"

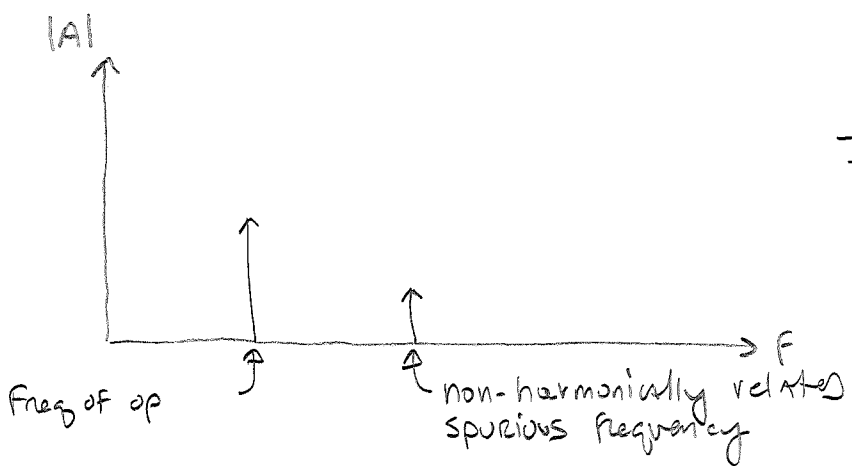


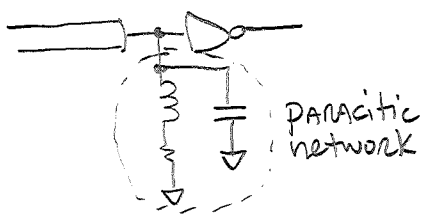
Problems caused by T-line phenomena

Ringing can be a source of EMI at unexpected frequencies

Misterminated T-lines often "ring" especially with fast edges.

The ringing frequency depends on parasitic L + C (or line length) and is not necessarily related to the driving frequency.

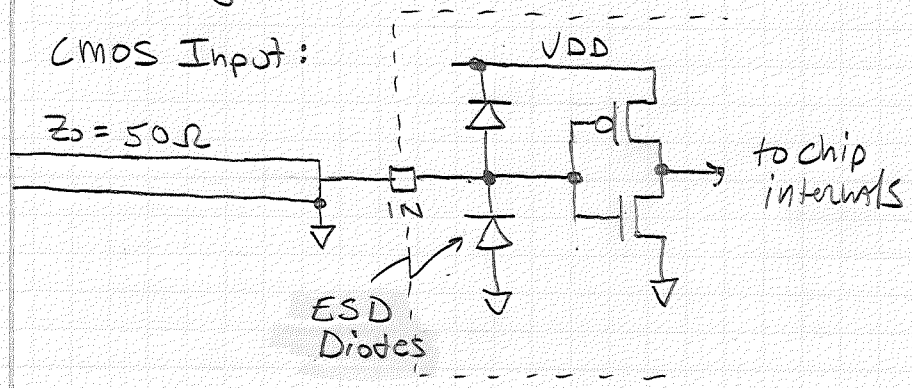


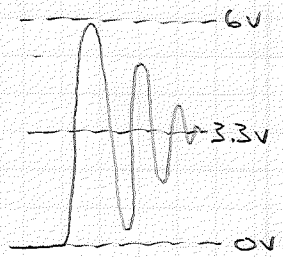


Problems caused by T-line phenomena.

Reliability Issues with Overshoot / Undershoot

CMOS Input:



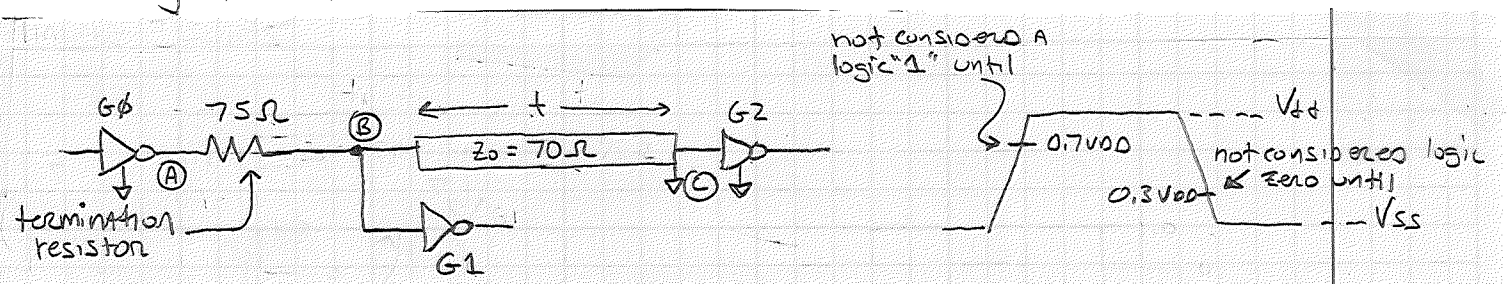


ESD diodes are very fast, very small diodes. Easially damaged.

Driven repeatedly from a 50Ω or less source will quickly kill them.

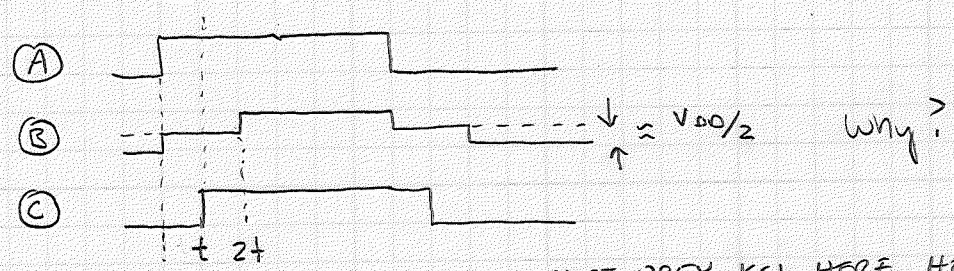
Another Problem

Timing Issues

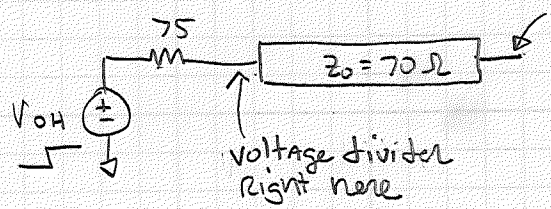


IF the switching threshold of G0, G1, G2 are 0.7VDD & 0.3VDD
For guaranteed V_{IH} & V_{IL}, who switches first, G1 or G2?

G2 switches first!

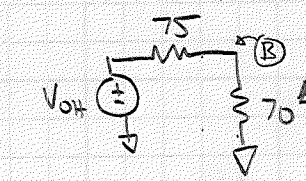


why?



MUST OBEY KCL HERE, HOW?

≡



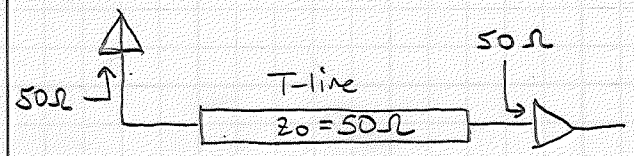
apparent resistance seen by wavefront

More Problems

MAXIMUM POWER TRANSFER

Receiver "Front End"

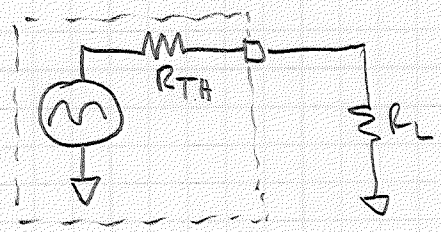
⇐ { the antenna "sees" a 50Ω load
the LNA is driven by a 50Ω source



low noise amplifier
(LNA)

Antenna is the 50Ω source. It is driving the LNA thru a T-line. For maximum power transfer the antenna should "look into" a 50Ω impedance.

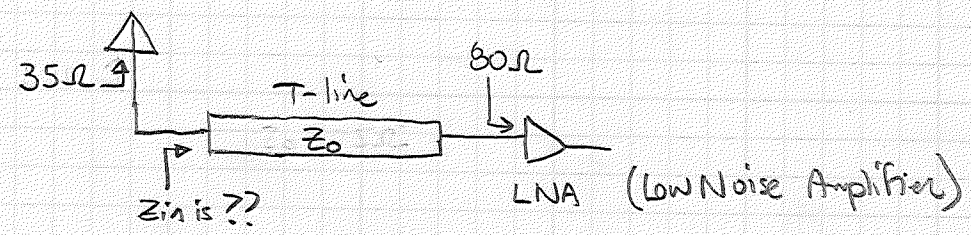
At the LNA, the T-line is the source and should present a 50Ω driving point impedance to the LNA for max power xfer.



MAX power is delivered when $R_L = R_{TH}$

Special Uses of Transmission Lines

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.

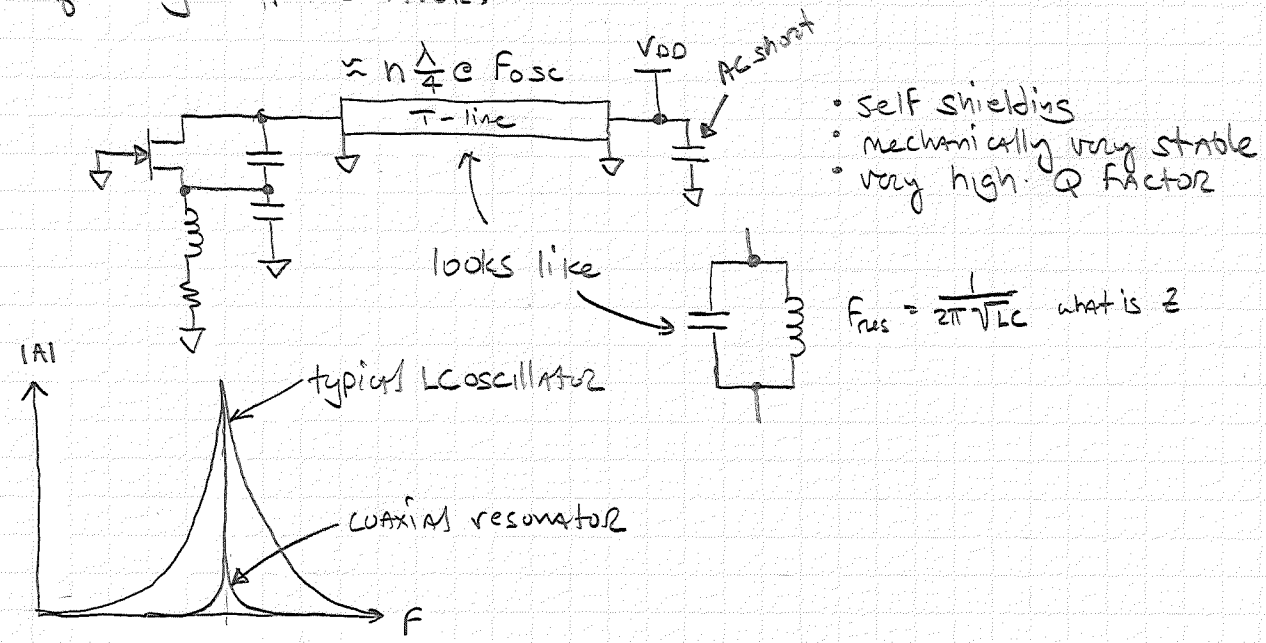
With continuous waveforms, depending on line length, frequency and line loss, a 50Ω coax may look like anything from 0Ω to ∞Ω.

This is actually good news! We can <u>transform impedances</u>.

In steady state AC condition apparent impedance looking into a T-line is defined by the terminal V_{in}/I_{in} condition.

Special Uses Cont.

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



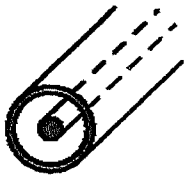
- self shielding
- mechanically very stable
- very high Q factor

$f_{res} = \frac{1}{2\pi\sqrt{LC}}$ what is Z

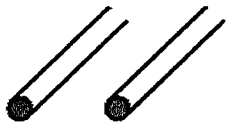
- At multiples of $\lambda/4$, T-lines look like a pure inductor or capacitor.

- At $\lambda/4$ multiples, T-lines may also be used to transform impedances like a transformer

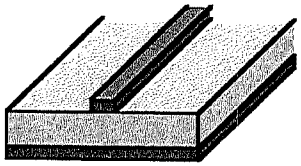
Transmission Line Examples



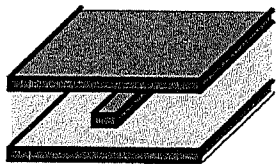
coaxial line



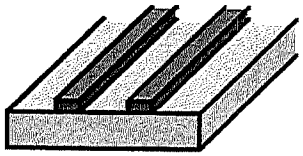
two-wire line (also twisted-pair)



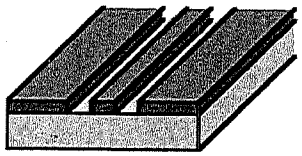
microstrip



stripline



coplanar strip (CPS)



coplanar waveguide (CPW)

- A conductor <u>pair</u> 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.

("looking into" the 50Ω line, it also may not "look like" 50Ω!)

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