Transmission Lines

Digital Design and Computer Architecture

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Transmission Lines :: Topics

- **Introduction**
- **Wave Propagation**
- **Termination**
- **Reflections**
- **Summary**

Introduction

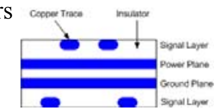
- We have assumed wires are *equipotential* nodes
  - Same voltage along the entire length of wire
- Signals actually propagate at the speed of light
  - Voltage and current will vary along the line
  - Important for long wires or high speeds
- Transmission lines capture this behavior

Return Paths

- Current always flows in loops
- We usually think about the current flowing out along a wire
- But there must be a path for the current to return
- Often returns through the GND network
- If this is not well controlled, interesting things may happen

Transmission Lines

- Many ways to provide a signal and a return path
- Printed Circuit Board
  - Typically use 4 or more multiple layers
  - Signal traces
  - Power/GND planes



- Coaxial Cable
  - Signal flows in the inner conductor
  - Returns in outer ground conductor
- Ad-Hoc
  - Current may return through unknown paths
  - May increase delay and cause unpredicable noise

Speed of Light in a Medium

- Speed of light in free space:

$$v = c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 3\times10^8 \text{ m/s}$$

- Speed of light in a medium

$$v = \frac{1}{\sqrt{\mu\varepsilon}} = \frac{1}{\sqrt{LC}}$$

- For a PCB with $\varepsilon = 4\ \varepsilon_0$, v = c/2 = 15 cm/ns

Transmission Time

- Flight time along a wire of length *l*

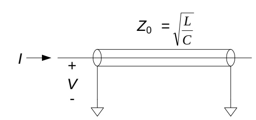
$$t_d = l / v$$

- Example: a 12” trace across a large board has a 2 ns flight time

Characteristic Impedance

- The *characteristic impedance* of a transmission line, Z_0, is the ratio of voltage to current in a wave traveling along the wire
  - Not the resistance of the wire (typically close to 0)
- Depends on inductance and capacitance
  - Typically 50 to 75 Ω

$$Z_0 = \sqrt{\frac{L}{C}}$$

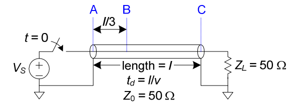


Transmission Line Behavior

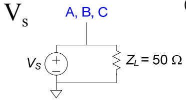
- Visualize wave of voltage propagating along the line at the speed of light
  - When the wave hits the end, it may be absorbed or reflected, depending on the *termination*
  - Reflections travel back along the line, adding to the votlage already on the line
  - After all reflections die out, the voltage will be the same as if the line were a simple wire
- Terminations
  - Matched
  - Open
  - Short
  - Mismatched

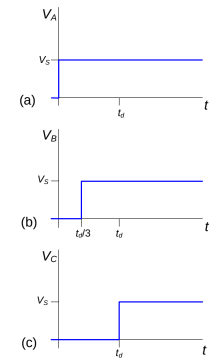
Matched Termination

- $Z_L = Z_0$



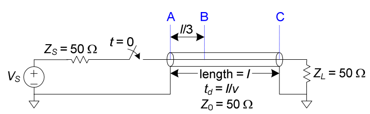
- Wave of V = V_s begins flowing down line
- Wave travels at velocity v
- Wave is absorbed by Z_L
- Equivalent steady-state circuit
  - Final value = V_s



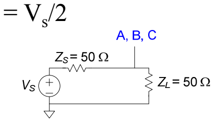


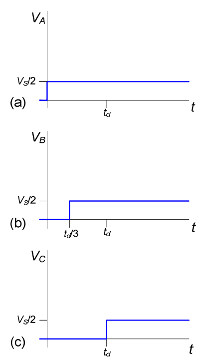
Matched Source and Load Termination

- $Z_S = Z_L = Z_0$



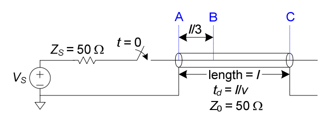
- Voltage divider at source
- Wave of V = $V_s/2$ begins flowing down line
- Equivalent steady-state circuit
  - Final value = $V_s/2$



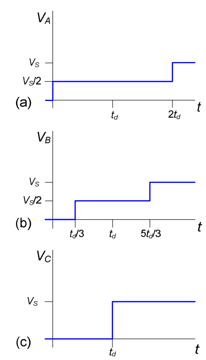


Open Termination

- $Z_S = Z_0 \quad Z_L = \infty$

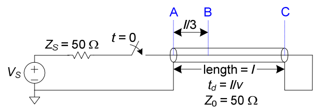


- Wave of V = $V_s/2$ begins flowing down line
- Current flowing down the line has nowhere to go at the end and must reflect

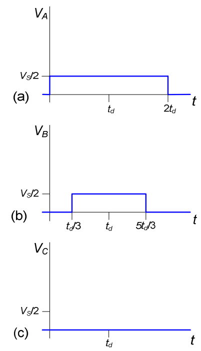


Short Termination

- $Z_S = Z_0 \quad Z_L = 0$



- Wave of $V = V_s/2$ begins flowing down line
- Voltage at the end must be 0, so a negative wave must be reflected



Reflectance Coefficient

- When a wave of voltage V_i reaches either end of a transmission line, part (V_r) will be reflected if the termination impedance Z_T does not match the line impedance

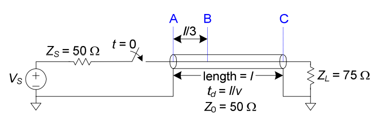
$$V_r = k_r V_i$$

$$k_r = \frac{Z_T - Z_0}{Z_T + Z_0}$$

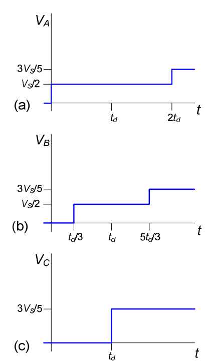
- Special cases
  - $Z_T = Z_0$: $k_r = 0$ (matched load, wave absorbed)
  - $Z_T = \infty$: $k_r = 1$ (open load, wave reflected)
  - $Z_T = 0$: $k_r = -1$ (short load, negative wave reflected)

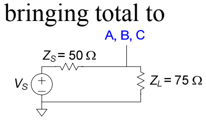
Mismatched Termination (Example 1)

- Load termination mismatched



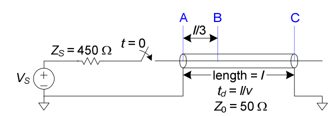
- Wave of $V = V_s/2$ begins flowing down line
- $k_r = (75\text{-}50)/(75\text{+}50) = 1/5$
- Wave of $(1/5)V_s/2 = V_s/10$ reflects off end, bringing total to $3V_s/5$



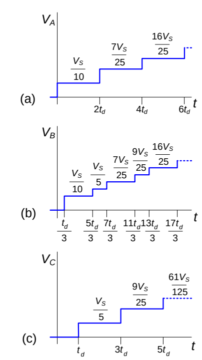


Mismatched Termination (Example 2)

- Both terminations mismatched

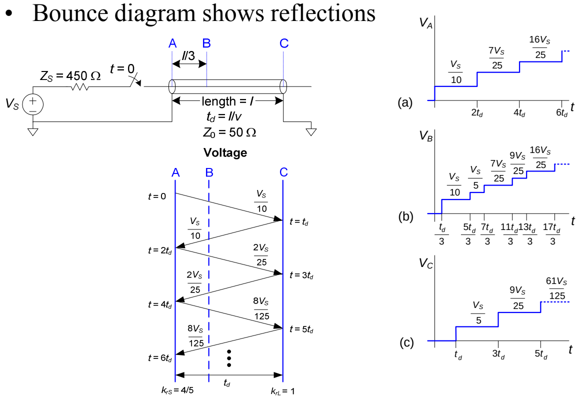


- Wave of $V = V_s/10$ begins flowing down line
- $k_r = 1$ at end, 4/5 at start
- Waves reflect off each end until line starts to approach its final value of V_s



Bounce Diagram

- Bounce diagram shows reflections

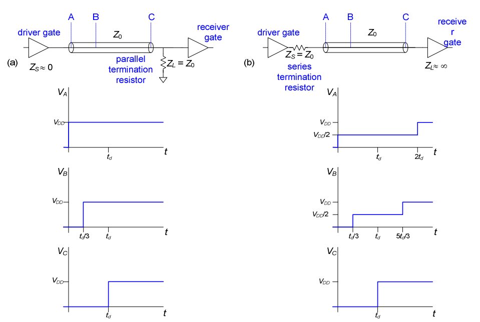


When to use Transmission Line Models

- Wires should be modeled as transmission lines when t_d > 20% of the rise/fall time of the signal
  - i.e. when reflections don't dissipate while signal is transitioning
- Recall that signals on a PCB travel at 15 cm/ns
- For a TTL signal with a 10 ns edge rate, treat a wire as a transmission line if it exceeds 30 cm
- For a fast signal with a 2 ns edge rate, treat a wire as a transmission line if it exceeds 6 cm (2.5 inches)
- Don't make signals faster than necessary

Proper Termination

- Transmission lines should be properly terminated at the load (parallel) or source (series)



Comparison

Parallel Termination

+ All points on the line see valid logic levels
+ Good for busses with multiple receivers
- Consumes lots of power (V^2/Z_0)

Series Termination

+ Consumes little power
- Midpoint sees indeterminate logic level for a time
- Only suitable for point-to-point links