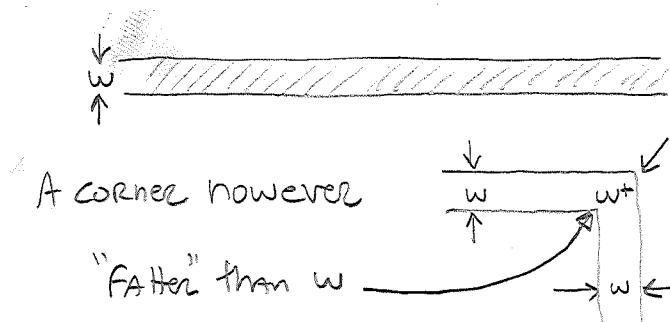


## The T-Line Neighborhood - PCB Models

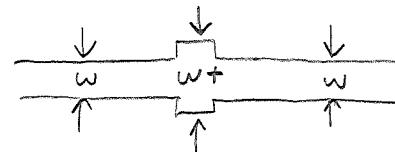
What about corners?

With a uniform interconnect, there are no reflections



Corners look like a very short segment of slightly wider trace.

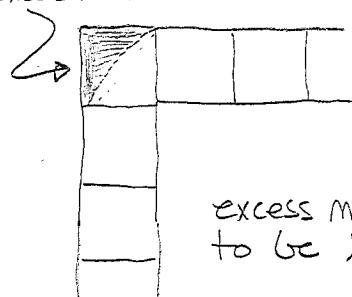
Another way to look at a corner would be:



Using the formula for the self-inductance of a wire,  $L = 5.08l \left[ \ln \left( \frac{4l}{d} - 1 \right) \right]$ , with  $d$ , diameter, acting as the width of our wire we see that a change in  $d$ , or width, makes little difference in inductance of the corner.

If we look at the corner's capacitance however, we can see a corner nearly doubles it.

excess metal



$$C_{\text{corner}} = 0.5 C_{\text{square}} \quad \text{where } C_{\text{square}} = \text{CAP. OF THE SQ.}$$
$$= 0.5 C_w$$

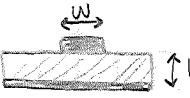
$C$  = capacitance / length  
 $w$  = width

excess metal is approximated to be  $\frac{1}{2}$  of the square

## The T-Line Neighborhood - PCB Models

In the digital domain, most work is done on FR-4 boards, in 2-8 trace layers with 2-4 VDD/VSS planes. Vias will be numerous, mostly around 10 mils in diameter. Most traces will be 5-8 mils in width configured as microstrip or striplines. Most boxes today will be 90% surface mount.

For traces:

microstrip :   $Z_0 = \frac{87}{\sqrt{1.41 + \epsilon_r}} \ln\left(\frac{5.98h}{0.8w+t}\right)$

stripline :   $Z_0 = \frac{60}{\sqrt{\epsilon_r}} \ln\left(\frac{2b+t}{0.8w+t}\right)$

$Z_0$  = characteristic impedance in ohms

\* dimensions in mils (.001")

$h$  = dielectric thickness

$w$  = line width

$b$  = plane to plane spacing

$t$  = metal thickness

$\epsilon_r$  = dielectric constant for dielectric

"mils" are the common dimensional unit for PCB manufacturers

The constraints on your PCB design are mostly not electrically motivated.

Most traces will exhibit a  $Z_0$  of between 30 - 120 ohms.

## The T-Line Neighborhood - PCB Models

Finding Capacitance per unit Length is a function of  $\epsilon_r$  &  $Z_0$ , we can find the Capacitance of A corner if we know the width of the trace.

$$v = \frac{c}{\sqrt{\epsilon_r}}$$

$$Z_0 = \frac{1}{\sqrt{\epsilon_r}}$$

$$Z_0 = \frac{1}{\sqrt{\epsilon_r}} C$$

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

$$Z_0 = \frac{\sqrt{\epsilon_r}}{C} \cdot \frac{1}{Z_0}$$

$$C = \frac{\sqrt{\epsilon_r}}{3 \times 10^8 \frac{m}{s} Z_0}$$

$$= \frac{3.33 \times 10^{-9} \frac{s}{m} \sqrt{\epsilon_r}}{Z_0}$$

$$C = \text{speed of light } 3 \times 10^8 \text{ m/s}$$

$$\epsilon = \text{cap. per unit length}$$

hmm... units here are  $(\frac{\text{sec}}{\text{meter} \cdot \text{ohms}})!!$

but sec = ohms \* farads

$$= \frac{\text{volts}}{\frac{\text{coulomb}}{\text{sec}}} \cdot \frac{\text{coulomb}}{\text{volts}} = \text{sec} \dots \text{so}$$

$$\frac{\text{sec}}{\text{meter} \cdot \text{ohms}} = \frac{\text{sec}}{\text{meter} \cdot \text{ohms}} = \frac{\text{farad} \cdot \text{ohm/s}}{\text{meter} \cdot \text{ohm/s}} = \text{F/m}$$

so the units are Farads/meter, now put into pF/inch

$$C = \frac{3.33 \times 10^{-9} \sqrt{\epsilon_r}}{Z_0} \cdot \frac{F}{in} \cdot \frac{1 \times 10^{12} \text{ pF}}{F} \cdot \frac{1 \text{ in}}{39.37 \text{ m}}$$

$\left. \begin{array}{l} \epsilon_r \text{ is dimensionless} \\ \text{its a ratio of 2 capacitances} \end{array} \right\}$

$$C = \frac{83.8 \sqrt{\epsilon_r}}{Z_0} \text{ pF/in}$$

So, the capacitance of a corner is

$$C_{\text{corner}} = 0.5(C)(w) = \left( \frac{42 \sqrt{\epsilon_r}}{Z_0} \right) w$$

(in pF)

## The T-Line Neighborhood - PCB Models

If we have a .8 mil trace on .002 FR4 ( $\epsilon_r = 4.5$ ) in a microstrip configuration we get:

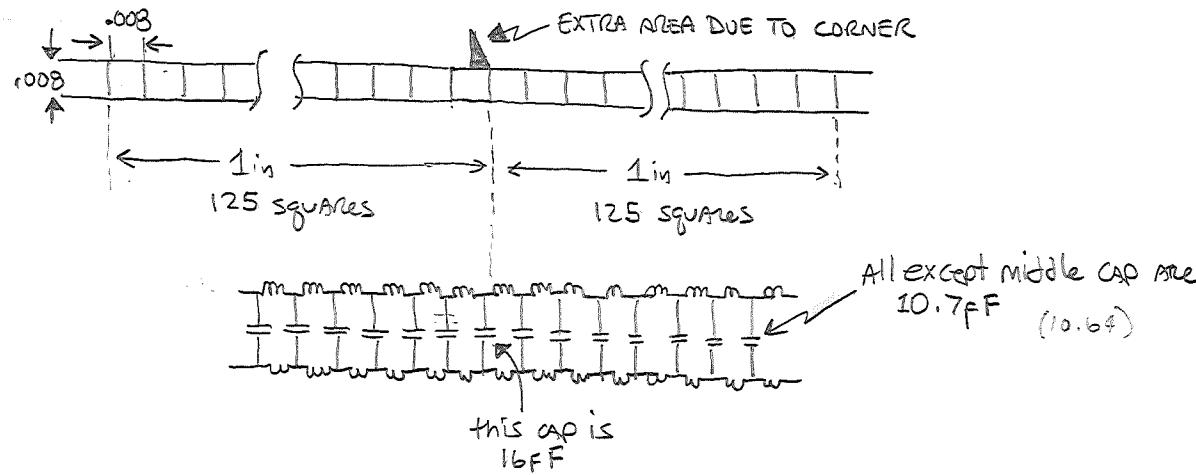
$$Z_0 = \frac{87}{\sqrt{1.41 + 4.5}} \ln\left(\frac{5.98(62)}{0.8(8) + 1.4}\right) = 133 \Omega$$

+  $C_{corner} = \frac{42\sqrt{4.5}}{133} (.008) = 5.36 \times 10^{-3} \text{ pF/corner}$   
 $5.36 \text{ fF/corner}$

Still, is it significant?

The uniform line  $C$  is  $\frac{83.8\sqrt{\epsilon_r}}{133} = 1.33 \text{ pF/in}$   
 $= 1330 \text{ fF/in}$

Imagine a 2in piece of this .008 trace with a corner in the middle.



The question to ask here is?.. IS it a lumped load?

## The T-Line Neighborhood - PCB Models

Is it a lumped load? Electrically speaking, how long is it?

$$T = \frac{300 \text{ mm/ns}}{\sqrt{\epsilon_r}} = \frac{300 \times 10^3 \text{ mm/ns}}{\sqrt{4.5}} = 141 \text{ mm} \cdot \frac{1 \text{ in}}{25.4 \text{ mm}} = 5.6 \text{ in/ns}$$

So the discontinuity is  $\frac{5.6 \text{ in}}{\text{ns}} = \frac{0.18 \text{ ns}}{\text{in}} \cdot \frac{0.18 \text{ in}}{\text{ns}} \cdot 0.008 \text{ in} = 1.44 \times 10^{-3} \text{ ns}$   
 $= 1.44 \text{ ps}$  long

Using our rule of: lumped if  $\frac{t_r}{T} > 6$  or if  $t_r > (6 \times 1.44 \text{ ps})$   
 $t_r > 8.6 \text{ ps}$  (astoundingly fast edge)

(don't worry if  $t_r > 8.6 \text{ ps}$ )

OR  
confidently lumped if  $f_T < 0.01T$

$$1.44 \text{ ps} < 0.01T$$

$$144 \text{ ps} < T$$

so at frequencies  $< \frac{1}{144 \text{ ps}} = 6.9 \text{ GHz}$  its lumped

Check via Spice? Sure, it's easy. [corner.sp]

So below 6.9 GHz we can safely ignore 90° corners for all but the most critical applications.

Feb 05, 10 12:44

corner.sp

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133 ohm T-line with a 90 deg corner  
 \*8 mil trace on .064 board  
 \*end terminated at Z0

\*input source with 5ns delay, 20ps edges, 40ns pulse width, 81ns cycle time  
 \*Vin vin 0 3.3 PULSE(0 3.3 5e-9 20ps 20ps 40e-9 81e-9)

\*input source with 5ns delay, 1ps edges, 40ns pulse width, 81ns cycle time  
 Vin vin 0 3.3 PULSE(0 3.3 5e-9 1ps 1ps 40e-9 81e-9)

\*source output impedance  
 rsrc vin tline\_input 0.1

\*two transmission lines, 133 ohm, .18ns electrical length  
 t1 tline\_input 0 corner 0 z0=133 td=0.18ns  
 t2 corner 0 tline\_output 0 z0=133 td=0.18ns

\*termination at end of T-line  
 rload tline\_output 0 133

c\_corner corner 0 5.4fF

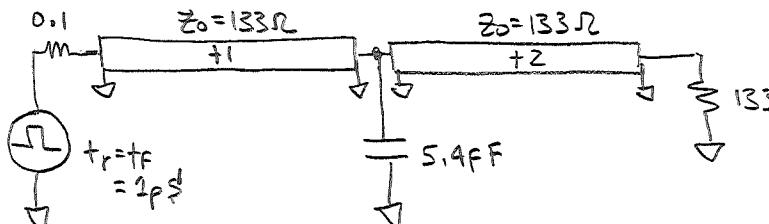
.control  
 op  
 tran 10ps 16ns  
 plot V(tline\_input) V(tline\_output) xl 1ns 16ns

set hcopydevtype=postscript  
 set hcopypscolor=true  
 set color0 = rgb:f/f/f  
 set color1 = rgb:0/0/0  
 set color2 = rgb:f/0/0  
 set color3 = rgb:f/0/f  
 hardcopy out.ps V(tline\_input) V(tline\_output) xl 0ns 20ns  
 .endc

.end

.endc

.end



*1 ps EDGES!!*

