ESE 570: Digital Integrated Circuits and VLSI Fundamentals

Lec 25: December 9, 2020

Transmission Lines

1

Lecture Outline

- Transmission Lines
  - Where transmission lines arise?
  - Lossless Transmission Line
  - Termination
  - Lossy Transmission Line

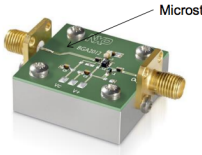
2

Where Transmission Lines Arise

3

Transmission Lines

- Cable: coaxial
- PCB
  - Strip line
  - Microstrip line
- Twisted Pair (Cat5)



4

Transmission Lines

- This is what wires/cables look like
  - Aren't an ideal equipotential
  - Signals do take time to propagate
  - Maintain shape of input signal
    - Within limits
  - Shape and topology of wiring effects how signals propagate
- Need theory/model to support design
  - Reason about behavior
  - Understand what can cause noise
  - Engineer high performance/speed communication

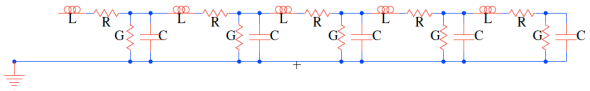
5

Wire Formulation

6

Wires

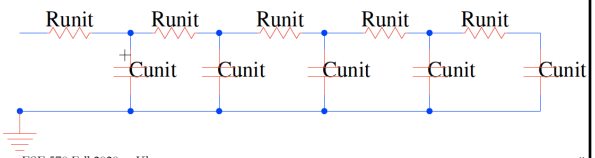
- In general, our "wires" have distributed R, L, C components



7

RC Wire

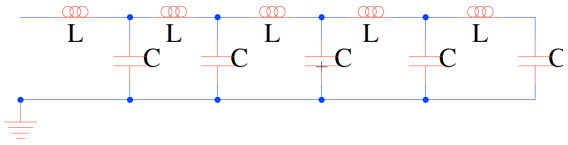
- When R dominates L
  - We have the distributed RC Wires
  - Typical of on-chip wires in ICs



8

Lossless Transmission Line

- When resistance is negligible
  - Have LC wire = Lossless Transmission Line
    - No energy dissipation (loss) through R's
  - More typical of Printed Circuit Board wires and bond wires



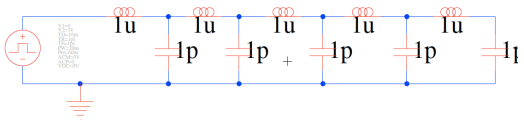
9

Intuitive: Lossless

- Pulses travel as waves without distortion
  - (up to a characteristic frequency)

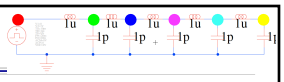
10

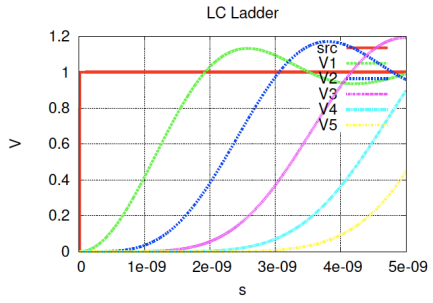
SPICE Simulation



11

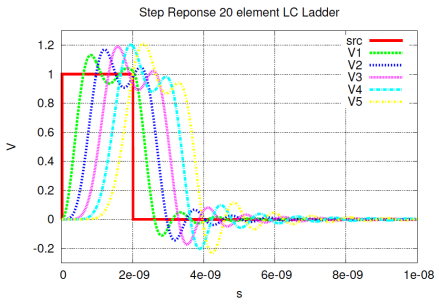
Step Response SPICE





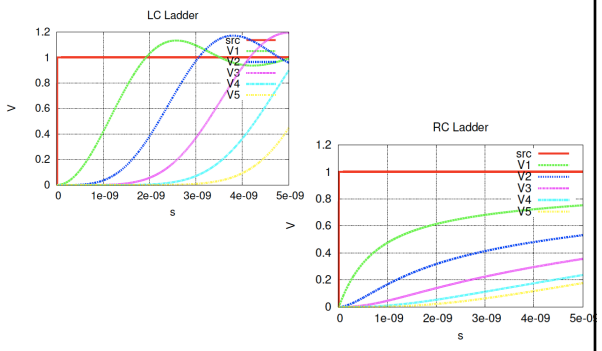
12

Pulse Response SPICE



13

Contrast



14

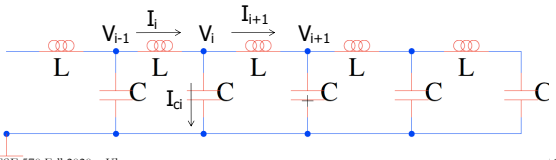
Model

- Now voltage is a function of time **and** position
  - Position along wire – distance from source
- Want to get V(x,t)
  - And I(x,t)

15

Setup Relations

- *i* is a node, *x* is the distance from source, ⊥*x* is distance between nodes
- Position along wire: $x = i \times \perp x$
- So $V_i(t) = V(x = i \perp x, t)$



16

Implication

- Wave equation:

$$\frac{\partial^2 V}{\partial x} = LC\frac{\partial^2 V}{\partial t}$$

- Solution:

$$V(x,t) = A + Be^{x-wt}$$

- What is w?

$$Be^{x-wt} = LCw^2 Be^{x-wt}$$

$$w = \sqrt{\frac{1}{LC}}$$

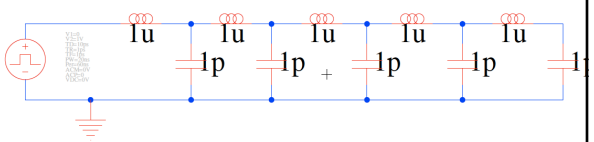
w is the rate of propogation

17

Propagation Rate in Example

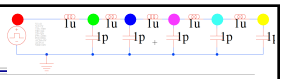
- L=1uH
- C=1pF
- What is w?

$$w = \frac{1}{\sqrt{LC}}$$

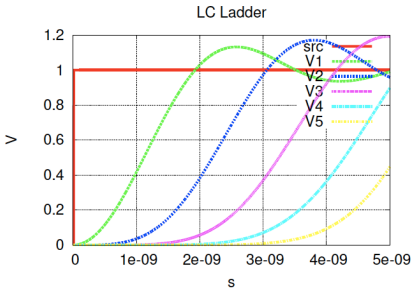


18

Signal Propagation

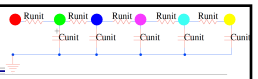


Delay linear in length

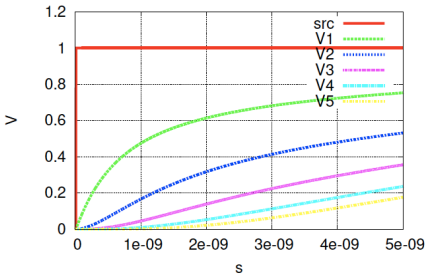


19

Contrast RC Wire



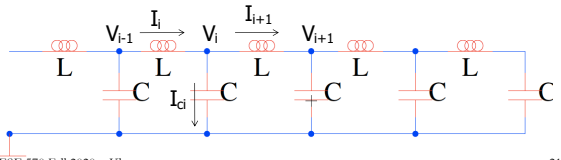
RC wire delay quadratic in length → $.5R_{un}C_{un}N^2$



20

Wire "Resistance"

- What is the resistance at V_i ?
  - Q needed to charge C to V_i?
  - I_i given velocity w?
  - $R = V_i/I_i$?



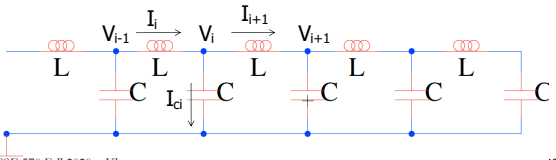
21

Wire "Resistance"

- $Q=CV_i$
- $I_i = dQ/dt$
- Moving at rate w
- $I_i=wCV_i$
- $R=V_i/I_i=1/(wC)$

$$w = \frac{1}{\sqrt{LC}}$$

$$R = \frac{\sqrt{LC}}{C}$$



22

Impedance

- Transmission lines have a characteristic impedance

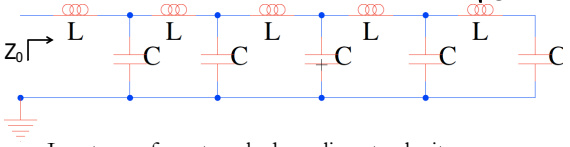
$$Z_0 = \sqrt{\frac{L}{C}}$$

23

Infinite Lossless Transmission Line

- Transmission line looks like resistive load

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



- Input waveform travels down line at velocity
  - Without distortion

$$w = \frac{1}{\sqrt{LC}}$$

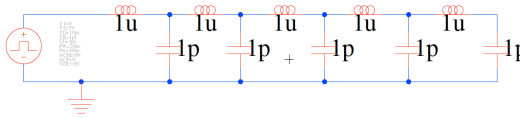
24

Termination

25

End of Line

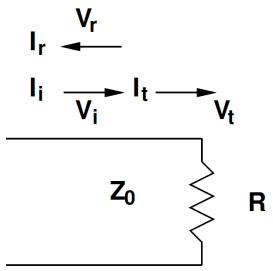
- What happens at the end of the transmission line?

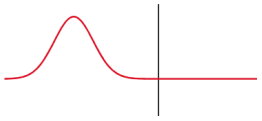


26

Analyze End of Line

- *I*ncident Wave, *R*eflected Wave, *T*ransverse Wave





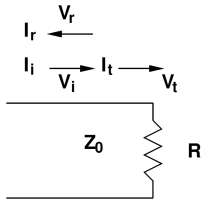
Source: https://en.wikipedia.org/wiki/Reflection_coefficient

27

Reflection

Reflection coefficient

$$V_i\left(\frac{R-Z_0}{R+Z_0}\right)=V_r$$



28

Analyze End of Line

- $V_i+V_r=V_t$

$$V_i\left(\frac{R-Z_0}{R+Z_0}\right)=V_r$$

$$V_i\left(\frac{R-Z_0}{R+Z_0}\right)=V_t-V_i$$

$$V_i\left(\frac{R-Z_0}{R+Z_0}+1\right)=V_t$$

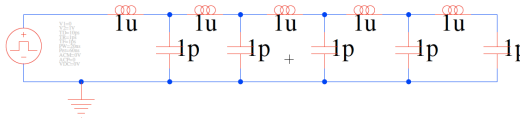
$$V_i\left(\frac{2R}{R+Z_0}\right)=V_t$$

Transmission coefficient

29

End of Line

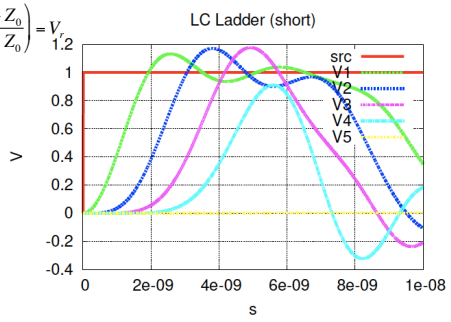
- What happens at the end of the transmission line?
  - Short Circuit, R=0
    - Hint: what must happen in steady state?
  - Terminate with R=Z_0
  - Open Circuit, R=∞



30

Short

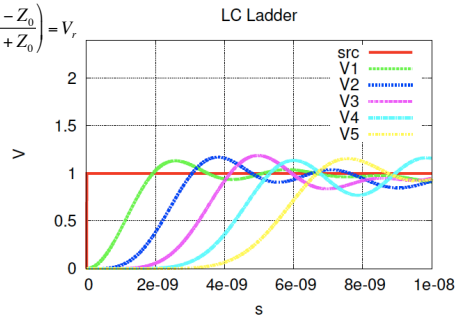
$$V_i\left(\frac{R-Z_0}{R+Z_0}\right)=V_r$$



31

Terminate R=Z_0

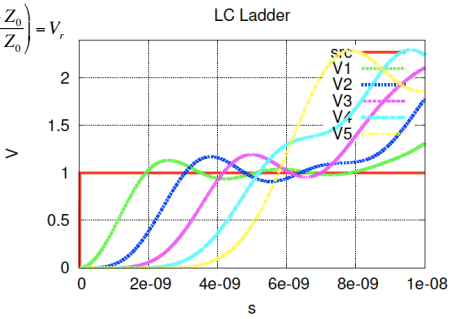
$$V_i\left(\frac{R-Z_0}{R+Z_0}\right)=V_r$$



32

Open

$$V_i\left(\frac{R-Z_0}{R+Z_0}\right)=V_r$$



33

Longer LC (open)

- 40 Stages
- L=100nH
- C=1pF

$$w=\frac{1}{\sqrt{LC}}=\frac{c_0}{\sqrt{\varepsilon_r\mu_r}}$$

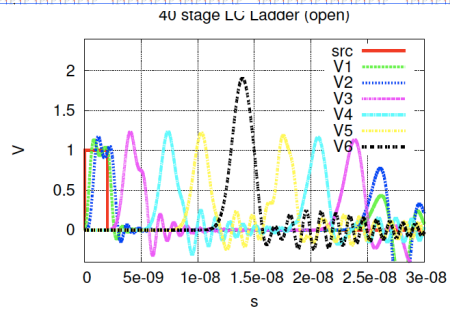
Stage delay? How long to propogate?

- Drive with 2ns Pulse
- No termination (open circuit)
  - What reflection do we expect?

34

Pulse Travel RC

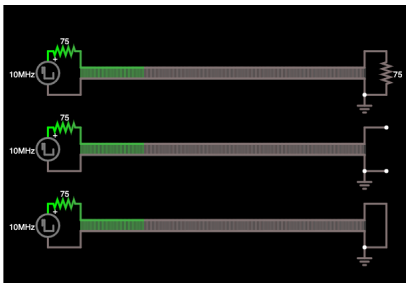
- V1,V3,V4,V5,V6 about 10 stages apart



35

Visualization

- http://educypedia.karadimov.info/electronics/javatransmissinlines.htm



36

Back to Source

37

Back at Source?

- What happens at source?
  - Depends on how it's terminated

38

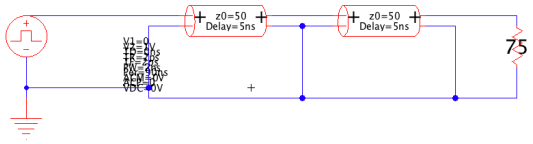
R≠Z_0

- What happens?
  - 75 Ω termination on 50 Ω line

39

Transmission Line Symbol

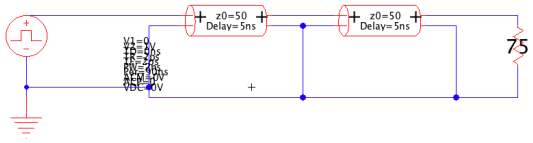
- Specify delay of full Tline and characteristic impedance
- Need reference



40

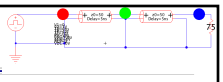
Simulation

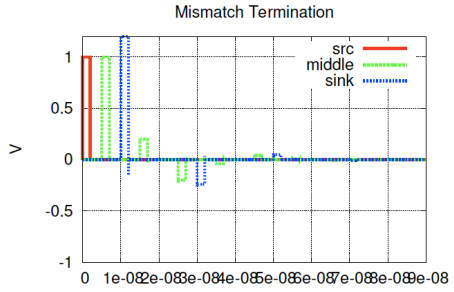
- For these, with direct drive from voltage source
  - Source looks like short circuit (not typical of CMOS)
    - Source cannot be changed



41

50Ω line, 75Ω termination

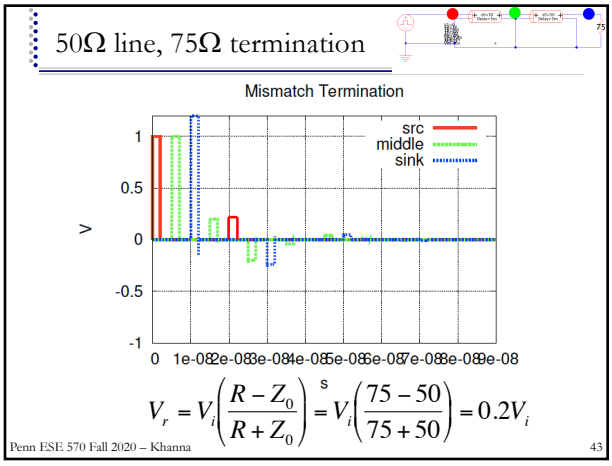




$$V_r = V_i\left(\frac{R - Z_0}{R + Z_0}\right) \overset{s}{=} V_i\left(\frac{75 - 50}{75 + 50}\right) = 0.2V_i$$

42

50Ω line, 75Ω termination



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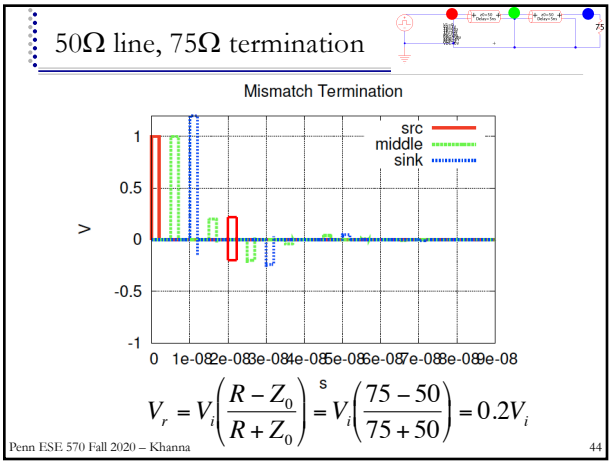
43

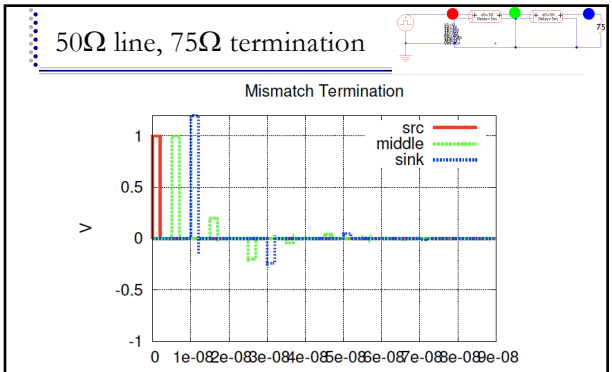
50Ω line, 75Ω termination



$$V_r = V_i\left(\frac{R - Z_0}{R + Z_0}\right) \overset{s}{=} V_i\left(\frac{75 - 50}{75 + 50}\right) = 0.2V_i$$

44

50Ω line, 75Ω termination

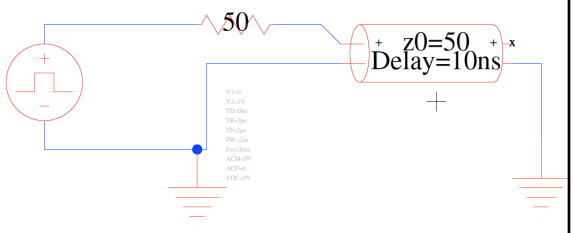


$$V_r = V_i\left(\frac{R - Z_0}{R + Z_0}\right) \overset{s}{=} V_i\left(\frac{75 - 50}{75 + 50}\right) = 0.2V_i$$

45

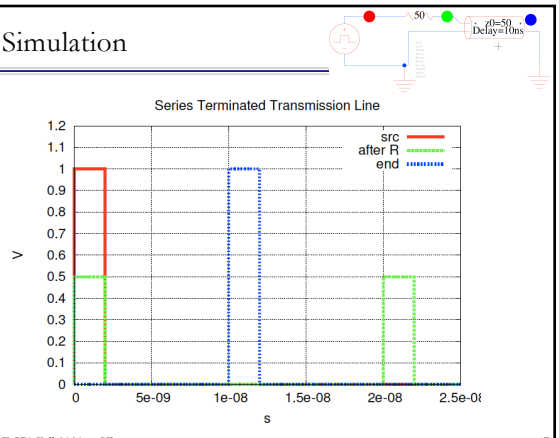
Source Series Termination

- What happens here?



46

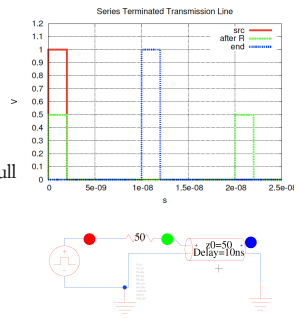
Simulation



47

Series Termination

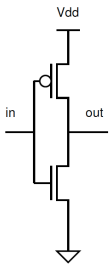
- $R_{series} = Z_0$
- Initial voltage divider
  - Half voltage pulse propogates down Tline
- End of line open circuit
  - Sees single transition to full voltage (full reflection)
- Reflection returns to source and sees termination $R_{series} = Z_0$
- No further reflections



48

CMOS Driver / Receiver

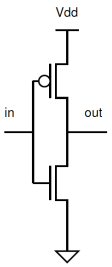
- Driver: What does a CMOS driver look like at the source?
  - $I_{d,sat}$=1200μA/μm @ 45nm, V_{dd}=1V
- Receiver: What does a CMOS inverter look like at the sink?



49

CMOS Driver / Receiver

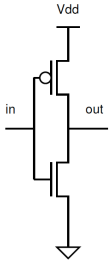
- Driver: What does a CMOS driver look like at the source?
  - $I_{d,sat}$=1200μA/μm @ 45nm, V_{dd}=1V
- Receiver: What does a CMOS inverter look like at the sink?
  - Infinite resistance → Open circuit



50

CMOS Driver

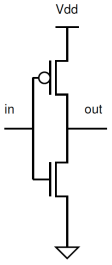
- Driver: What does a CMOS driver look like at the source?
  - $I_{d,sat}$=1200μA/μm @ 45nm, V_{dd}=1V
  - Min size:
    - I_{drive}=1200μA/μm*45nm=54μA
    - R_{out}=V_{dd}/I_{drive}=18kΩ



51

CMOS Driver

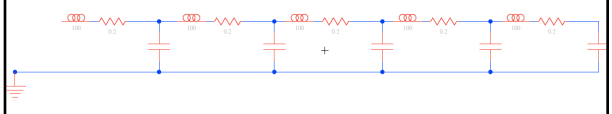
- Driver: What does a CMOS driver look like at the source?
  - $I_{d,sat}$=1200μA/μm @ 45nm, V_{dd}=1V
  - Min size:
    - I_{drive}=1200μA/μm*45nm=54μA
    - R_{out}=V_{dd}/I_{drive}=18kΩ
  - W=370
    - I_{drive}=1200μA/μm*45nm*370=20mA
    - R_{out}=V_{dd}/I_{drive}=50Ω



52

Lossy Transmission Line

- How do addition of R's change?
  - Concretely, discretely think about R=0.2Ω every meter on Z_0=100Ω
    - what does each R do?



53

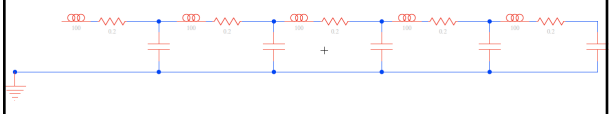
Lossy Transmission Line

- Each R is a mismatched termination

$$V_t = V_i\left(\frac{2(R+Z_0)}{(R+Z_0)+Z_0}\right)$$

- Each R is a voltage divider

$$V_{i+1} = V_t\left(\frac{Z_0}{R+Z_0}\right)$$

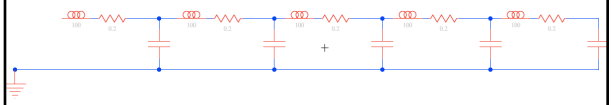


54

Lossy Transmission Line

$$V_{i+1} = V_i\left(\frac{2(R+Z_0)}{(R+Z_0)+Z_0}\right)\left(\frac{Z_0}{R+Z_0}\right)$$

$$V_{snk} = V_{src}\left(\left(\frac{2(R+Z_0)}{(R+Z_0)+Z_0}\right)\left(\frac{Z_0}{R+Z_0}\right)\right)^N$$

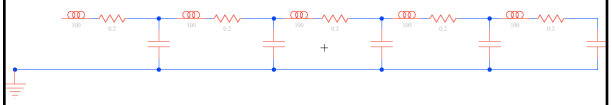


55

Lossy Transmission Line

- How long before drop voltage by half?
  R=0.2Ω every meter on Z_0=100Ω

$$V_{snk} = V_{src}\left(\left(\frac{2(R+Z_0)}{(R+Z_0)+Z_0}\right)\left(\frac{Z_0}{R+Z_0}\right)\right)^N$$



56

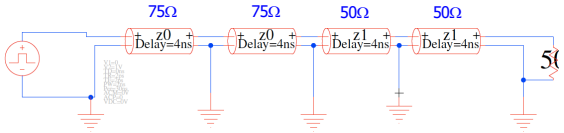
More Examples…

Time Permitting

57

Impedance Change (Preclass 5)

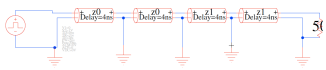
- What happens if there is an impedance change in the wire? Z_0=75Ω, Z_1=50Ω
  - What reflections and transmission do we get?



58

Z_0=75, Z_1=50 (Preclass 5)

- At junction:
  - Reflects
    - V_r=(50-75)/(50+75)V_i=-0.2V_i
  - Transmits
    - V_t=(100/(50+75))V_i=0.8V_i

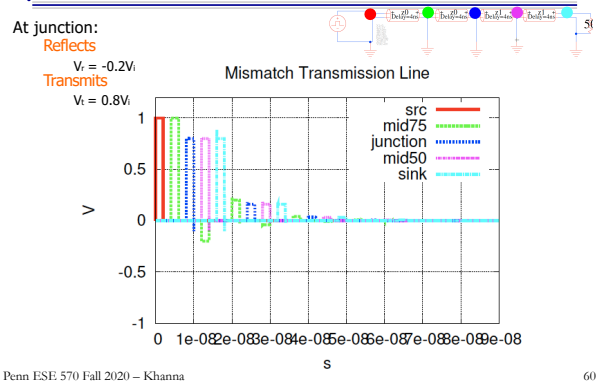


$$V_i\left(\frac{R-Z_0}{R+Z_0}\right) = V_r \qquad V_i\left(\frac{2R}{R+Z_0}\right) = V_t$$

59

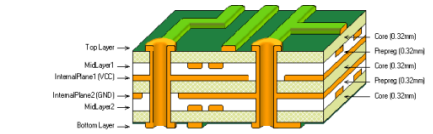
Impedance Change Z_0=75, Z_1=50 (Preclass 5)

At junction:
Reflects
V_r = -0.2V_i
Transmits
V_t = 0.8V_i

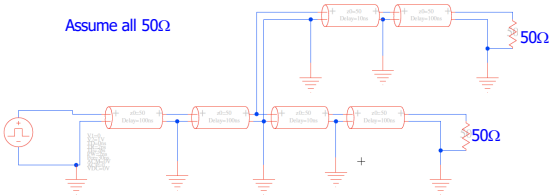


60

What happens at branch?



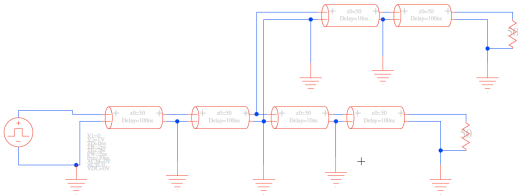
Assume all 50Ω



61

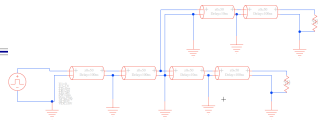
Branch

- Transmission line sees two Z_0 in parallel
  - Looks like $Z_0/2$



62

Z_0=50, Z_1=25



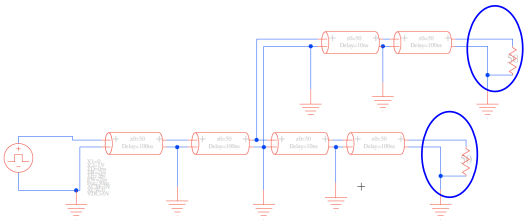
- At junction:
  - Reflects
    - $V_r=(25-50)/(25+50)V_i=-0.33V_i$
  - Transmits
    - $V_t=(50/(25+50))V_i=0.67V_i$

$$V_i\left(\frac{R-Z_0}{R+Z_0}\right)=V_r \qquad V_i\left(\frac{2R}{R+Z_0}\right)=V_t$$

63

End of Branch

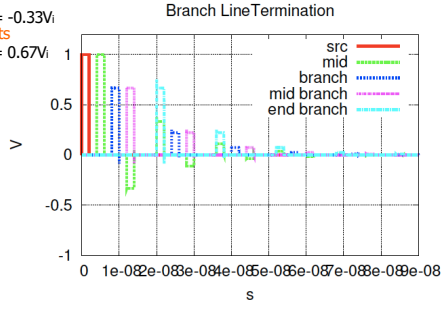
- What happens at end?
- If ends in matched, parallel termination
  - No further reflections



64

Branch Simulation

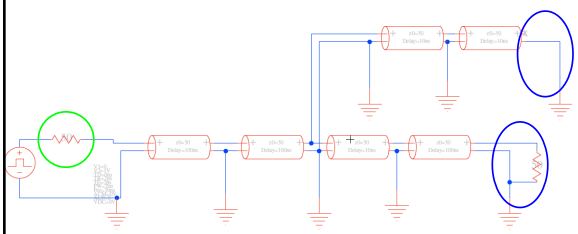
At junction:
Reflects
V_r = -0.33V_i
Transmits
V_t = 0.67V_i



65

Branch with Open Circuit?

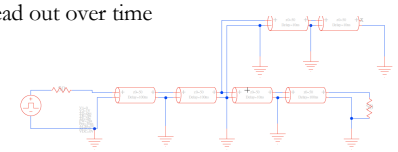
- What happens if branch open circuit?
- And source termination?



66

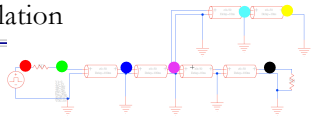
Branch with Open Circuit

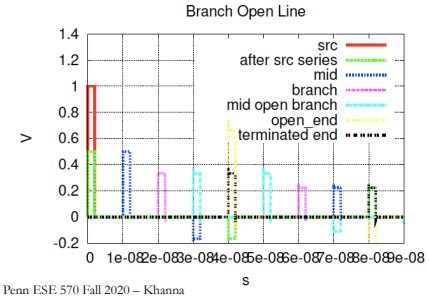
- Reflects at end of open-circuit stub
- Reflection returns to branch
  - …and encounters branch again
  - Send transmission pulse to both
    - Source and other branch
- Sink sees original pulse as multiple smaller pulses spread out over time



67

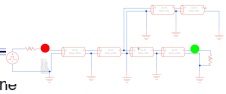
Open Branch Simulation

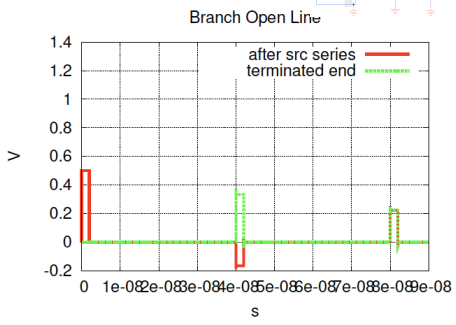




68

Open Branch Simulation





69

Idea

- Transmission lines
  - high-speed
  - high throughput
  - long-distance signaling
  - termination

70

Admin

- Final Project
  - Design CLB
    - EC for best figure of merits
      - FOM = Area*avgEnergy/maxFrequency
  - Due 12/10 (last day of class)
    - Can turn in up to 12/17 with no penalty

71