Limiting Models of Interconnect

- Comparison between two cases of modeling interconnect
  - RC model and RLC model

- The practical on-chip case is the RLC model

- RC model has been used as a good approximation

- Factors that make the inductance effect significant in modern technologies
  - Transition times are much shorter
  - Wide lines at higher metal layers
    - Decreases interconnect resistance
  - Introduction of lower resistance materials for interconnect

\[ \rho_{\text{Copper}} \approx \frac{1}{3} \rho_{\text{Aluminum}} \]
**RLC Transmission Line Model of the Interconnect**

- Interconnect can be accurately modeled as an *RLC* transmission line [Deutsch]
  - $G$ can be neglected

- Inductance can be neglected only in specific cases

- Errors that result from using an *RC* model compared to an *RLC* model can be as large as 103% for rise time and 31% for propagation delay [Deutsch]
  - 10 W driver
  - 2.5 V voltage swing
  - 1.6 cm interconnect length
  - 0.9 mm interconnect length
  - Inductance in the range of 1-10 nH
  - 100 ps rise time
  - Parallel far ground as a return path

Signal Propagation in Lossy Transmission Lines

- The voltage across a lossy transmission line for a sinusoidal input is

\[ V(z, t) = \text{Re}\{ V_1 e^{(j\omega t - \gamma z)} + V_2 e^{(j\omega t + \gamma z)} \} \]

- \( V_1 \) is the summation of all the voltage waves traveling in the positive \( z \) direction
- \( V_2 \) is the summation of all the voltage waves traveling in the negative \( z \) direction

- Propagation Constant

\[ \gamma = \alpha + j\beta \]

\[ V(z, t) = V_1 e^{-\alpha z} \cos(\omega t - \beta z) + V_2 e^{\alpha z} \cos(\omega t + \beta z) \]

- The attenuation constant \( \alpha \) represents the attenuation the waves suffers as they propagate across the line
- The phase constant \( \beta \) determines the speed of propagation of the signals across the line

\[ v = \frac{\omega}{\beta} \]
Signal Propagation in Lossy Transmission Lines (cont.)

- Input signal launched towards load
  - Propagation velocity, \( v = \frac{\omega}{\beta} \)
- Signal attenuates as it travels across lossy line
- If mismatch between load and characteristic impedance, a reflected wave is generated which propagates back towards the source
- Reflected wave attenuates as it travels towards source
- Reflection process is repeated infinite times
  - practically, the signal reaches steady state when reflections become negligible
- Higher the attenuation (lossier or longer line), the faster the steady state is reached
- Voltage wave attenuation is \( \propto e^{-2\alpha l} \) for a round trip
  - more resistive the line, more the line behaves as an RC line
Effect of Input Rise Time

- If the transition time of the signal at the input of the CMOS gate driving the transmission line is greater than twice the time of flight across the line, the inductance is insignificant.

\[ t_r < 2l \sqrt{LC} = 2T_0 \]

- When this inequality is satisfied, inductance is significant.
Effect of Attenuation

- As the attenuation increases, the magnitude of subsequent reflections decreases.

- A useful figure of merit is the asymptotic value of the attenuation:
  \[
  \frac{Rl}{2 \sqrt{\frac{C}{L}}} < 1 \quad \text{or} \quad R_l C_t < 4 \frac{L_t}{R_t}
  \]

- If this inequality is satisfied, inductance is significant.
Figures of Merit to Characterize On-Chip Inductance

- A distributed $RLC$ model of an interconnect line as compared to a distributed $RC$ model

- The $RC$ model is sufficiently accurate if one of the following two conditions is satisfied
  \[ \frac{Rl}{2} \sqrt{\frac{C}{L}} > 1 \]
  - Attenuation sufficiently large to make reflections negligible
  \[ t_r > 2l\sqrt{LC} = 2T_0 \]
  - Waveform transition time slower than twice the time of flight

- Range of $l$ for which inductance is significant
  \[ \frac{t_r}{2\sqrt{LC}} < l < \frac{2}{R}\sqrt{\frac{L}{C}} \]
Inductance is Significant for a Range of Interconnect Length

- $L = 10^{-7} \text{H/cm}$, $R = 400 \text{W/cm}$, $C = 10^{-12} \text{F/cm}$, and $t_r = 0.25 \text{ ns}$

$0.3259 \text{ cm} < l < 1.58 \text{ cm}$
Inductance is Negligible Despite the Length of the Interconnect Line

- \( L = 10^{-8} \text{ H/cm} \), \( R = 400 \text{ W/cm} \), \( C = 10^{-12} \text{ F/cm} \), and \( t_r = 0.25 \text{ ns} \)

\[ 1.25 \text{ cm} < l < 0.5 \text{ cm} \]
Region Where Inductance is Significant

- As inductance increases, the region where inductance is significant increases

- As resistance increases, the region where inductance is significant decreases

- As capacitance increases, the region where inductance is significant decreases

\[ t_r = 4 \frac{L}{R} \] - point of intersection