Chapter 5

Nonideal Interconnect Issues

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Outline

- Transmission Line Losses
- Variations in the Dielectric Constant
- Serpentine Traces
- Intersymbol Interference
- Effects of 90^0 Bends
- Effect of Topology

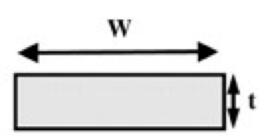
Transmission Line Losses

- Introduction
  - Why Losses are so Important?
    - Development of high speed digital system → Requirement of smaller dimensions and faster signal rate (high-frequency content) → Resistive losses become more and more severe → The signal amplitude is decreased, thus affecting noise margins and slowing edge rates, which in turn affects timing margins.
    - One kind of dispersion is caused by the loss variations of transmission line with frequencies, and the other is caused by the phase variations of transmission lines with frequencies.

Transmission Line Losses

- DC Losses
  - Conductor DC Losses
    - DC losses are of particular concern in small-geometry conductors, very long lines, and multiload buses.
    - The DC loss depends primarily on two factors: the resistivity of the conductor and the total area in which the current is flowing.
    - The losses in the ground return path are usually negligible at DC because the cross-sectional area is very large compared to the signal line.

$$R = \frac{\rho L}{A} = \frac{\rho L}{Wt} \quad \text{ohms}$$



Transmission Line Losses

- DC Losses
  - Dielectric DC Losses
    - The dielectric losses at DC for conventional substrates, however, are usually very negligible and can be ignored.
- Skin Effect
  - Definition
    - At high frequencies, the current flowing in a conductor will migrate toward the periphery or skin of the conductor.

When frequency increases beyond DC up to 15 GHz, the substrate loss dominates over the conductor loss as for the FR4 substrate.

Transmission Line Losses

- Skin Effect
  - Frequency-Dependent Resistance
    - As frequency increases, the changing current distribution causes the cross-section of the current to shrink, thus making the resistance to increase with the square root of frequency.
    - The skin depth is defined as the depth while the electric field amplitude is decayed by a factor of e^{-1} of its initial value at the surface.
    - Approximately 63% of the total current will flow in one skin depth.

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}} = \sqrt{\frac{\rho}{\pi F \mu}} \qquad \text{meters}$$

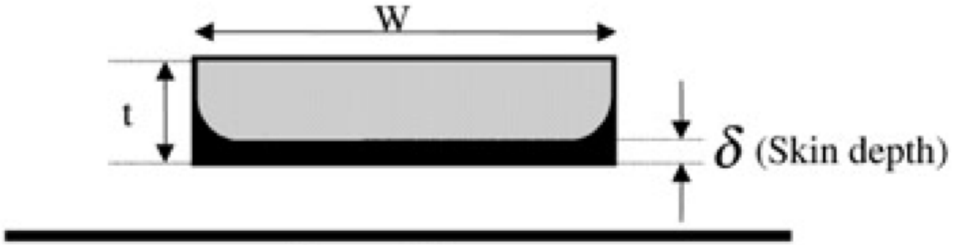
Transmission Line Losses

Why the inductance is larger when the current is distributed uniformly among the cross-section of the conductor? Think of the even-mode excitation.

- Skin Effect
  - Frequency-Dependent Inductance
    - As frequency increases, the changing current distribution causes the total inductance to fall asymptotically toward a static value called the ***external inductance***.
    - External inductance is the value calculated when it is assumed that all the current is flowing on the exterior of the conductor.
    - In most high-speed digital systems, the frequency components of the signals are high enough so that it is a valid approximation to ignore the frequency dependence of inductance.

Transmission Line Losses

- Skin Effect
  - Frequency-Dependent Conductor Losses in a Microstrip
    - Notice that the current distribution is concentrated on the bottom edge of the transmission line. This is because the fields between the signal line and the ground plane pull the charge to the bottom edge.
    - Also notice that the current distribution curves up the side of the conductor. This is because there is still significant field concentration along the thickness *t*.

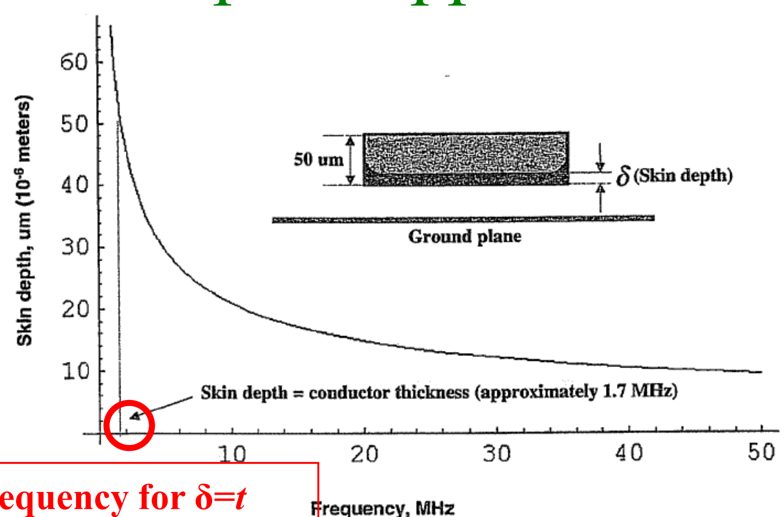


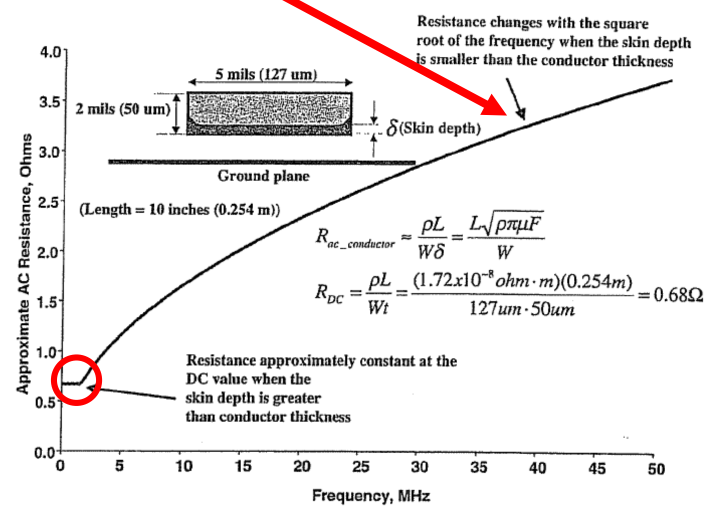
Transmission Line Losses

- Skin Effect
  - Frequency-Dependent Conductor Losses in a Microstrip
    - The losses per unit length (L=1) in the conductor can be approximated as

$$R_{\text{ac signal}} \approx \frac{\rho}{W\delta} = \frac{\sqrt{\rho\pi\mu F}}{W} \qquad \Omega/\text{m}$$

  - Example Copper Cross Section





Transmission Line Losses

- Skin Effect
  - Frequency-Dependent Conductor Losses in a Microstrip
    - When simulating both the ac and dc resistance in SPICE, it is a good way to combine

$$R_{\text{total}} \approx \sqrt{R_{\text{ac}}^2 + R_{\text{dc}}^2}$$

    - For the ac resistance, there are two components, one from the signal line and the other from the ground return path.
    - An approximate current density distribution in the ground plane for a microstrip transmission line is

$$I(D) \approx \frac{I_o}{\pi H} \frac{1}{1 + (D/H)^2}$$

Transmission Line Losses

- Skin Effect
  - Frequency-Dependent Conductor Losses in a Microstrip
    - First, assuming that the ground current flows entirely in one skin depth δ.
    - Second, since $\int_{-3H}^{3H} \frac{I_o}{\pi H} \frac{1}{1+(D/H)^2} = \frac{2I_o}{\pi} \tan^{-1}(3) \approx 0.795 I_o$

      $= 79.5\%$ of the total current
    - 79.5% of the current is contained within a distance of ±3H (6H total width), thus we assume that W=6H.
    - Thus, the ground return path resistance can be approximated by a conductor of cross section $A_{\text{ground}} = \delta \times 6H$.

$$R_{\text{ac ground}} \approx \frac{\rho}{A_{\text{ground}}} = \frac{\rho}{6\delta H} = \frac{\rho}{6H}\sqrt{\frac{\pi \mu F}{\rho}}$$

$$= \frac{\sqrt{\rho \pi \mu F}}{6H} \qquad \Omega/\text{m}$$

Transmission Line Losses

- Skin Effect
  - Frequency-Dependent Conductor Losses in a Microstrip
    - The total ac resistance is:

$$R_{\text{ac microstrip}} = R_{\text{ac signal}} + R_{\text{ac ground}}$$
$$\approx \frac{\sqrt{\rho\pi\mu F}}{W} + \frac{\sqrt{\rho\pi\mu F}}{6H} = \sqrt{\rho\pi\mu F}\left(\frac{1}{W} + \frac{1}{6H}\right) \qquad \Omega/\text{m}$$

    - A more exact formula can be derived through conformal mapping techniques:

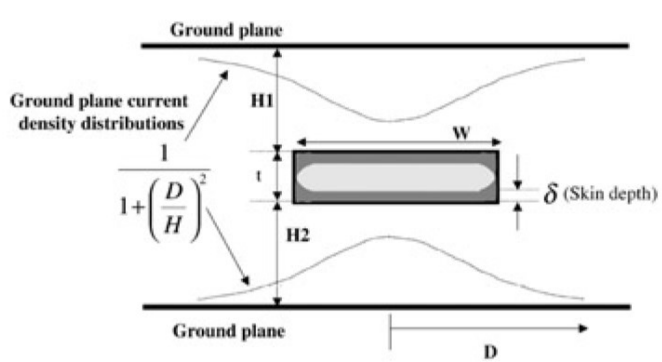
$$R_{\text{signal}} = [\text{loss ratio}]\left(\frac{1}{\pi} + \frac{1}{\pi^2}\ln\frac{4\pi W}{t}\right)\frac{\sqrt{\pi\mu F\rho}}{W}$$

$$\text{Loss ratio} = \begin{cases} 0.94 + 0.132\dfrac{W}{H} - 0.0062\left(\dfrac{W}{H}\right)^2 & \text{for} \quad 0.5 < \dfrac{W}{H} < 10 \\ 1 & \text{for} \quad 0.5 \geq \dfrac{W}{H} \end{cases} \quad (4$$

$$R_{\text{ground}} = \frac{W/H}{W/H + 5.8 + 0.03(H/W)}\frac{\sqrt{\pi\mu F\rho}}{W} \qquad \text{for} \quad 0.1 < \frac{W}{H} < 10$$

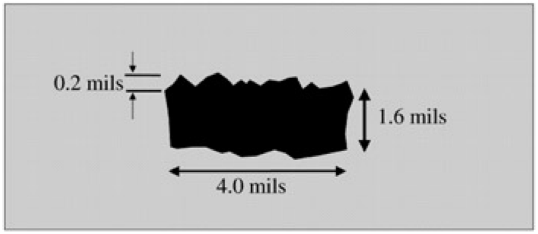
Transmission Line Losses

- Skin Effect
  - Frequency-Dependent Conductor Losses in a Stripline
    - The current density will depend on the proximity of the local ground planes.
    - Thus, the resistance of a stripline can be approximated by the parallel combination of the resistance in the top and bottom portions of the conductor. $R_{\text{ac stripline}} = \dfrac{(R_{(H1)\text{ac microstrip}})(R_{(H2)\text{ac microstrip}})}{R_{(H1)\text{ac microstrip}} + R_{(H2)\text{ac microstrip}}} \quad \Omega/\text{m}$



Transmission Line Losses

- Skin Effect
  - Effect of Conductor Surface Roughness
    - In reality, the metal surfaces will be rough, which will effectively increase the resistance of the material when the mean surface roughness is a significant percentage of the skin depth.
    - Losses are higher than those calculated with the ideal formulas by as much as 10 to 50%.
    - The roughness of the conductor is usually described as the ***tooth structure*** and the magnitude of the surface variations is described as ***tooth size***.



Transmission Line Losses

- Skin Effect
  - Effect of Conductor Surface Roughness
    - Typical FR4 boards will have an average tooth size of 4 to 7 μm.
    - Conductor surfaces that are exposed to the etching process will usually have a significantly smaller magnitude of tooth size.
  - Surface Resistance (R_S)
    - Since the ac resistance is defined as

$$R_{ac} = R_s\sqrt{F}$$

    - The surface resistance R_S could be derived by dividing this equation with the square root of F.

Transmission Line Losses

- Skin Effect
  - Surface Resistance (R_S)

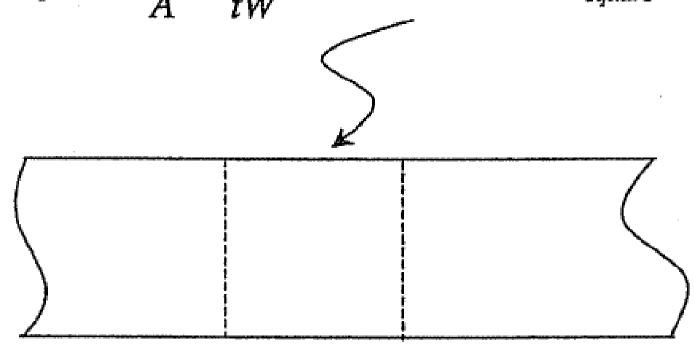
$$\delta = \sqrt{\frac{2\rho}{\omega\mu}} = \sqrt{\frac{\rho}{\pi F \mu}} \qquad \text{meters}$$

- Since the ac resistance is defined as

$$R_{\text{ac signal}} \approx \frac{L\rho}{W\delta} = \frac{L\sqrt{\rho\pi\mu F}}{W} \qquad \Omega/\text{m}$$

$$R_s = \begin{cases} \frac{L}{W}\frac{\rho}{\delta} = \frac{L}{W}\sqrt{\rho\pi\mu} & \text{ohms}\cdot\sqrt{\text{seconds}} \\ \boxed{\sqrt{\rho\pi\mu} \qquad \text{ohms}\cdot\sqrt{s}/\text{square} \quad (L=W)} \end{cases}$$

- The ac resistance is obtained by multiplying R_S by the length and the square root of the frequency and dividing by the width. $R_{square} = \frac{\rho L}{A} = \frac{\rho L}{tW}$ but L=W, so $R_{square} = \frac{\rho}{t}$



Transmission Line Losses

- Skin Effect
  - Effect of AC Losses on Signals
    - The Fourier expansion of a periodic square wave at a 50% duty cycle is
      $$f(x) = \frac{2}{\pi} \sum_{n=1,3,5,\ldots} \frac{1}{n} \sin 2\pi n F x$$
    - These components are referred to as ***harmonics***, where n=1 corresponds to the first harmonic, n=3 corresponds to the third harmonic, and so on.
    - A real-life signal is not a perfect square wave with 50% duty cycle and infinitely fast rise times.
    - The even harmonics become present in the spectrum if the waveform is not 50% duty cycle.

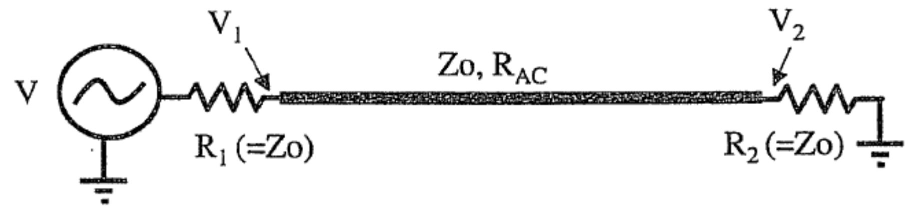
Transmission Line Losses

- Skin Effect
  - Effect of AC Losses on Signals
    - The ac resistance is usually measured with a vector network analyzer (VNA).
    - In a matched system, the attenuation factor α can easily be calculated at a single frequency which is based on the voltage divider.

$$V_1 = V\frac{R_{ac}+R_2}{R_1+R_{ac}+R_2}$$

$$V_2 = V\frac{R_2}{R_1+R_2+R_{ac}}$$

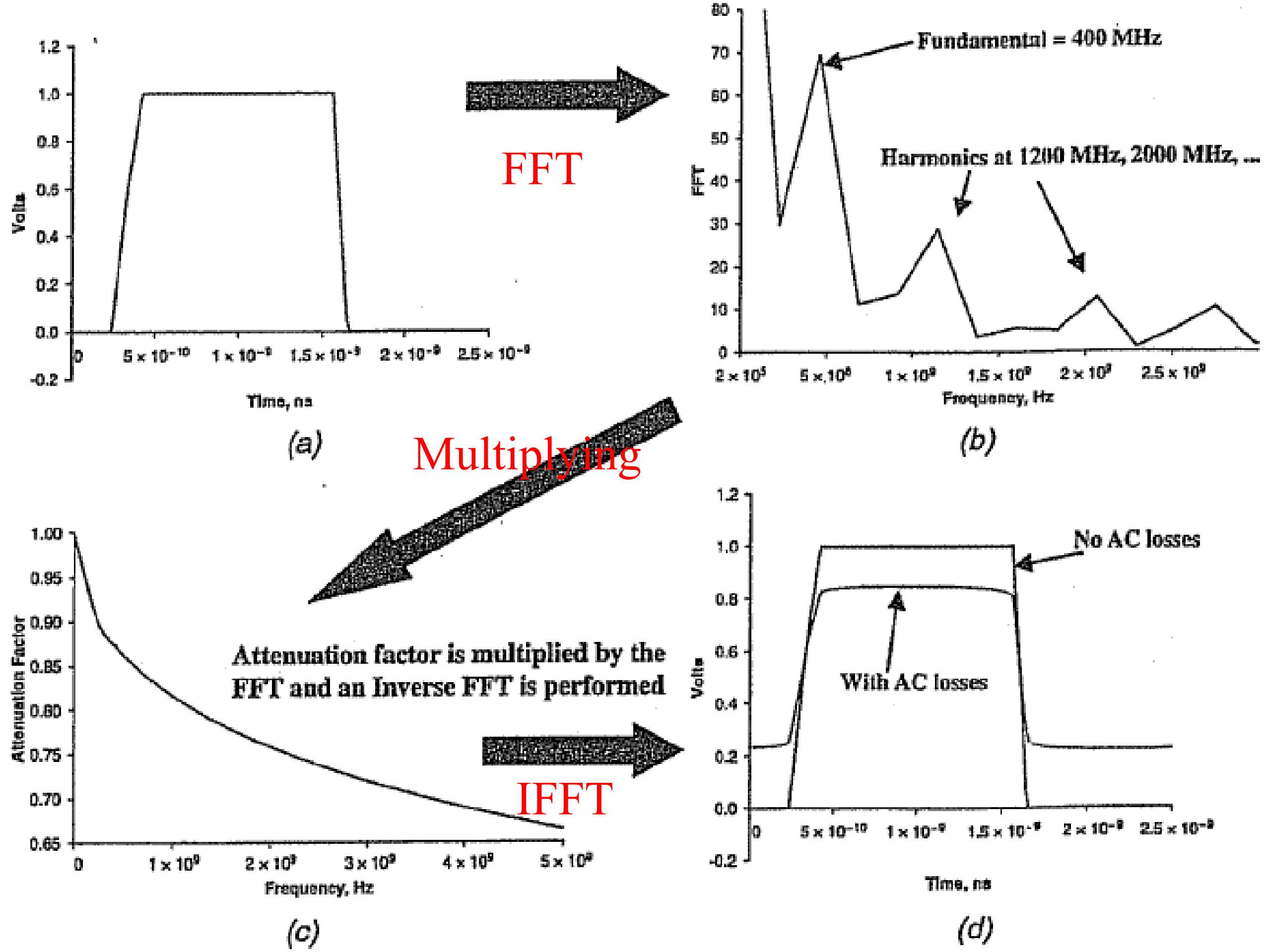
$$\alpha = \frac{V_2}{V_1} = \frac{R_2}{R_{ac}+R_2}.$$



Transmission Line Losses

- Skin Effect
  - Effect of AC Losses on Signals

The wave shape is rounded, the edge rate has been decayed due to the attenuation of the high-frequency components.
The amplitude has been attenuated since the low-frequency components of the signal have been attenuated.



Transmission Line Losses

- Frequency-Dependent Dielectric Losses
  - Definition
    - When a time-varying electric field is impressed onto a material, any molecules in the material that are polar in nature will tend to align in the direction opposite that of the applied field. This is called ***electric polarization***.
    - The response to the applied electric fields involves damping mechanisms that change with frequency.
    - The dielectric loss are caused by these mechanisms.
    - When dielectric losses are accounted for, the dielectric constant of the material becomes complex:

$$\varepsilon = \varepsilon' - j\varepsilon''$$

Transmission Line Losses

- Frequency-Dependent Dielectric Losses
  - Definition

$$\begin{aligned}\nabla \times H &= j\omega\varepsilon E \\ &= j\omega(\varepsilon' - j\varepsilon'')E \\ &= j\omega\varepsilon' E + \omega\varepsilon'' E \\ &= j\omega\varepsilon' E + \sigma E \\ &= j\omega\varepsilon' E + (1/\rho)E \\ &\propto (j\omega C_{11} + G)E\end{aligned}$$

- This loss mechanism is equivalent to a conductivity $1/\rho = 2\pi F\varepsilon''$.
- The typical method of loss characterization in dielectrics is by the loss tangent

$$\tan|\delta_d| = \frac{1}{2\rho\pi F\varepsilon} = \frac{\varepsilon''}{\varepsilon'}$$

- This loss tangent will result in a parallel conductance in a transmission line model

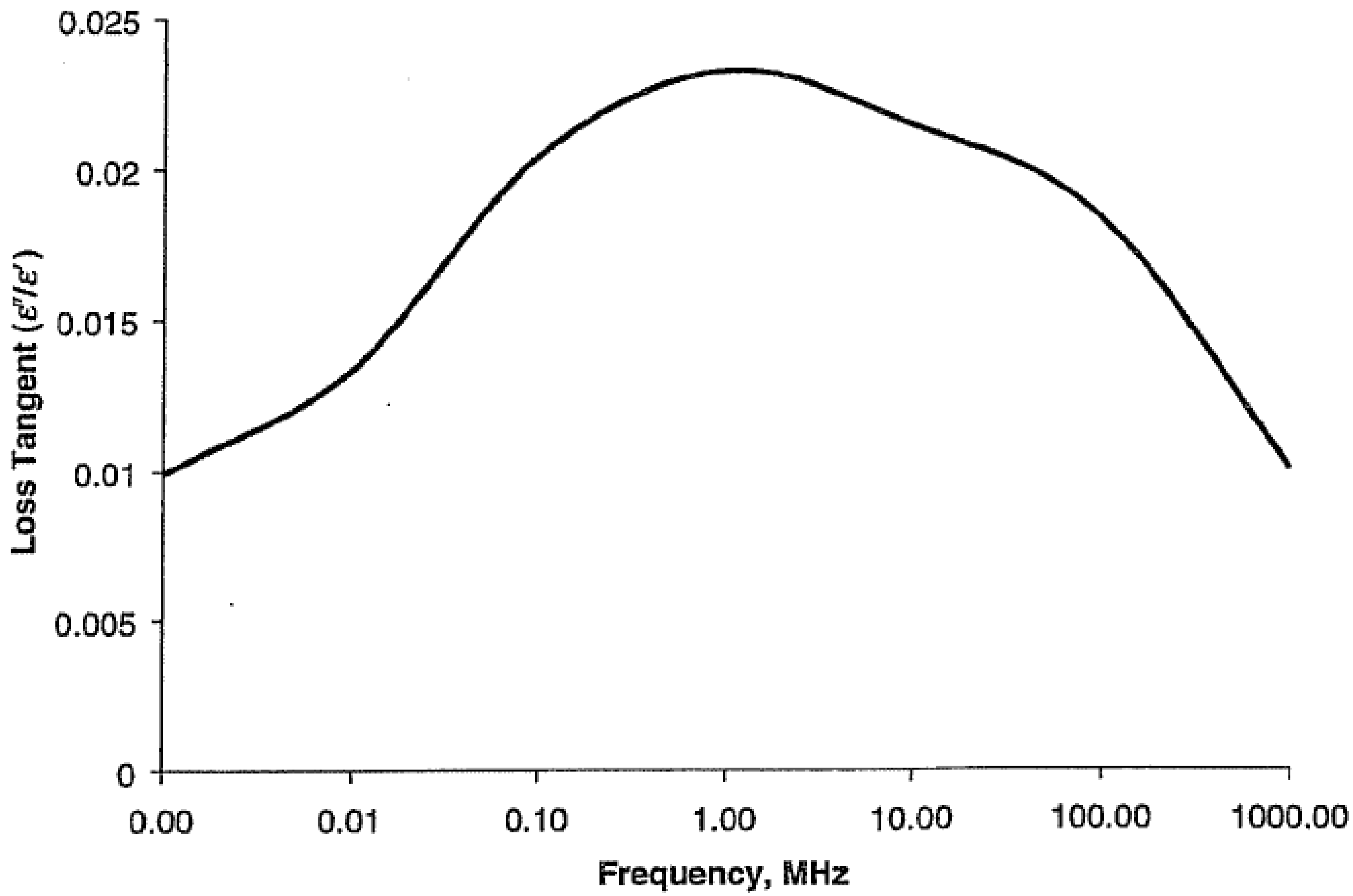
$$G/\sigma = C_{11}/\varepsilon'$$

$$G = \frac{\varepsilon''}{\varepsilon'}(2\pi F C_{11}) \qquad \text{siemens}$$

- where C_{11} is the self-capacitance per unit length.

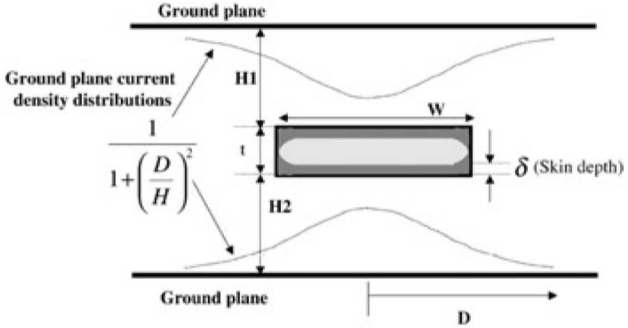
Transmission Line Losses

- Frequency-Dependent Dielectric Losses
  - Loss Tangent in Typical FR4 Dielectric



Transmission Line Losses

- Frequency-Dependent Dielectric Losses
  - Calculating Losses
    - 1. Calculate the surface resistivity (R_S) assuming that W=5mils, H_1=H_2=10mils, t=0.63mil, and ε_r=4.0.
    - 2. Determine how the resistance will change as a function of the frequency.
    - 3. Calculate the series resistance due to the conductor losses at 400 MHz.
    - 4. Calculate the shunt resistance due to the dielectric losses at 400 MHz.

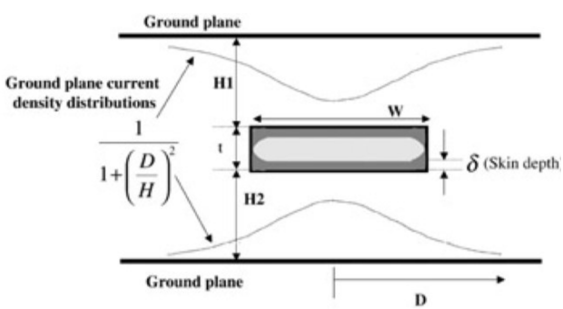


Transmission Line Losses

- Frequency-Dependent Dielectric Losses
  - Calculating Losses
    - To solve (1), the following equations are used.

Step 1

$$R_{\text{signal}} = [\text{loss ratio}]\left(\frac{1}{\pi} + \frac{1}{\pi^2}\ln\frac{4\pi W}{t}\right)\frac{\sqrt{\pi\mu F\rho}}{W}$$



$$\text{Loss ratio} = \begin{cases} 0.94 + 0.132\dfrac{W}{H} - 0.0062\left(\dfrac{W}{H}\right)^2 & \text{for} \quad 0.5 < \dfrac{W}{H} < 10 \\ 1 & \text{for} \quad 0.5 \geq \dfrac{W}{H} \end{cases} \quad (4$$

$$R_{\text{ground}} = \frac{W/H}{W/H + 5.8 + 0.03(H/W)}\frac{\sqrt{\pi\mu F\rho}}{W} \qquad \text{for} \quad 0.1 < \frac{W}{H} < 10$$

$$R_{\text{ac microstrip}} = R_{\text{signal}} + R_{\text{ground}} \qquad \Omega/\text{m}$$

Step 2

$$R_{\text{ac stripline}} = \frac{(R_{(H1)\text{ac microstrip}})(R_{(H2)\text{ac microstrip}})}{R_{(H1)\text{ac microstrip}} + R_{(H2)\text{ac microstrip}}} \qquad \Omega/\text{m}$$

Step 3

$$R_{\text{ac}} = R_s\sqrt{F}$$

Transmission Line Losses

- Frequency-Dependent Dielectric Losses
  - Calculating Losses
    - Since $\frac{W}{H} = \frac{5}{10} = 0.5$ → Loss ratio = 1.0

$$R_{\text{signal}} = 1.0\left(\frac{1}{\pi} + \frac{1}{\pi^2}\ln\frac{4\pi(5)}{0.63}\right)\frac{\sqrt{(\pi \cdot 12.56 \times 10^{-7})1.72 \times 10^{-8}(F)}}{(0.005\ \text{in.})(0.0254\ \text{m/in.})}$$

$$= 0.00172\sqrt{F} \qquad \Omega/\text{m}$$

$$R_{\text{ground}} = \left(\frac{1}{0.5 + 5.8 + 0.03 \cdot 0.5}\right)\frac{\sqrt{(\pi \cdot 12.56 \times 10^{-7})1.72 \times 10^{-8}(F)}}{(0.005\ \text{in.})(0.0254\ \text{m/in.})}$$

$$= 0.0003\sqrt{F} \qquad \Omega/\text{m}$$

$$R_{(H1)\text{ac microstrip}} = R_{\text{signal}} + R_{\text{ground}} = (0.00172 + 0.0003)\sqrt{F}$$

$$= 0.0020\sqrt{F} \qquad \Omega/\text{m}$$

$$R_{(H2)\text{ac microstrip}} = R_{(H1)\text{ac microstrip}}$$

$$R_{\text{ac stripline}} = \frac{(R_{(H1)\text{ac microstrip}})(R_{(H2)\text{ac microstrip}})}{R_{(H1)\text{ac microstrip}} + R_{(H2)\text{ac microstrip}}} \rightarrow R_s = 0.0010\frac{\Omega}{\text{m}\cdot\sqrt{\text{Hz}}}$$

$$= \frac{R_{(H1)\text{ac microstrip}}}{2} = 0.0010\sqrt{F} \qquad \Omega/\text{m}$$

Transmission Line Losses

- Frequency-Dependent Dielectric Losses
  - Calculating Losses
    - To solve (2), it is necessary to determine the frequency at which the skin depth becomes smaller than the conductor thickness.

$$\delta = \sqrt{\frac{2\rho}{\omega\mu}} = \sqrt{\frac{\rho}{\pi F \mu}}$$

$$\longrightarrow 0.63 \text{ mil}\frac{25.4\times10^{-6}\text{ m}}{\text{mil}} = \sqrt{\frac{1.72\times10^{-8}\ \Omega\cdot\text{m}}{\pi[12.56\times10^{-7}\text{ (H/m)}]F}} \Rightarrow F = 17\text{ MHz}$$

- Below 17 MHz, the resistance of this conductor is approximately equal to the dc resistance

$$R = \frac{\rho L}{A} = \frac{\rho L}{Wt} \quad \text{ohms} \longrightarrow R_{dc} = \frac{1.72\times10^{-8}\ \Omega\cdot\text{m}}{5\text{ mil}\frac{25.4\times10^{-6}\text{ m}}{\text{mil}}\left(0.63\frac{25.4\times10^{-6}\text{ m}}{\text{mil}}\right)} = 8.5\ \Omega/\text{m}$$

- Above 17 MHz, the resistance will vary with the square root of frequency: $R_{ac} = (0.0010)\sqrt{F} \quad \Omega/\text{m}$

Transmission Line Losses

- Frequency-Dependent Dielectric Losses
  - Calculating Losses
    - For (3), therefore, the resistance at 400 MHz is

$$R_{ac}(400\ \text{MHz}) = 0.0010\sqrt{400 \times 10^6} = 20.2\ \Omega/\text{m}$$

    - To solve (4), first, we calculate

$$\text{PD} = \frac{\sqrt{\varepsilon_r}}{c} = \frac{\sqrt{4}}{3 \times 10^8\ \text{m/s}} = 6.67\ \text{ns/m}$$

$$Z_o = \frac{60}{\sqrt{4.0}} \ln \frac{4(10 + 10 + 0.63)}{0.67\pi[0.63 + 0.8(5)]} = 64\ \Omega$$

$$C = \frac{\text{PD}}{Z_o} = \frac{\sqrt{LC}}{\sqrt{L/C}} = \frac{6.67 \times 10^{-9}}{64} 104\ \text{pF/m.}$$

$$\rightarrow G = \frac{\varepsilon''}{\varepsilon'}(2\pi F C_{11}) = 0.013(2\pi)(400\ \text{MHz})(104\ \text{pF})$$

$$= 0.0034\ \text{m}/\Omega \Rightarrow \frac{1}{G} = 294\ \Omega/\text{m}$$

Variations in the Dielectric Constant

- PCB
  - General Properties
    - Some of the characteristics that are dependent on ε_r include propagation velocity, characteristic impedance, and crosstalk.
    - The value of ε_r is not always constant for a given material but varies as a function of frequency, temperature, and moisture absorption.
    - Additionally, for a composite material, the material dielectric properties will change as a function of the relative proportions of its components.

Variations in the Dielectric Constant

- PCB
  - FR4
    - It consists of an epoxy matrix reinforced by a woven glass cloth.
    - Consequently, the dielectric properties can differ substantially from sample to sample.
    - A first-order approximation of the dielectric constant of FR4 composite may be calculated as

$$\varepsilon_r = \varepsilon_{\mathrm{rsn}} V_{\mathrm{rsn}} + \varepsilon_{\mathrm{gls}} V_{\mathrm{gls}}$$

$$V_{\mathrm{rsn}} \approx 1 - \frac{H_{\mathrm{gls}}}{H}$$

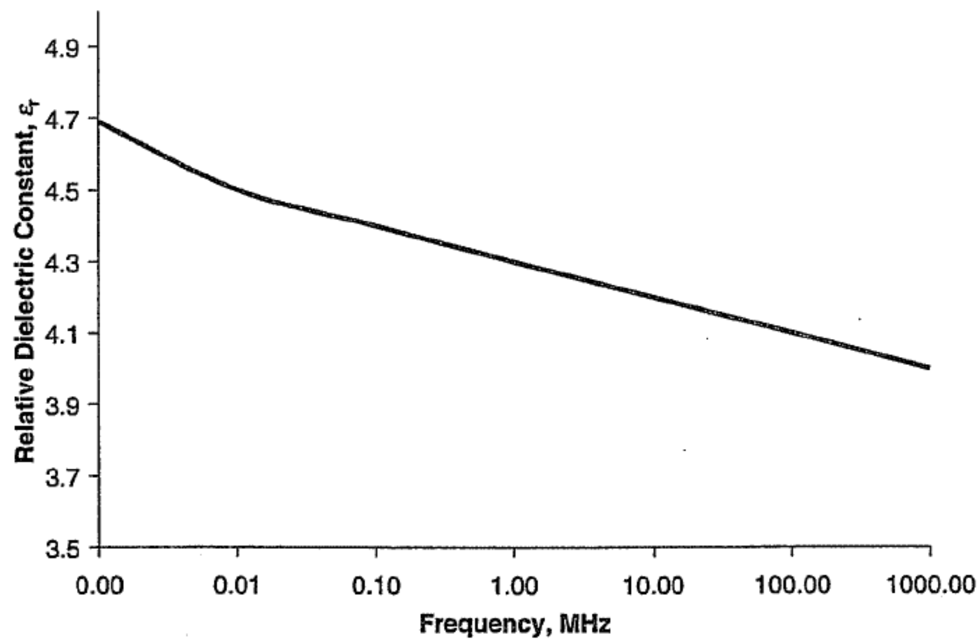
V_{gls}

    - According to measurement, an approximate equation for the prediction of the relative dielectric constant of FR4 is

$$\varepsilon_r(V_{\mathrm{rsn}}, F) = 6.32 - [2.17 + 0.168 \log_{10} F(\mathrm{kHz})] V_{\mathrm{rsn}}$$

Variations in the Dielectric Constant

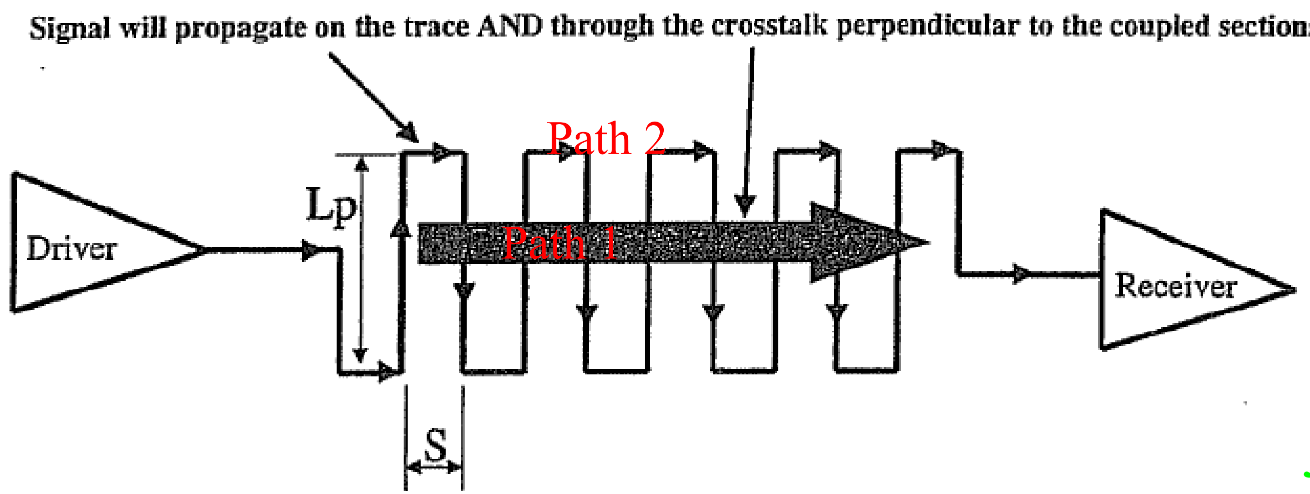
- PCB
  - FR4
    - It has been determined that the glass cloth reinforcement experiences no dielectric constant variation in this frequency range (Vrsn dominant).
    - Dielectric variation with frequency for a typical sample of FR4.



Serpentine Traces

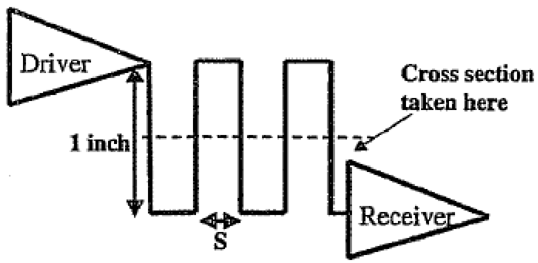
- Fundamental Ideas
  - Why Using Serpentine Traces?
    - Board aspect ratios, timing requirements, and real estate limitations
    - For example, when the design specification of a digital system requires all the traces on the PCB to be length equalized and there is limited real estate on the board to do so.

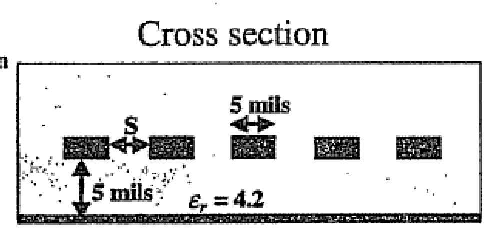
Because of the coupling between parallel lines, part of the signal will arrive earlier than those on the traces.



Serpentine Traces

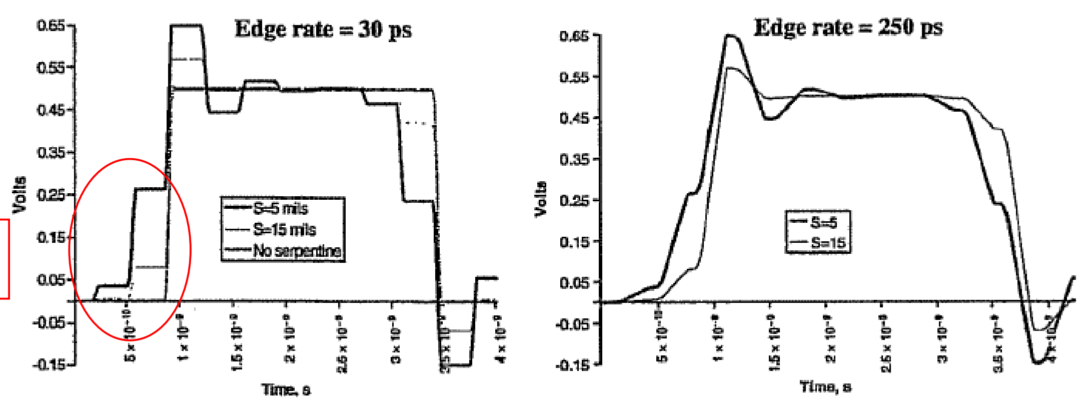
- Effects on Signal Integrity and Timing
  - The duration of the ledges are proportional to the physical length of the coupled sections (L_P) and the voltage magnitude of the ledges depend on the space between parallel sections.





Waveform at receiver

Early arrival



Serpentine Traces

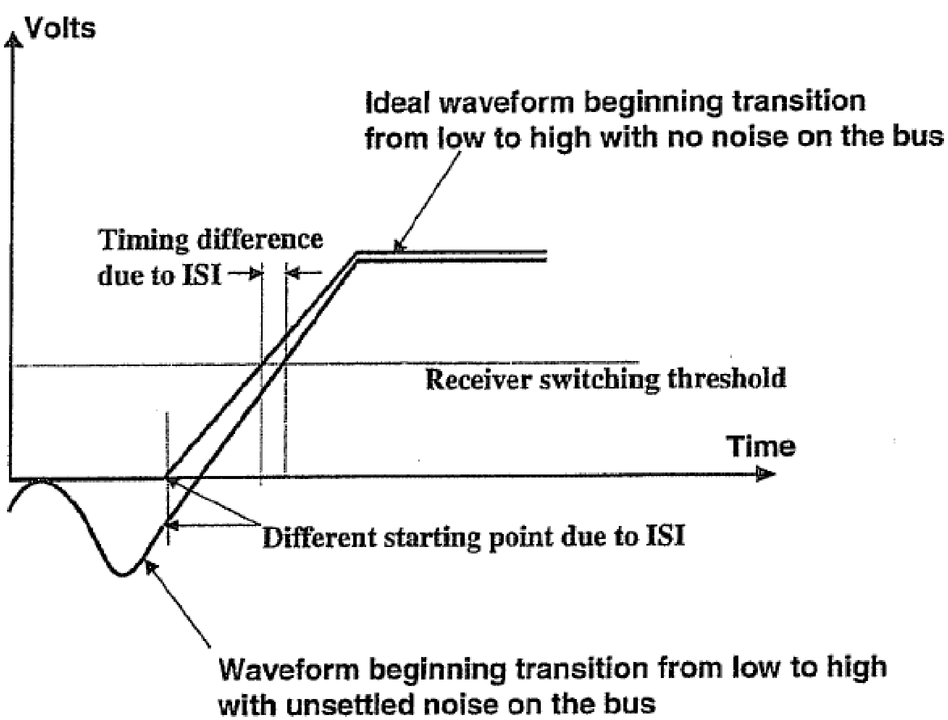
- Rule of Thumb
  - Make the minimum spacing between parallel sections (S) at least $3H$ to $4H$, where H is the height of the signal conductor above the reference ground plane. This will minimize coupling between parallel sections.
  - Minimize the length of the serpentined sections (L_p) as much as possible. This will reduce the total magnitude of the coupling.
  - Embedded microstrips and striplines exhibit fewer serpentine effects than do microstrip lines.
  - Do not serpentine clock traces.

Intersymbol Interference

- Fundamental Characteristic
  - Definition
    - When reflections, crosstalk, or any other source has not settled completely, the signal launched onto the line will be affected.
    - ISI is a major concern in any high-speed design, but especially so when the period is smaller than two times the delay of the transmission line.
    - To capture the full effects of ISI, it is important to perform many simulations with long pseudorandom bit patterns.

Intersymbol Interference

- Effects on Signal
  - Effect of ISI on Timings
    - The timing difference between the ideal waveform and the noisy waveform that begins the transition with unsettled noise on the bus.

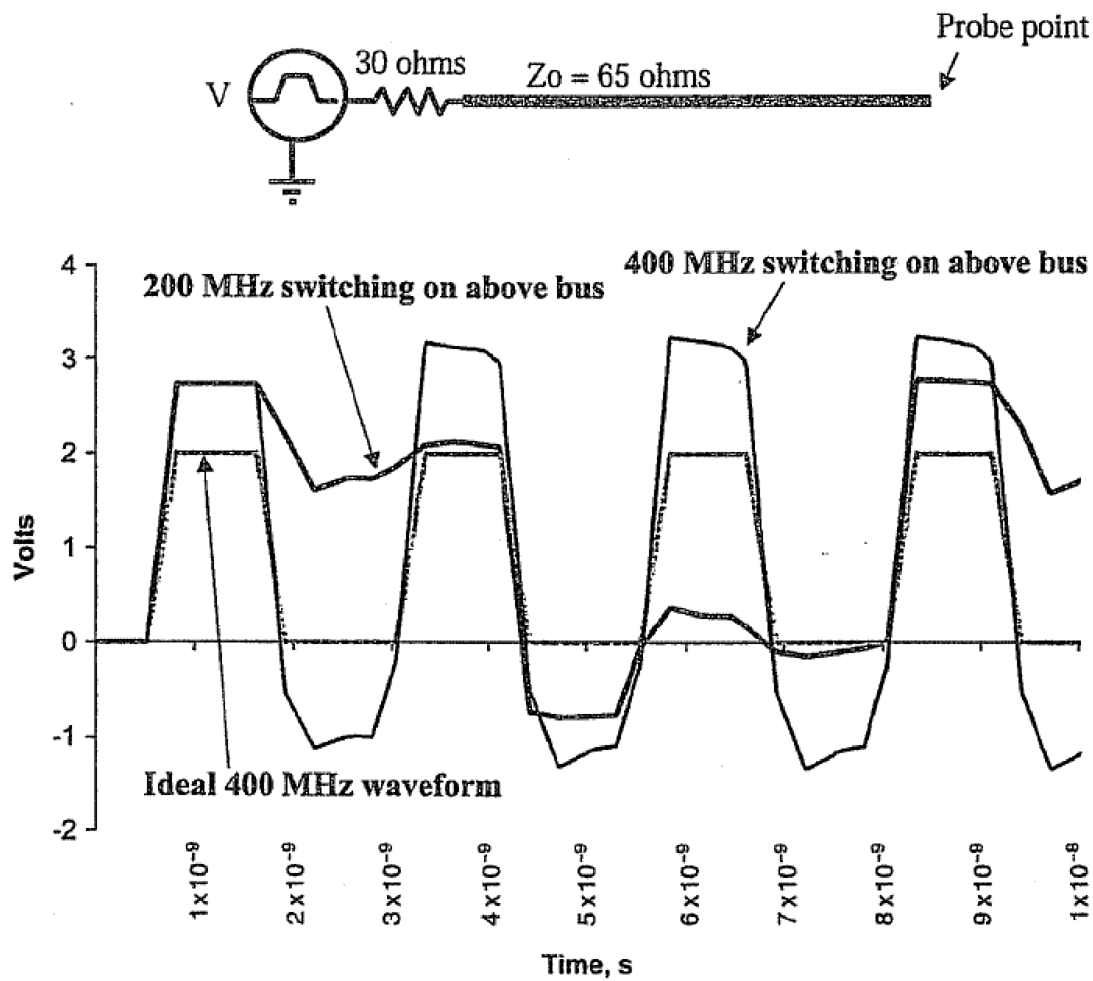


Intersymbol Interference

- Effects on Signal
  - Alternative Simulation Method
    - To capture most of the timing impacts, however, simulations can be performed with a single periodic bit pattern at the fastest bus period and then at 2× and 3× multiples of the fastest bus period.
    - This will represent the following data patterns:
      - 010101010101010
      - 001100110011001
      - 000111000111000
    - This analysis can be completed in a fraction of the time that it takes to perform a similar analysis using long pseudorandom patterns.

Intersymbol Interference

- Effects on Signal
  - Effect of ISI on Signal Integrity



Intersymbol Interference

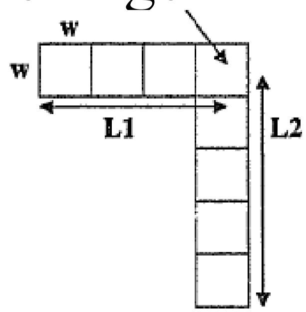
- Rule of Thumb
  - Minimize reflections on the bus by avoiding impedance discontinuities and minimizing stub lengths and large parasitics (i.e., from packages, sockets, or connectors).
  - Keep interconnects as short as possible.
  - Avoid tightly coupled serpentine traces.
  - Avoid line lengths that cause signal integrity problems (i.e., ringback, ledges, overshoot) to occur at the same time that the bus can transition.
  - Minimize crosstalk effects.

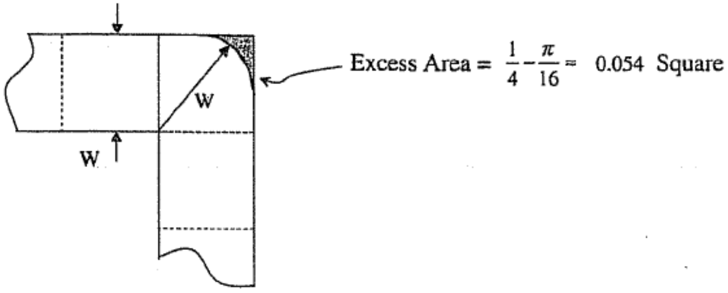
Effects of 90^0 Bends

- Basics
  - Capacitive Effects
    - The excess capacitance for a 90° bend for a typical 50- to 65-Ω line widths is approximated as

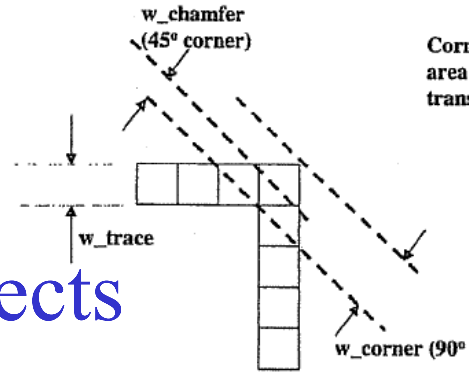
$$C_{90^{\circ}\text{ bend}} \approx C_{11} w$$

    - where C_{11} is the self-capacitance of the line and w is the line width.
    - To calculate the extra capacitance, one full square in the above equation is considered. This full square area is larger than the physical extra area.





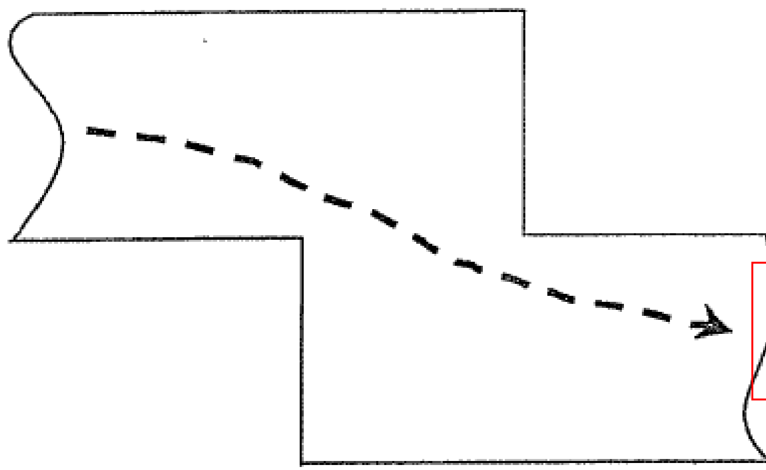
Effects of 90^0 Bends



- Ways to Reduce the Capacitive Effects
  - Rounding
    - Simply rounding the corners to produce a constant width around the bend will virtually eliminate the effect.
    - Round corners, however, cause problems with many layout tools.
  - Chamfering
    - Another approach is to chamfer the edge by 45°.
  - Usage of 45^0 Bend
    - Completely avoid the use of 90° bends by using 45° bends instead.

Effects of 90^0 Bends

- Two Bends
  - Different Current Paths
    - Some component of the current may hug corners leading to signals arriving early at destination.

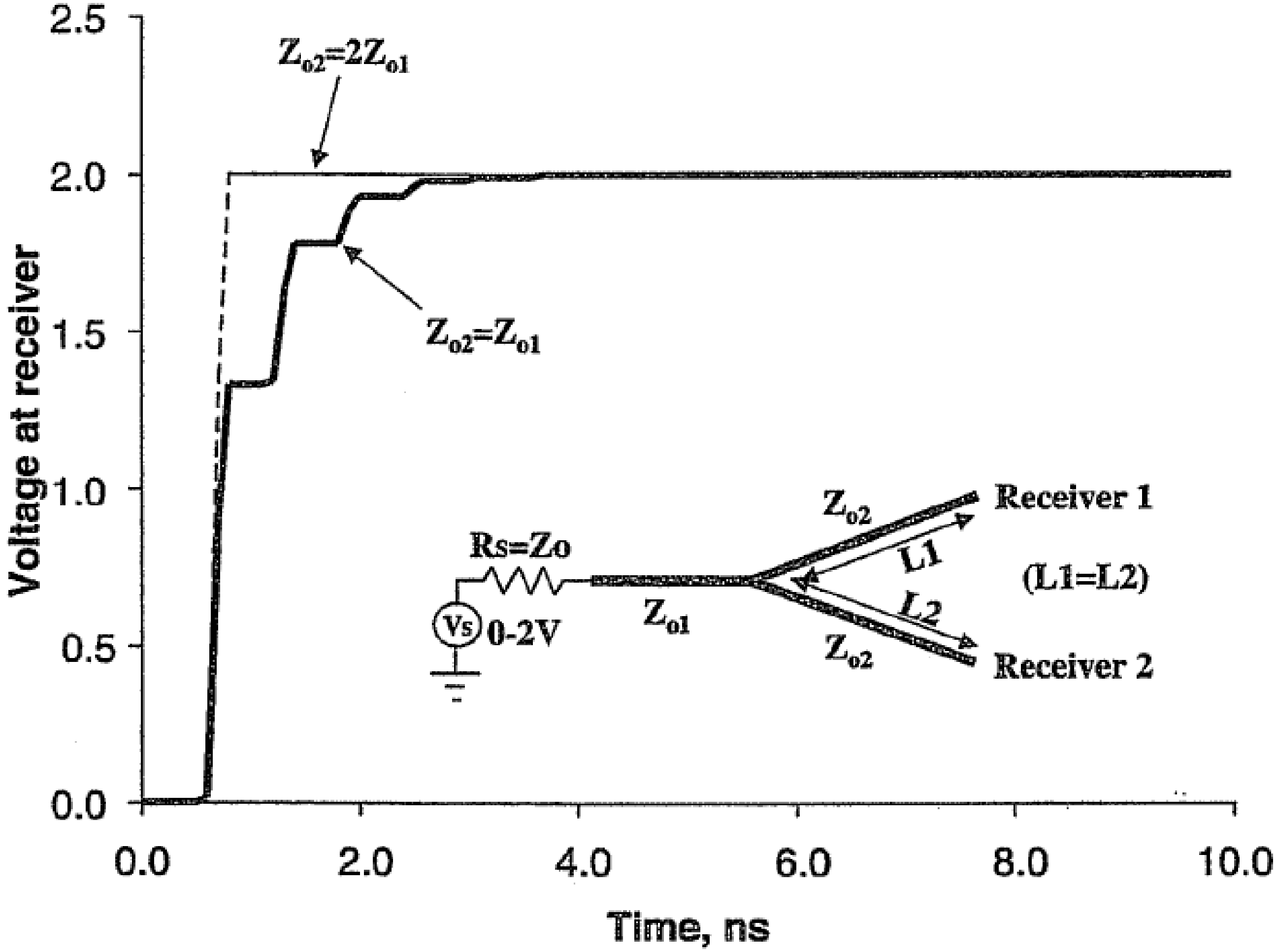


High frequency currents path

What about the low frequency current path?

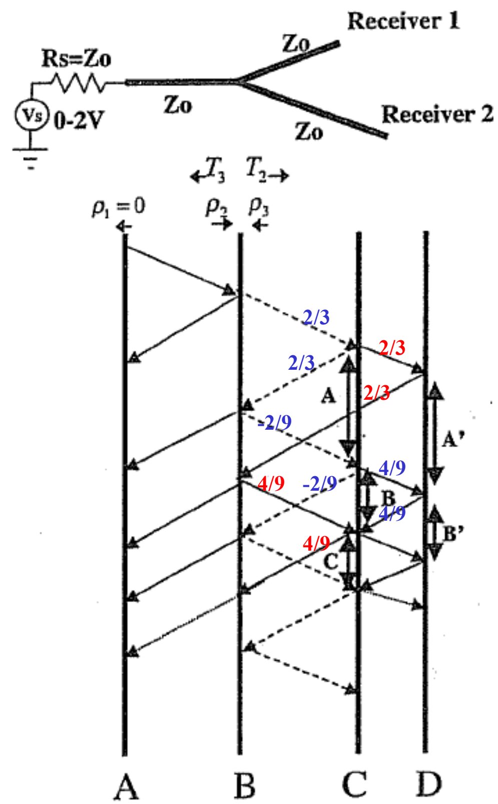
Effects of Topology

- Balanced T Topology
  - Matched and Mismatched Loads



Effects of Topology

- Unbalanced T Topology
  - Matched Load
    - Furthermore, differences in the loading at each leg will cause similar instabilities.



$$V_{initial} = 2v\frac{Zo}{Zo+Rs} = 1v$$

$$\rho_2 = \rho_3 = \frac{\frac{Zo}{2} - Zo}{\frac{Zo}{2} + Zo} = -\frac{1}{3}$$

$$T_2 = T_3 = 1 + \rho = \frac{2}{3}$$

$$A = \frac{2}{3} + \frac{2}{3} = \frac{4}{3}$$

$$B = \frac{2}{3} + \frac{2}{3} - \frac{2}{9} - \frac{2}{9} = \frac{8}{9}$$

$$C = \frac{2}{3} + \frac{2}{3} - \frac{2}{9} - \frac{2}{9} + \frac{4}{9} + \frac{4}{9} = \frac{16}{9}$$

$$A' = \frac{2}{3} + \frac{2}{3} = \frac{4}{3}$$

$$B' = \frac{2}{3} + \frac{2}{3} + \frac{4}{9} + \frac{4}{9} = \frac{20}{9}$$

Effects of Topology

- Unbalanced T Topology
  - Matched Load
    - The signal integrity will deteriorate dramatically.

What do we learn from this?
1. Symmetry topology is important. (length and loading of each leg)
2. Minimization of discontinuities at the topology junction.