ECE 451
Signal Integrity

Fall 2004

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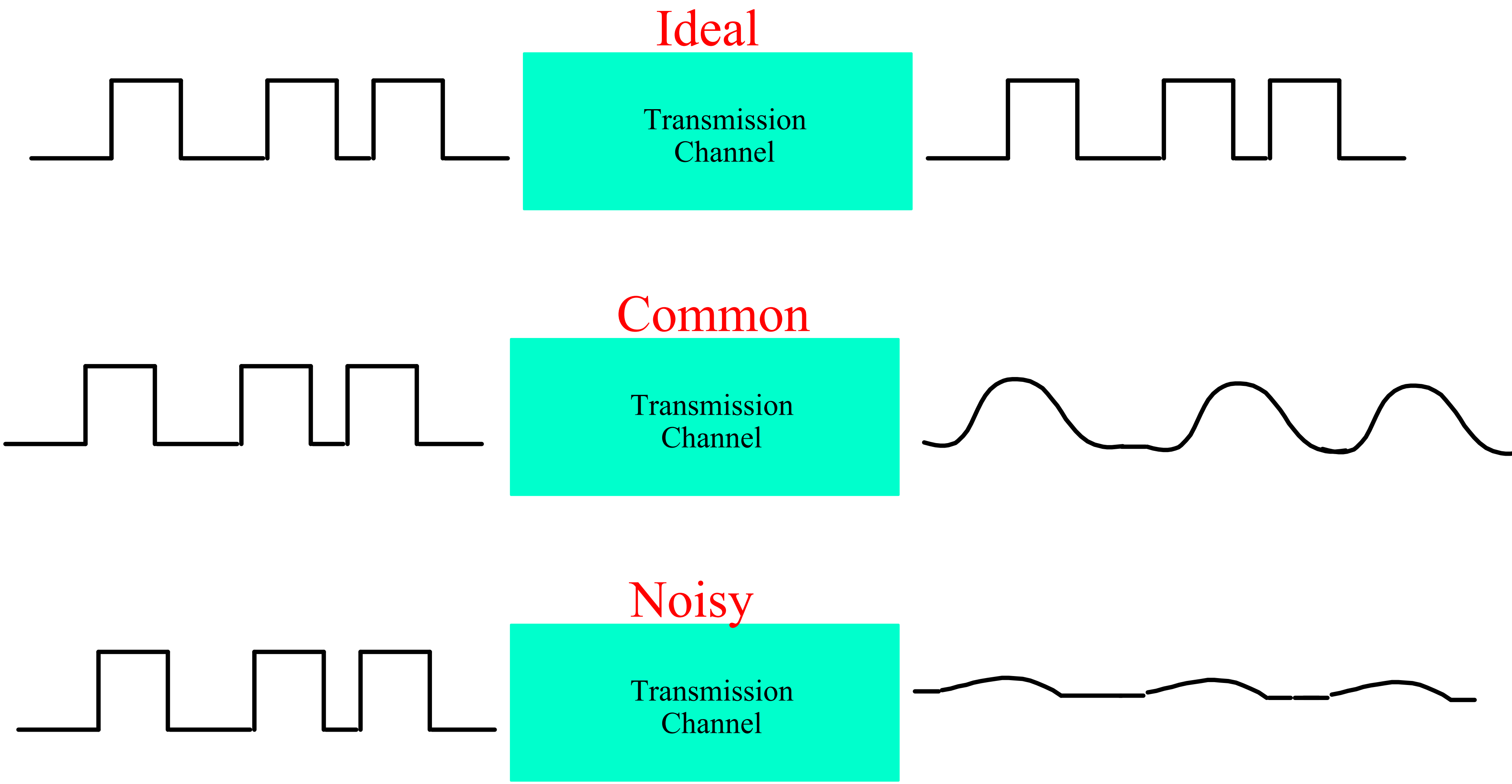
Signal Integrity



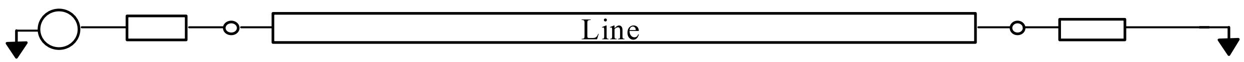
Signal Integrity

- Attenuation & Loss (skin effect, on-chip loss)
- Crosstalk (interconnect proximity, coupling)
- Dispersion (frequency dependence of parameters)
- Reflection (unmatched loads, reactive loads, ISI)
- Distortion (nonlinear loads)
- Interference & Radiation (EMI/EMC)
- Rise time degradation
- Clock skew (different electrical path lengths)

The Interconnect Bottleneck

Technology Generation	MOSFET Intrinsic Switching Delay	Response Time
1.0 um	~ 10 ps	~ 1 ps
0.01 um	~ 1 ps	~ 100 ps

Chip-Level Interconnect Delay

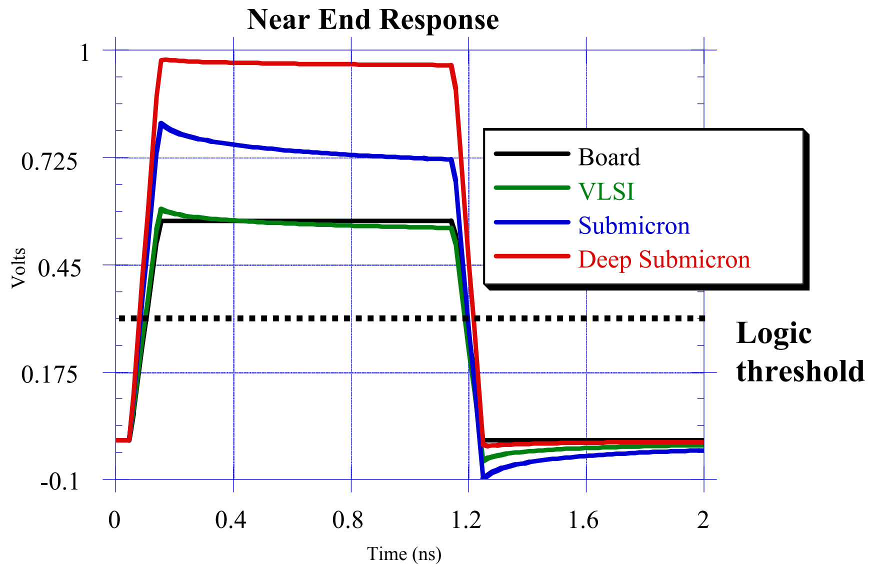


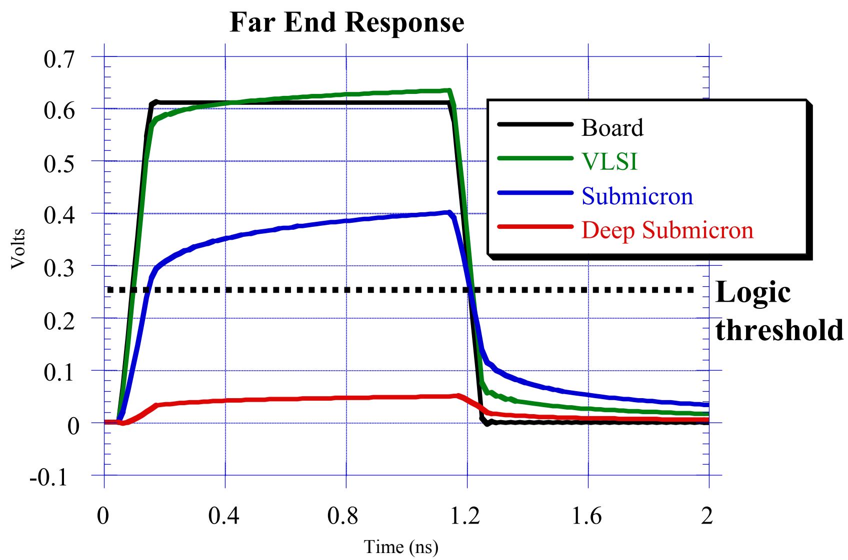
Pulse Characteristics:

- rise time: 100 ps
- fall time: 100 ps
- pulse width: 4ns

Line Characteristics

- length : 3 mm
- near end termination: 50 Ω
- far end termination 65 Ω

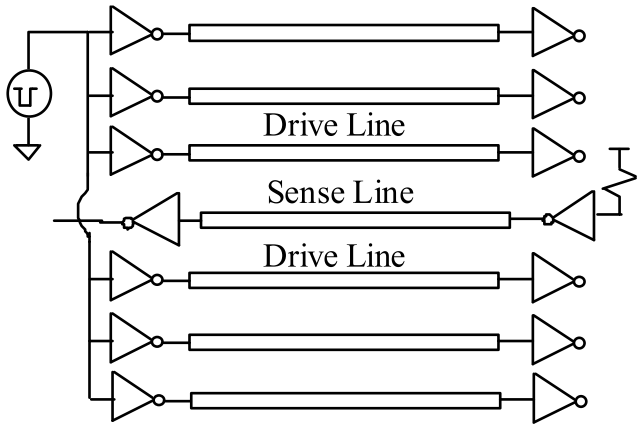


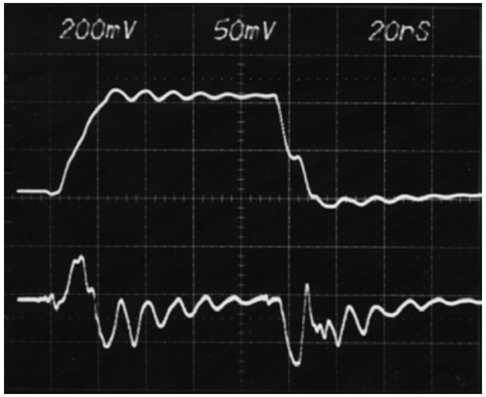


Interconnect Bottleneck

Signal Integrity

Crosstalk	**Dispersion**	**Attenuation**
Reflection	**Distortion**	**Loss**
Delta I Noise	**Ground Bounce**	**Radiation**



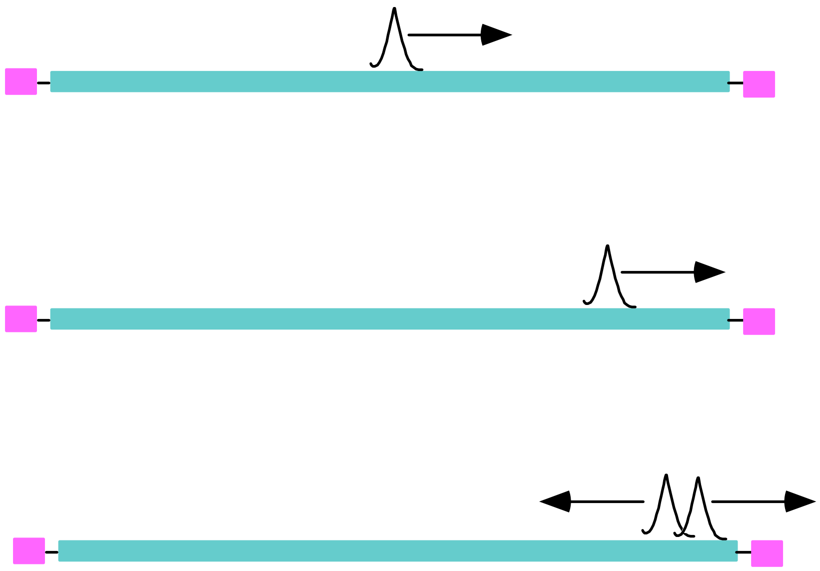


Reflection in Transmission Lines

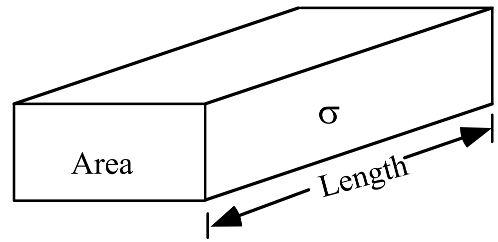
1.

2.

3.



Metallic Conductors



Resistance : R

$$R = \frac{\text{Length}}{\sigma \ \text{Area}}$$

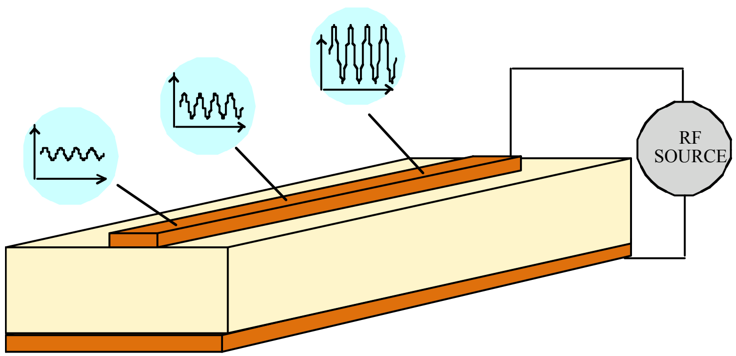
Package level:
W=3 mils
R=0.0045 Ω/mm

Submicron level:
W=0.25 microns
R=422 Ω/mm

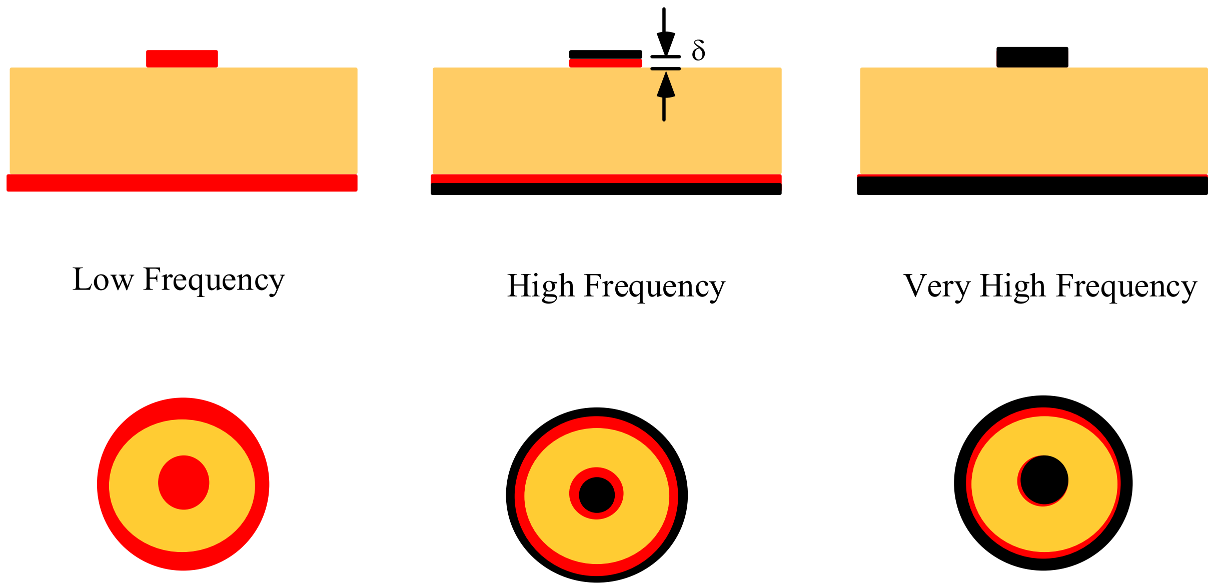
Metallic Conductors

Metal	Conductivity $\sigma\ (\Omega^{-1}\ m^{-1} \times 10^{-7})$
Silver	6.1
Copper	5.8
Gold	3.5
Aluminum	1.8
Tungsten	1.8
Brass	1.5
Solder	0.7
Lead	0.5
Mercury	0.1

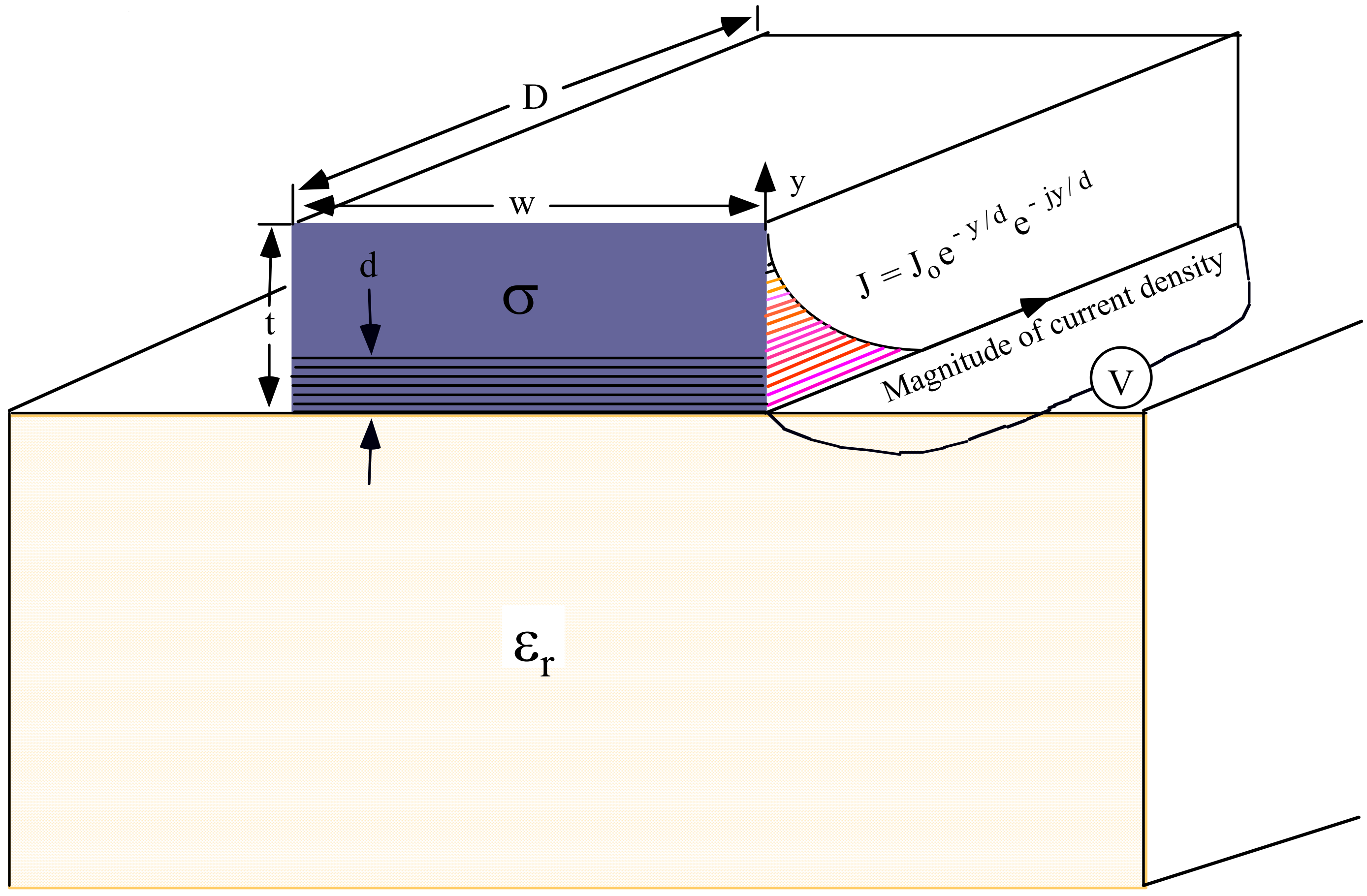
Loss in Transmission Lines



Skin Effect in Transmission Lines

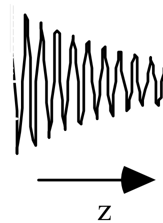


Skin Effect in Microstrip



Skin Effect

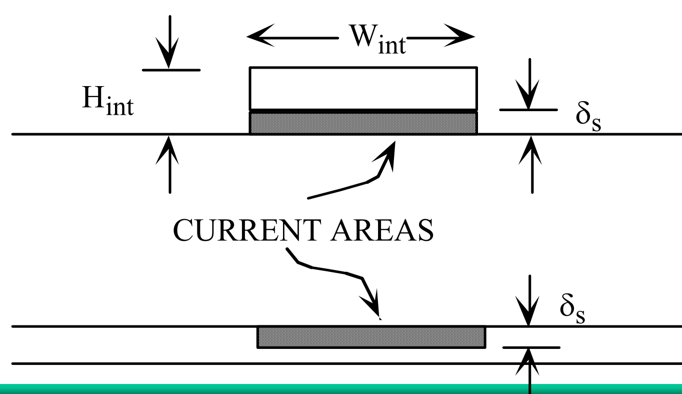
The electric field in a material medium propagates as



$$E_o e^{-\gamma z} = E_o e^{-\alpha z} e^{-j\beta z}$$

where $\gamma = \alpha + j\beta$. We also have

$$\gamma = \omega\sqrt{\mu\varepsilon\left(1 + j\frac{\sigma}{\omega\varepsilon}\right)}\ .$$



Skin effect and internal inductance

Current density varies as

$$J = J_o e^{-y/\delta} e^{-jy/\delta}$$

Note that the phase of the current density varies as a function of y. The total current is given by:

$$I = \int_0^\infty J_o w e^{-y/\delta} e^{-jy/\delta} dy = \frac{J_o w \delta}{1+j}$$

$$\sigma E_o = J_o \Rightarrow E_o = \frac{J_o}{\sigma}$$

The voltage measured over a section of the conductor of length L is:

$$V = E_o D = \frac{J_o D}{\sigma}$$

Skin effect and internal inductance

The "skin effect" impedance is therefore

$$Z_{skin} = \frac{V}{I} = \frac{J_o D}{\sigma} \frac{(1+j)}{J_o w \delta} = \frac{D}{w}(1+j)\sqrt{\pi f \mu \rho}$$

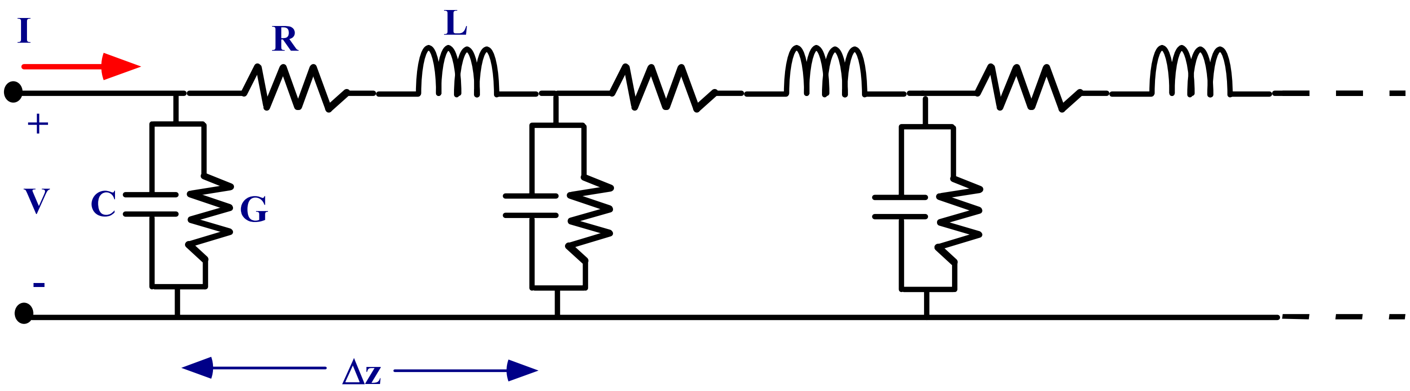
where $\rho = \frac{1}{\sigma}$ is the bulk resistivity of the conductor

$$\mathrm{Z_{skin} = R_{skin} + jX_{skin}}$$

with

$$R_{skin} = X_{skin} = \frac{D}{w}\sqrt{\pi f \mu \rho}$$

Lossy Transmission Line

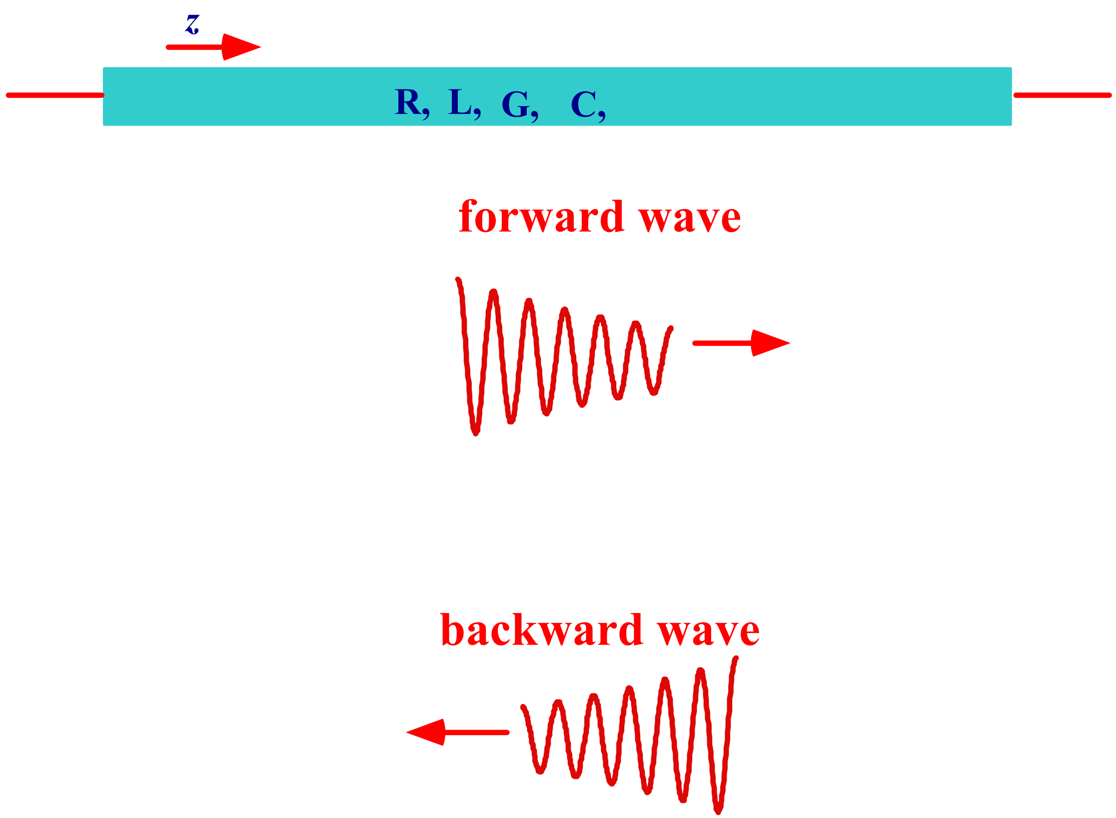


Telegraphers Equation

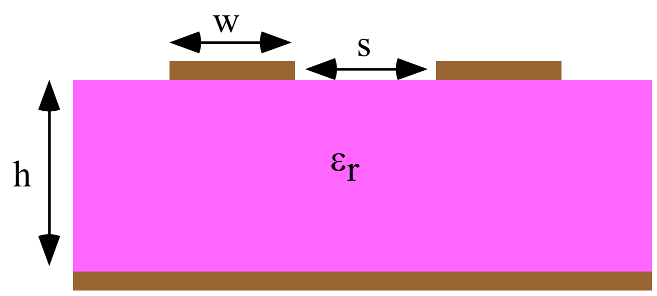
$$-\frac{\partial V}{\partial z} = (R + j\omega L)I = ZI$$

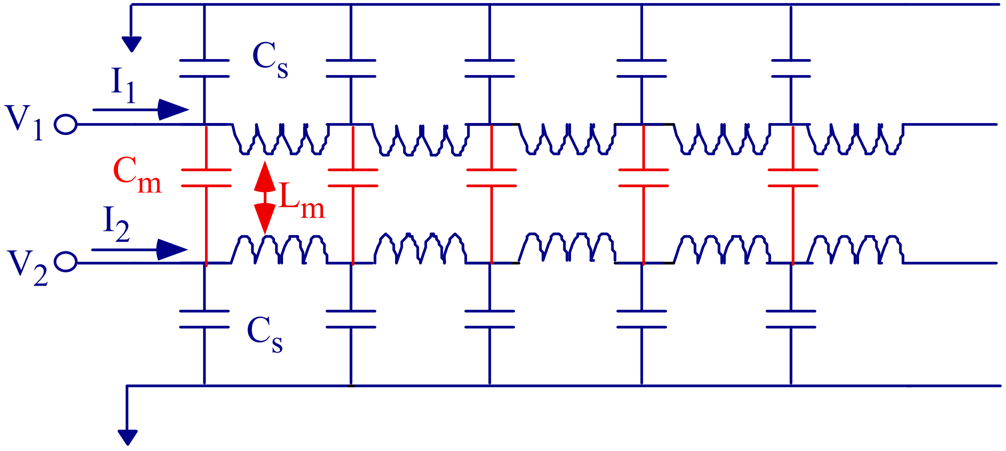
$$-\frac{\partial I}{\partial z} = (G + j\omega C)V = YV$$

Lossy Transmission Line

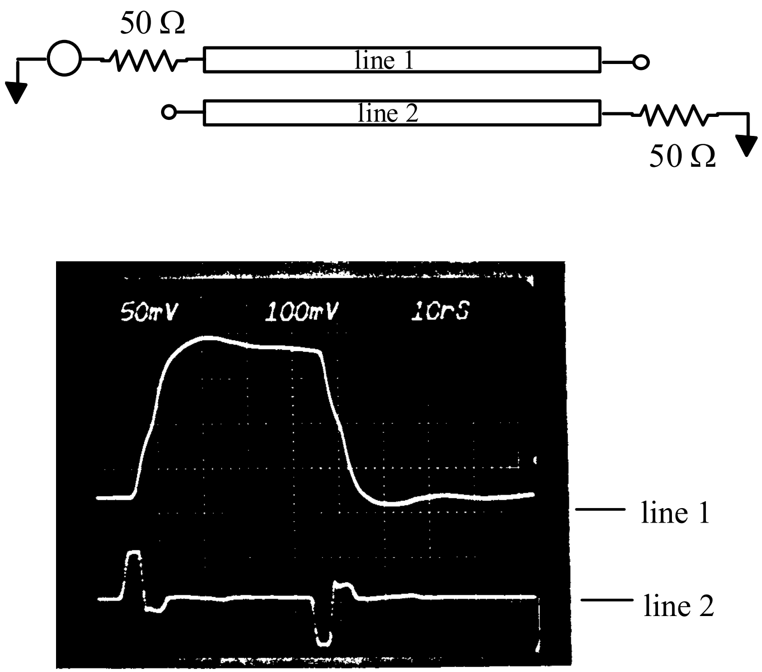


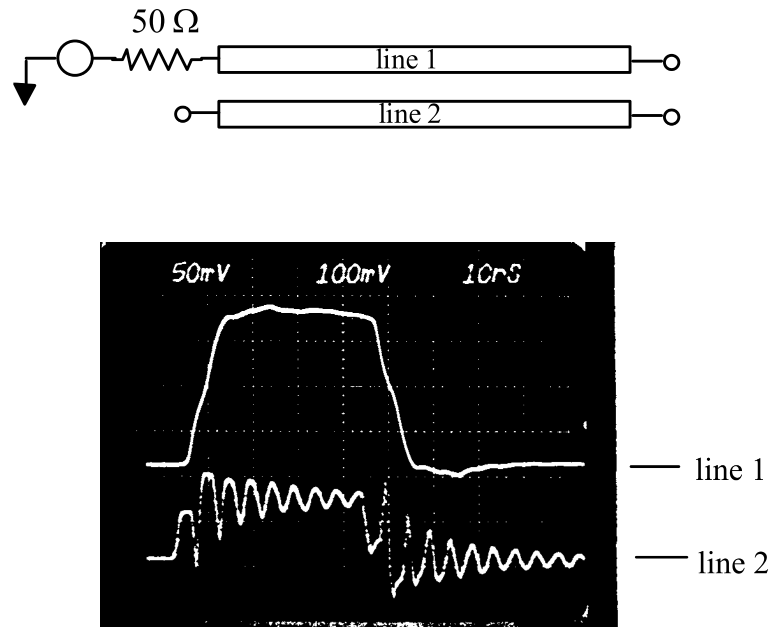
Coupled Lines and Crosstalk



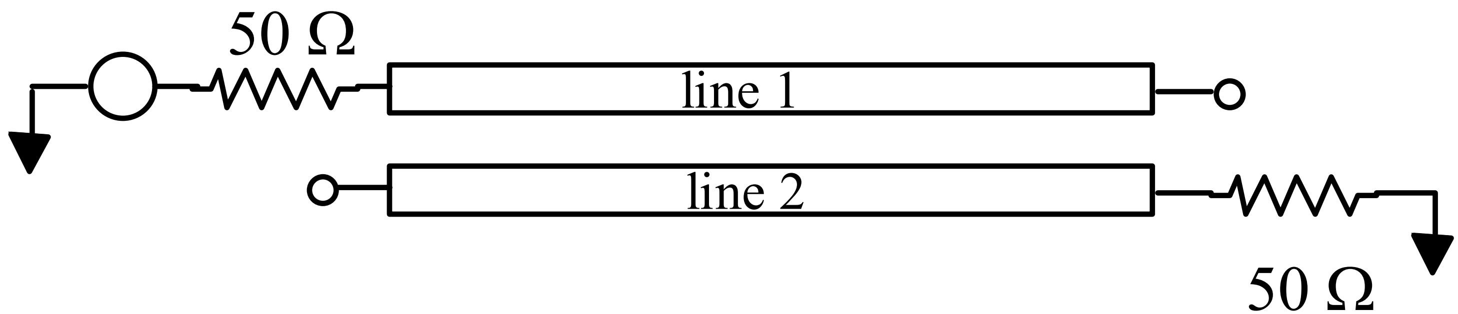


Crosstalk noise depends on termination

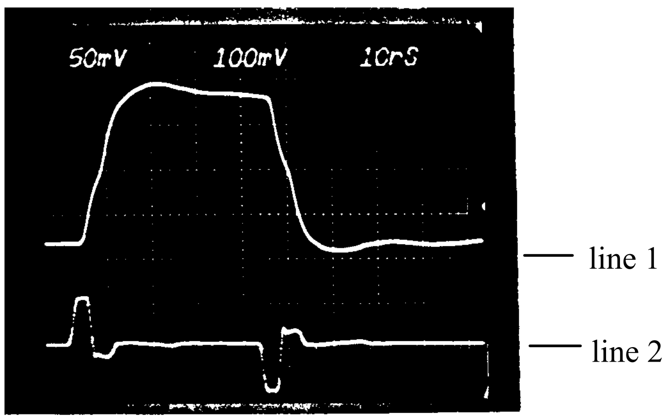




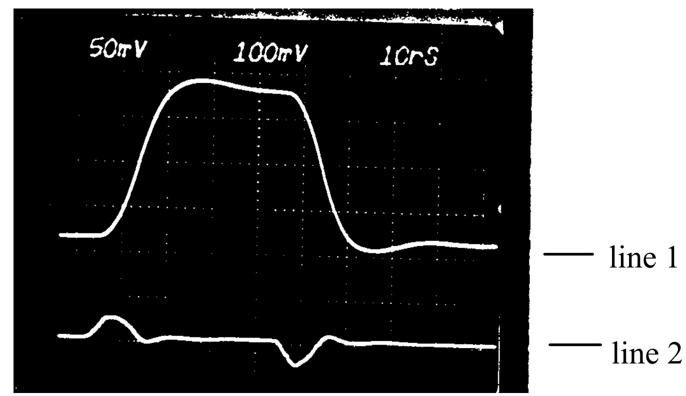
Crosstalk depends on signal rise time



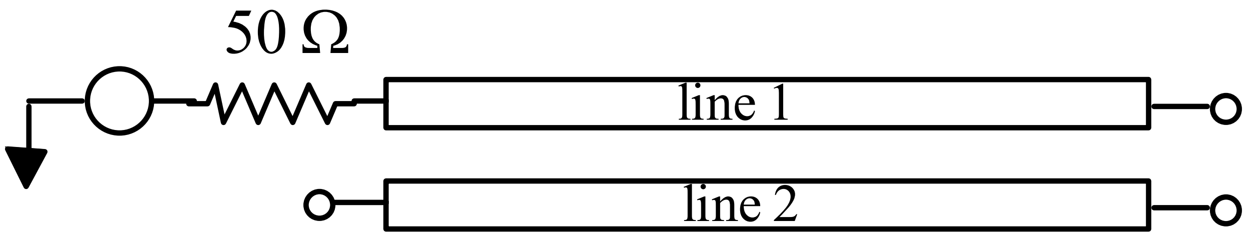
t_r = 1 ns



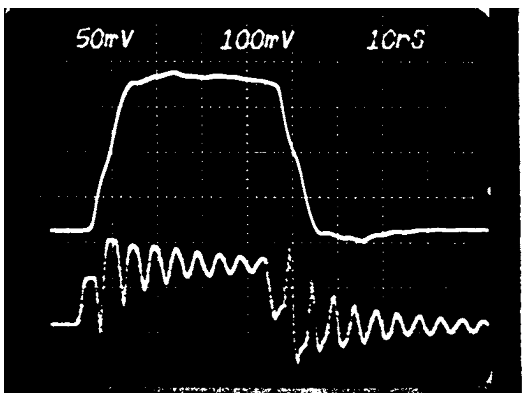
t_r = 7 ns



Crosstalk depends on signal rise time



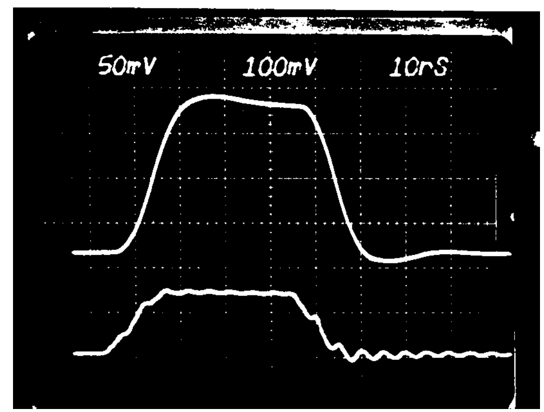
t_r = 1 ns



line 1

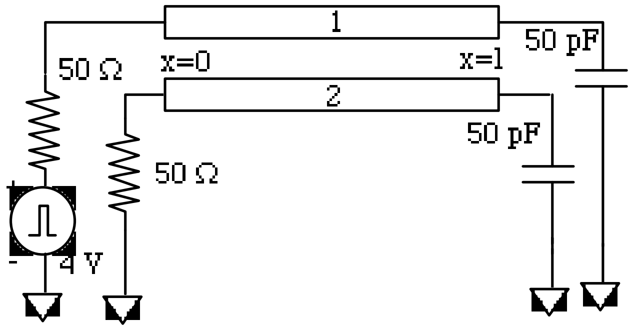
line 2

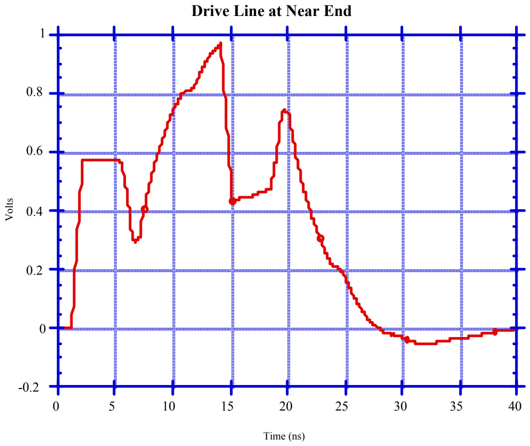
t_r = 7 ns

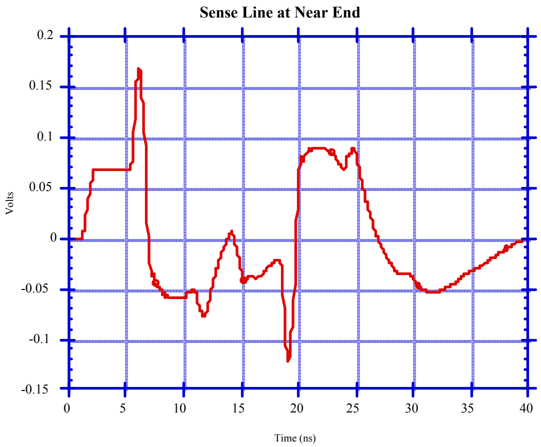


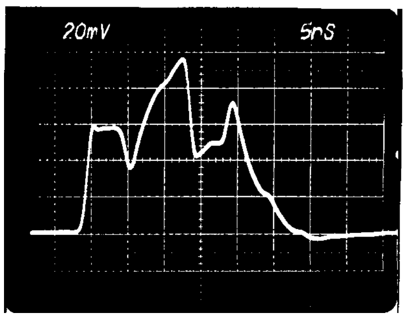
line 1

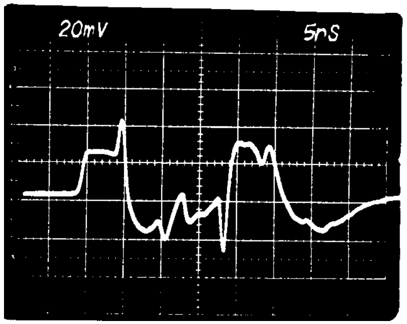
line 2


1
2
50 Ω
x=0
x=1
50 pF
50 pF
50 Ω
4 V

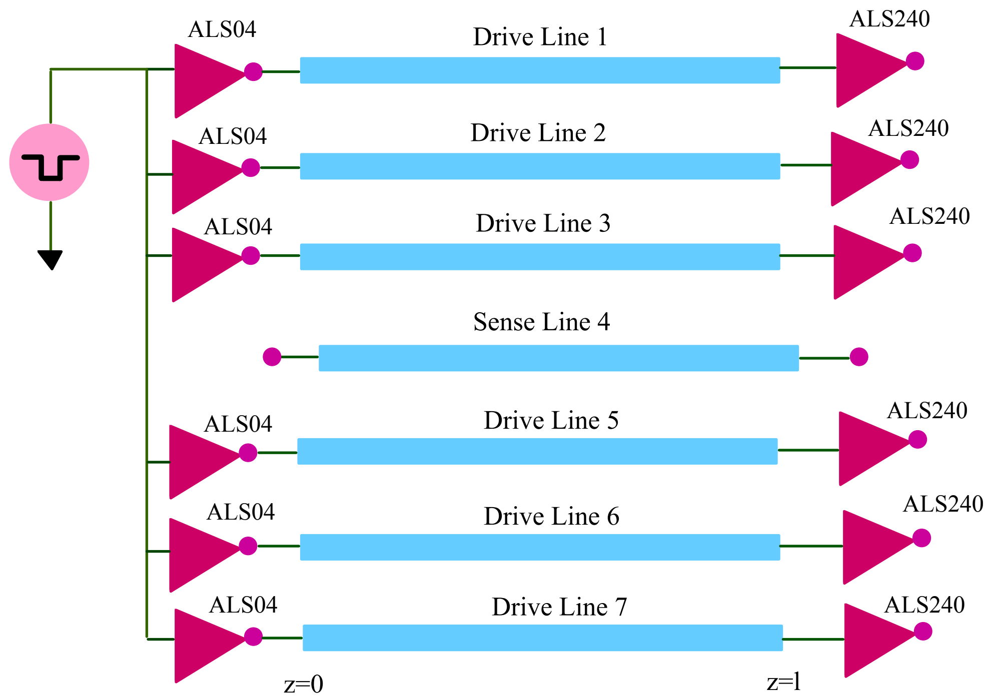

Drive Line at Near End
Volts
Time (ns)
1
0.8
0.6
0.4
0.2
0
-0.2
0
5
10
15
20
25
30
35
40


Sense Line at Near End
Volts
Time (ns)
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
0
5
10
15
20
25
30
35
40


20mV
5nS


20mV
5nS

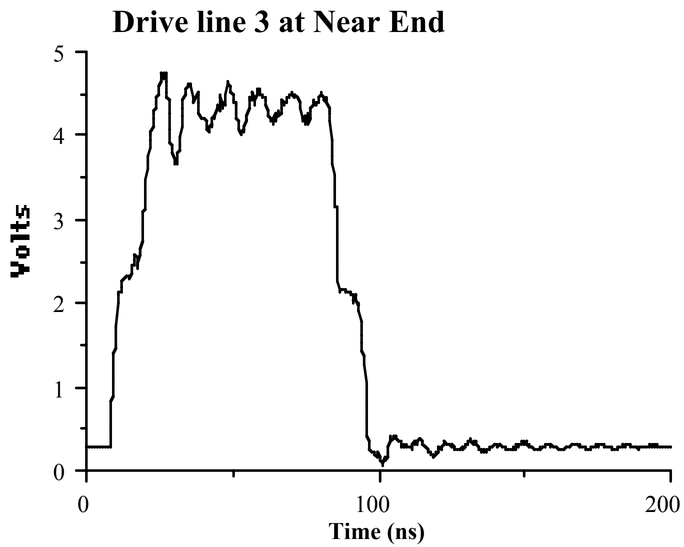
7-Line Coupled-Microstrip System

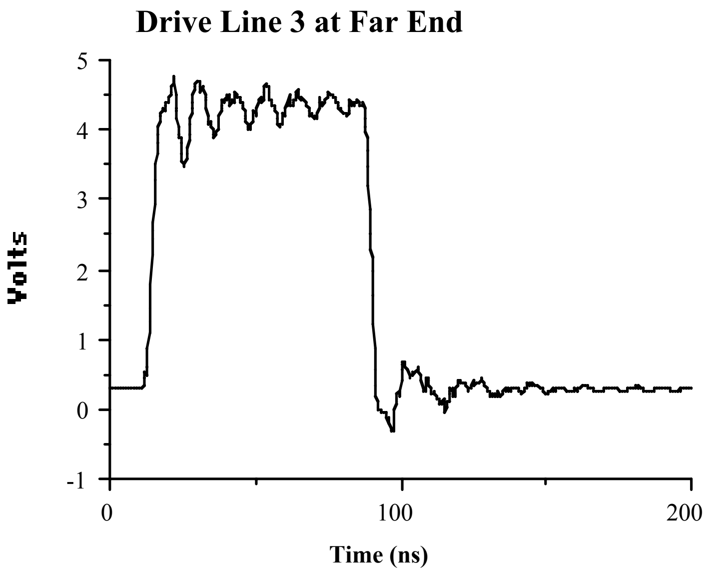


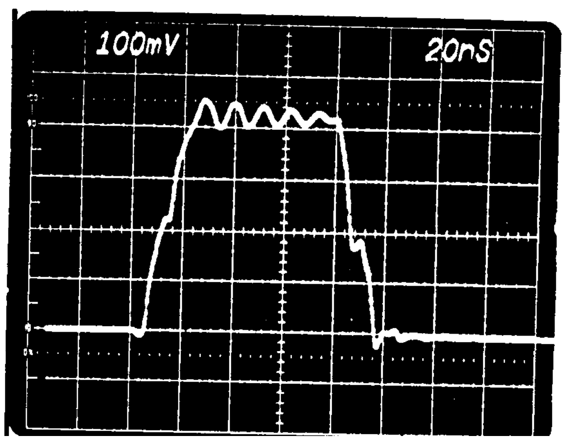
$L_s = 312$ nH/m; $C_s = 100$ pF/m;

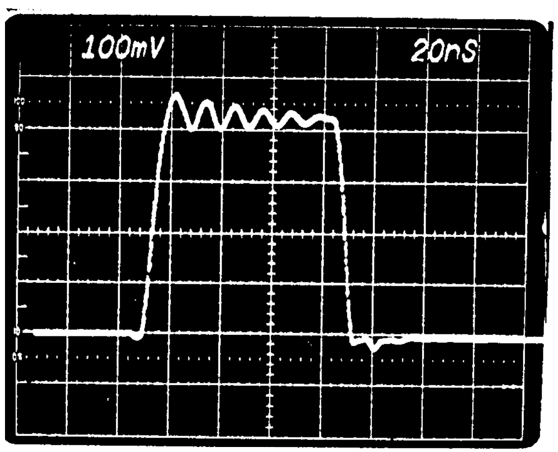
$L_m = 85$ nH/m; $C_m = 12$ pF/m.

Drive Line 3

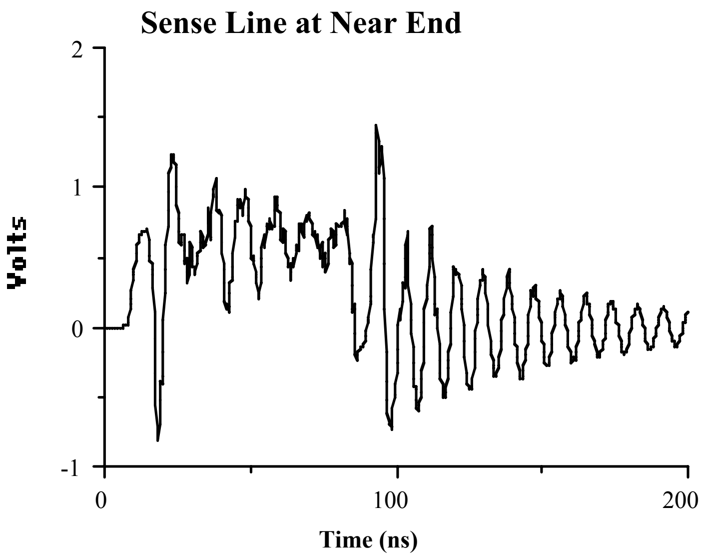

Drive line 3 at Near End
Volts
0
1
2
3
4
5
0
100
200
Time (ns)


Drive Line 3 at Far End
Volts
-1
0
1
2
3
4
5
0
100
200
Time (ns)

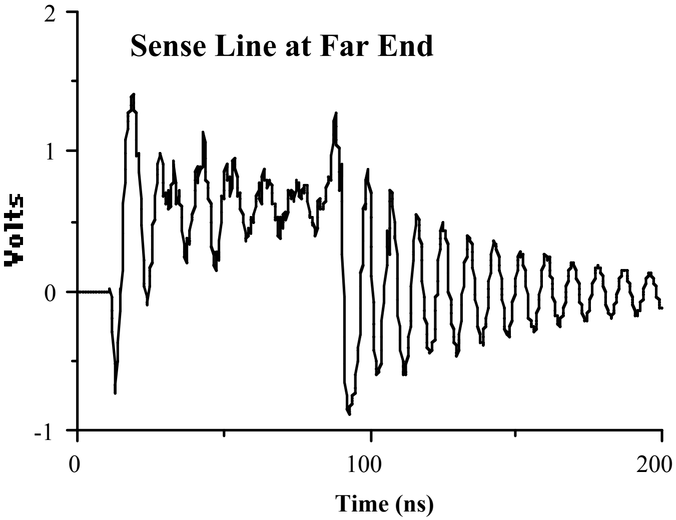

100mV
20nS


100mV
20nS

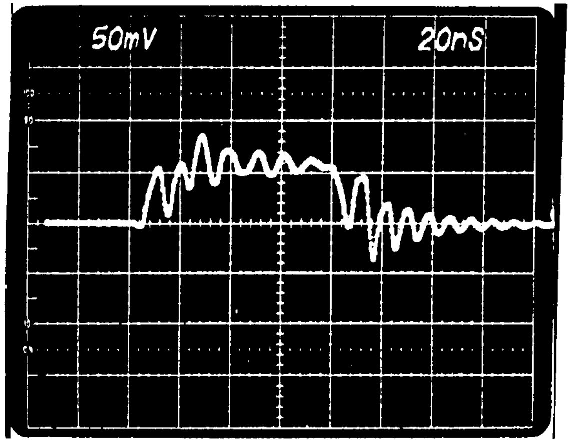
Sense Line



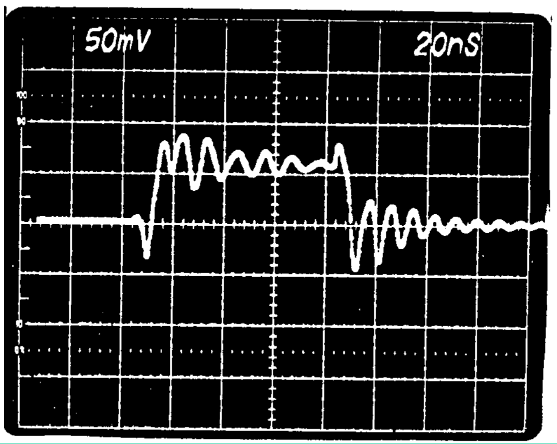
Sense Line at Near End
Volts
2
1
0
-1
0
100
200
Time (ns)



Sense Line at Far End
Volts
2
1
0
-1
0
100
200
Time (ns)

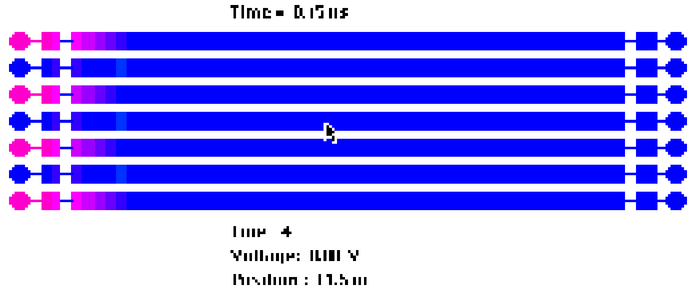


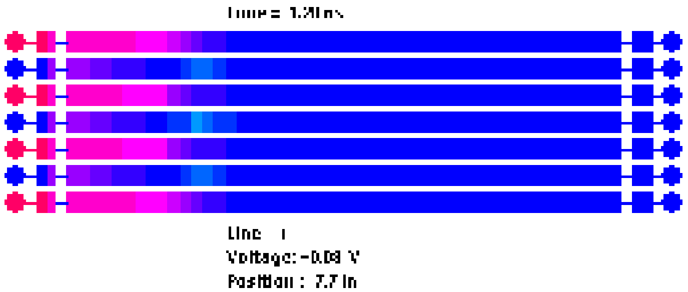
50mV
20nS

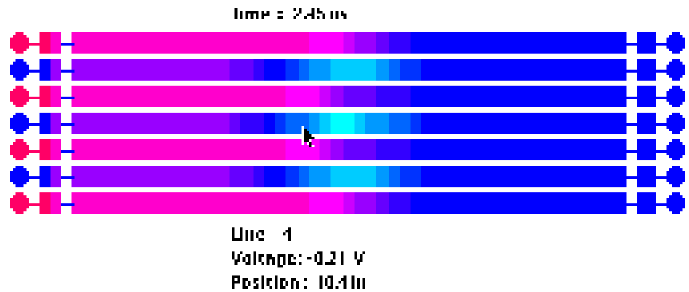


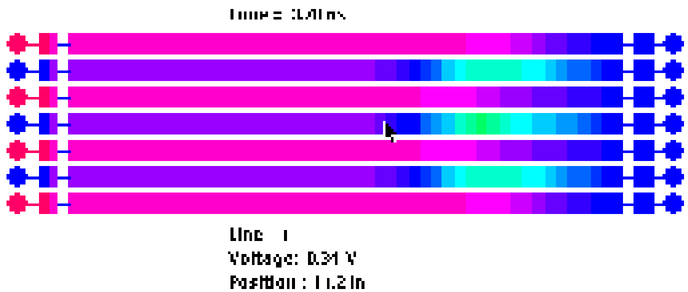
50mV
20nS

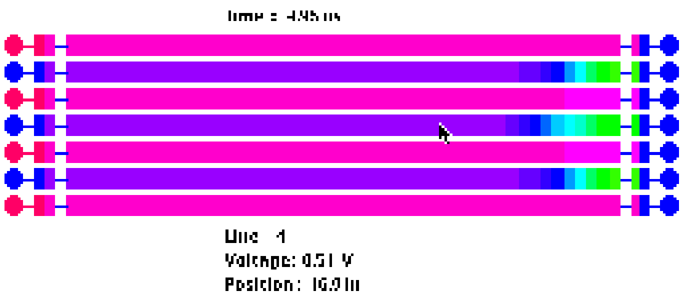
Multiconductor Simulation

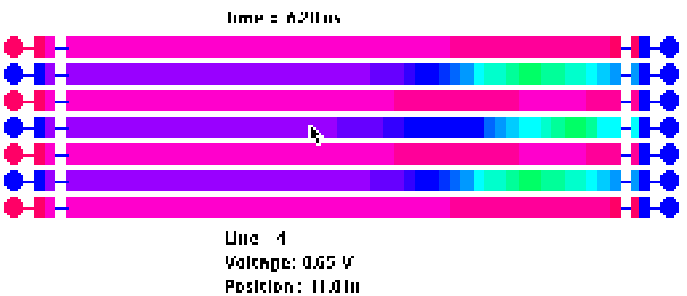








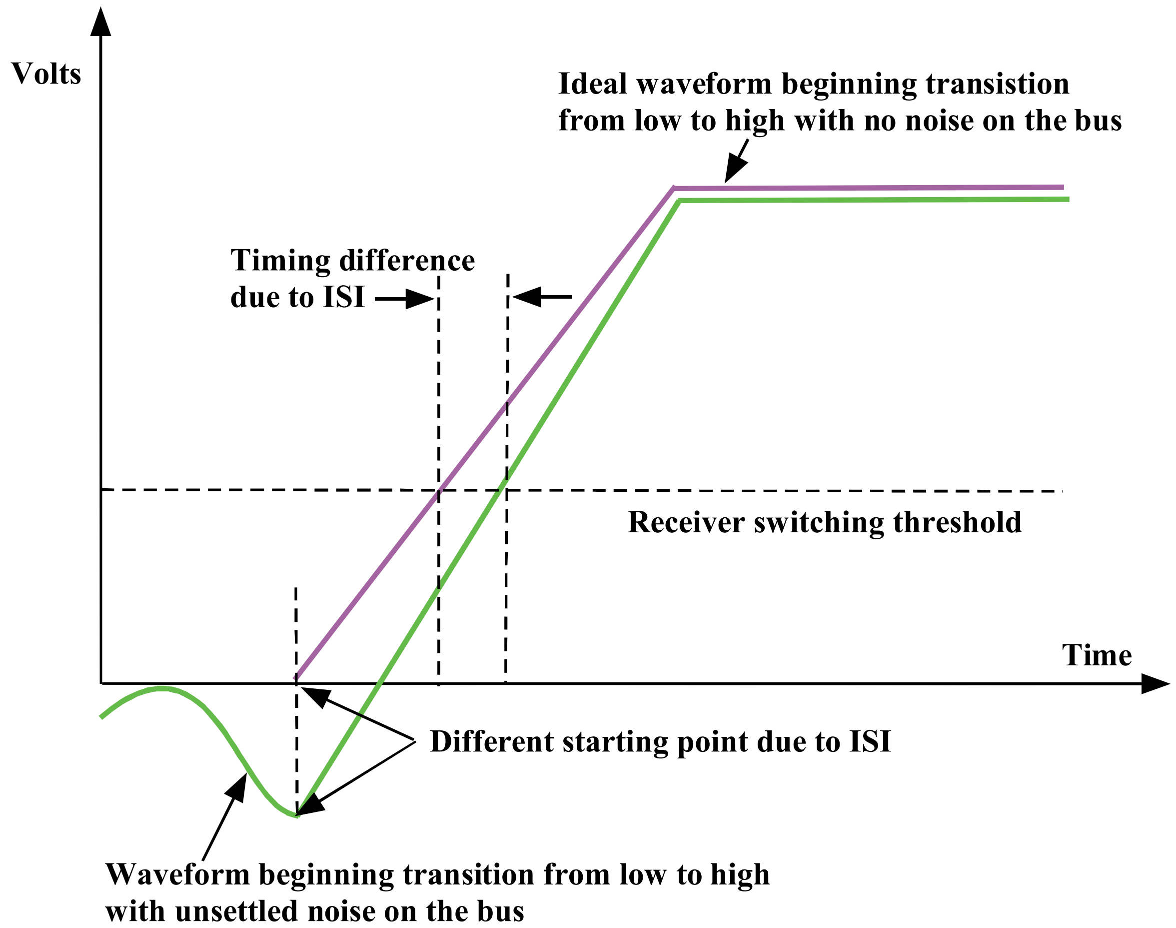




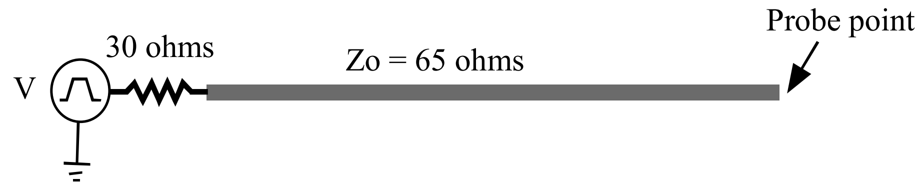
Intersymbol Interference (ISI)

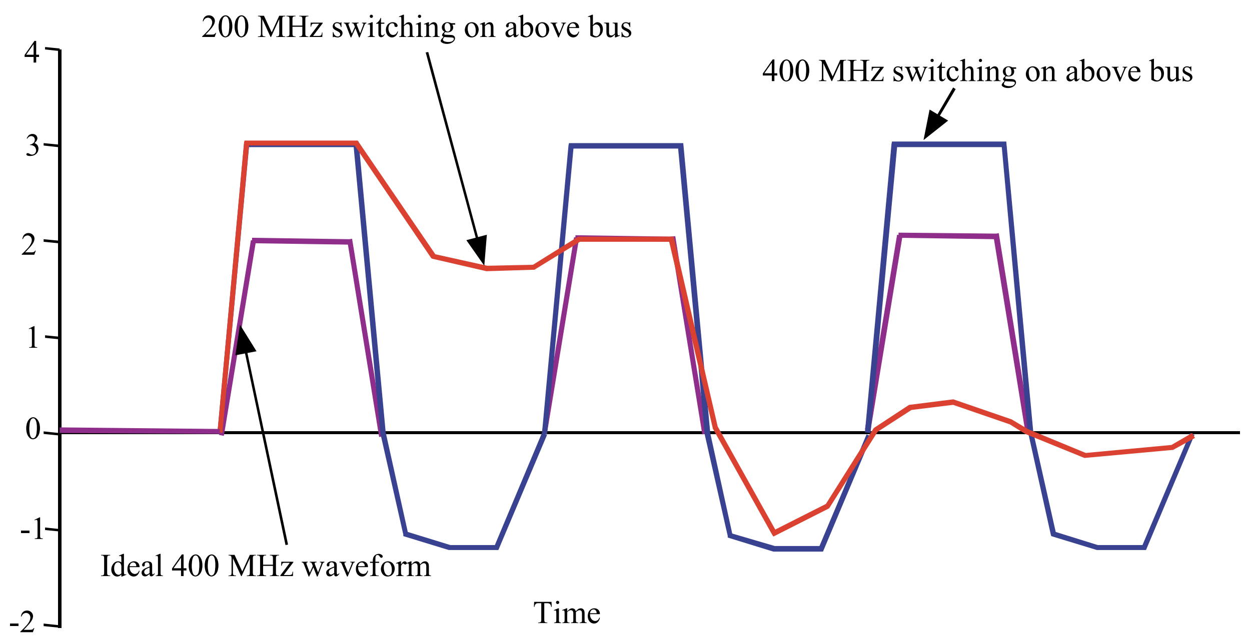
- Signal launched on a transmission line can be affected by previous signals as result of reflections
- ISI can be a major concern especially if the signal delay is smaller than twice the time of flight
- ISI can have devastating effects
- Noise must be allowed to settled before next signal is sent

Intersymbol Interference



Intersymbol Interference and Signal Integrity

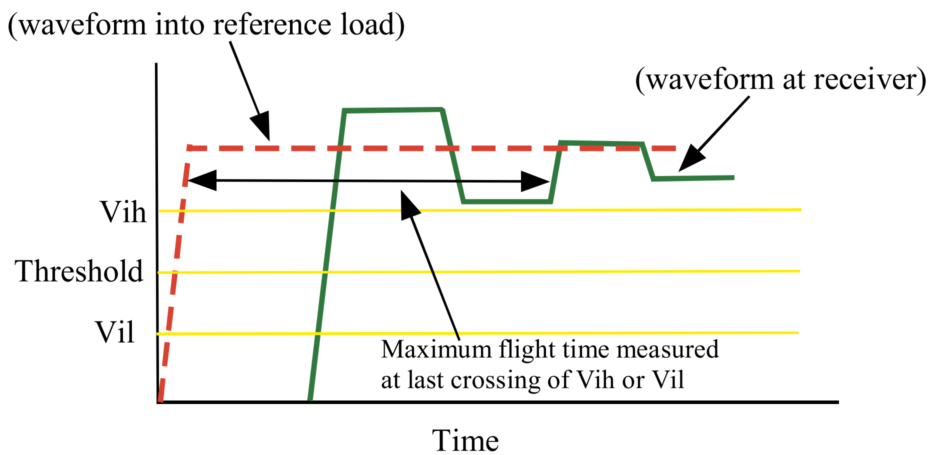




Minimizing ISI

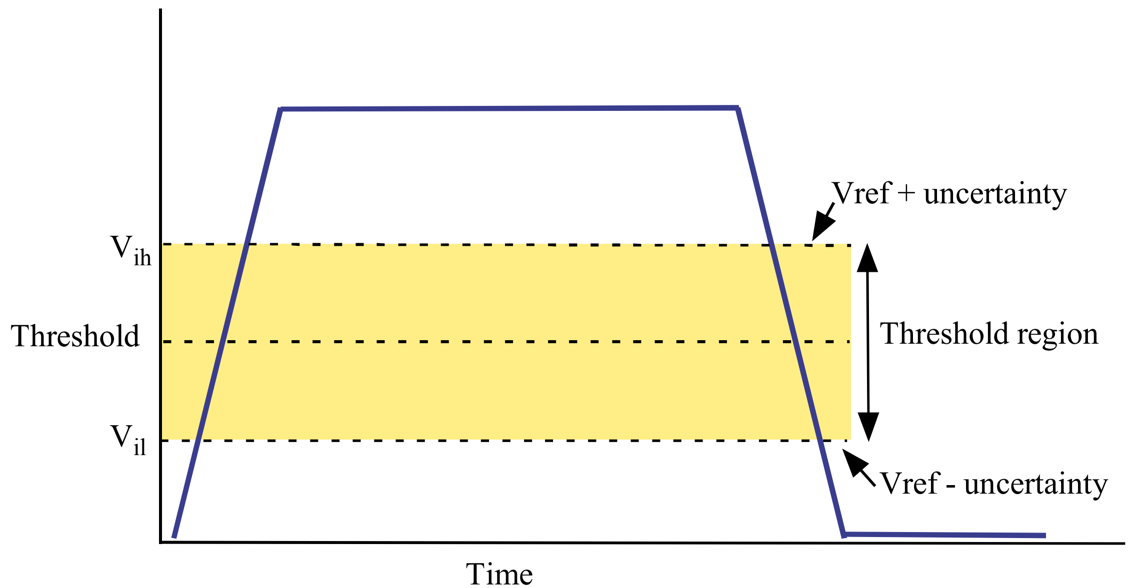
- **Minimize reflections on the bus by avoiding impedance discontinuities**
- **Minimize stub lengths and large parasitics from package sockets or connectors**
- **Keep interconnects as short as possible (minimize delay)**
- **Minimize crosstalk effects**

Ringback and Rise Time Control



- Violation into threshold region
- Detrimental even if threshold is not crossed
- Can exacerbate ISI
- Can be aggravated by nonlinear (time varying) terminations
- Can increase skew between signals

Voltage Reference Uncertainty



Major Contributors

- Power supply effects (SSN, ground bounce, rail collapse)
- Noise from IC
- Receiver transistor mismatches
- Return path discontinuities
- Coupling to reference voltage circuitry

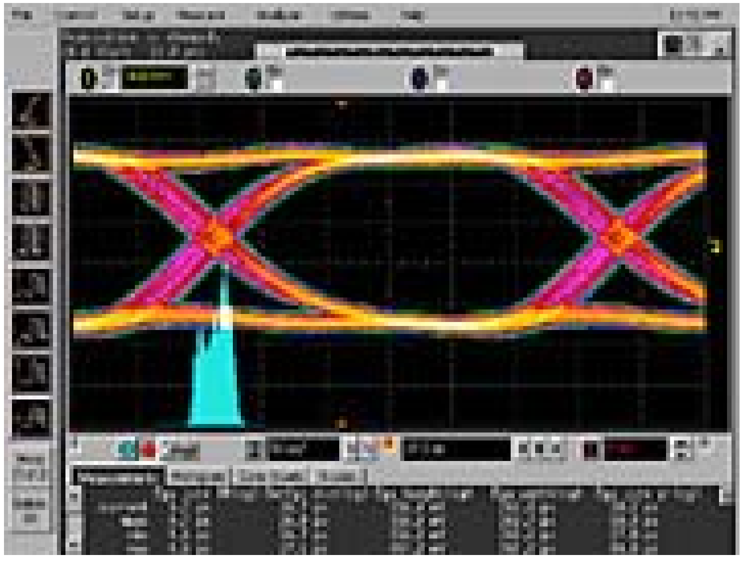
Jitter Definition

Jitter is difference in time of when something was ideally to occur and when it actually did occur.

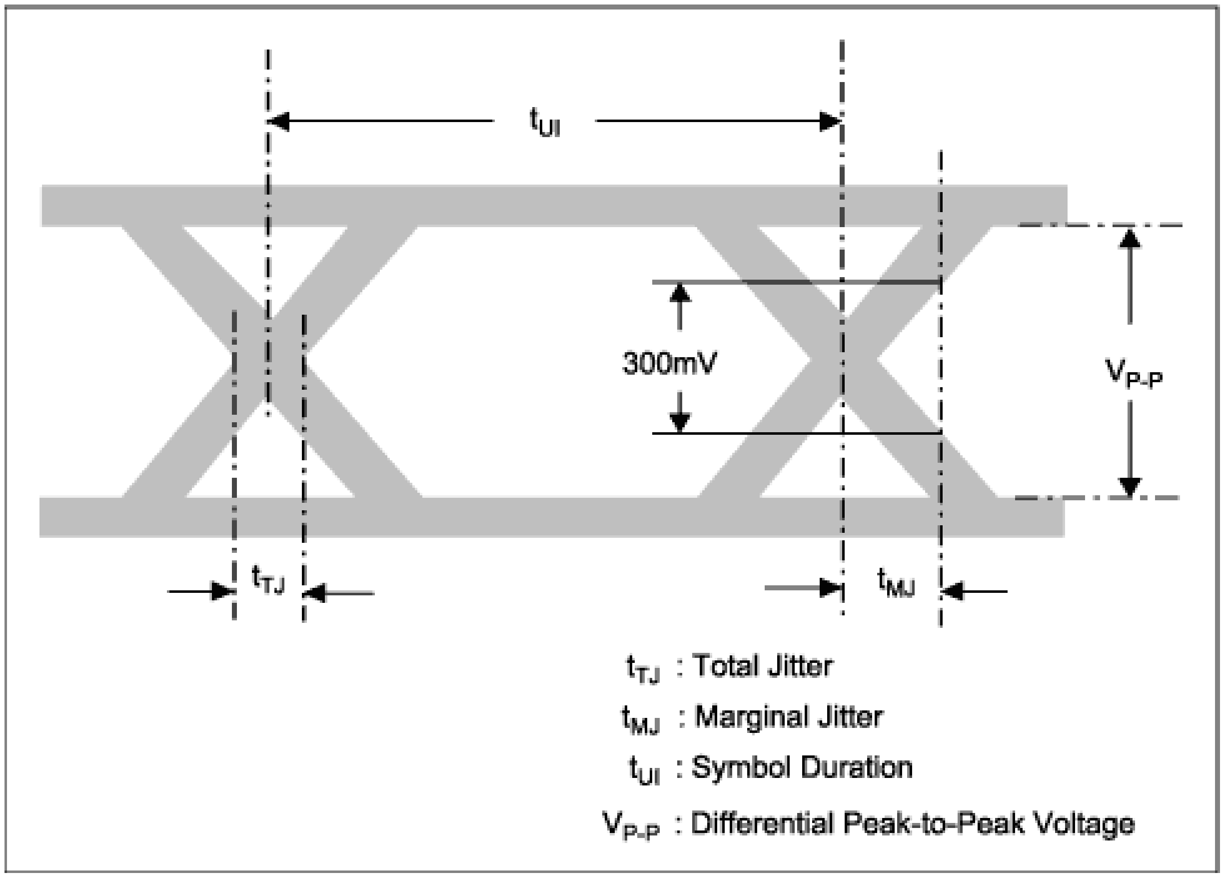
Some devices specify the amount of marginal jitter and total jitter that it can take to operate correctly. If the cable adds more jitter than the receiver’s allowed marginal jitter and total jitter the signal will not be received correctly. In this case the jitter is measured as in the below diagram

Eye Diagrams

• Eye diagrams are a time domain display of digital data triggered on a particular cycle of the clock. Each period is repeated and superimposed. Each possible bit sequence should be generated so that a complete eye diagram can be made

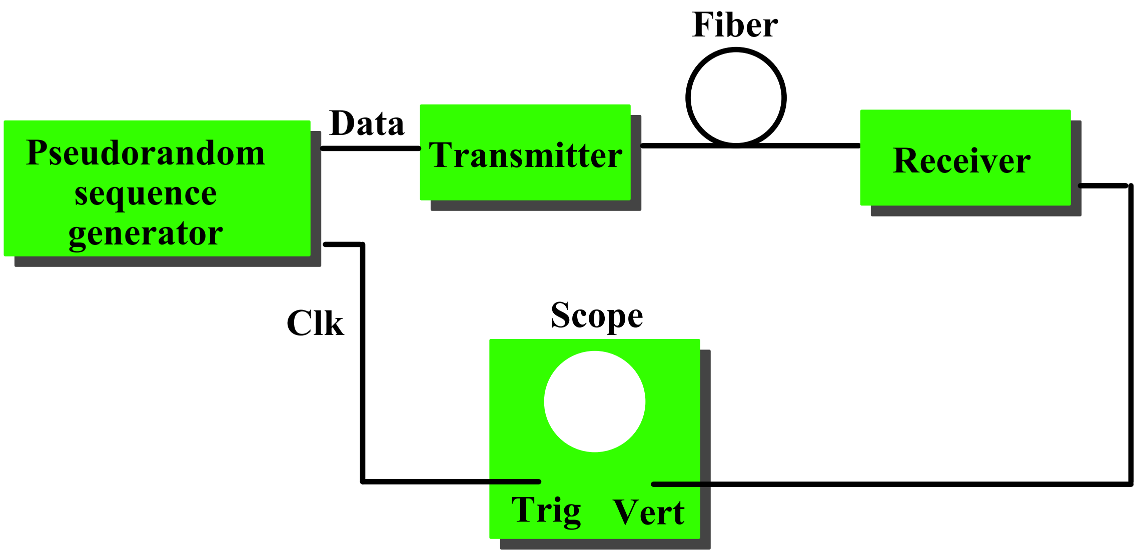


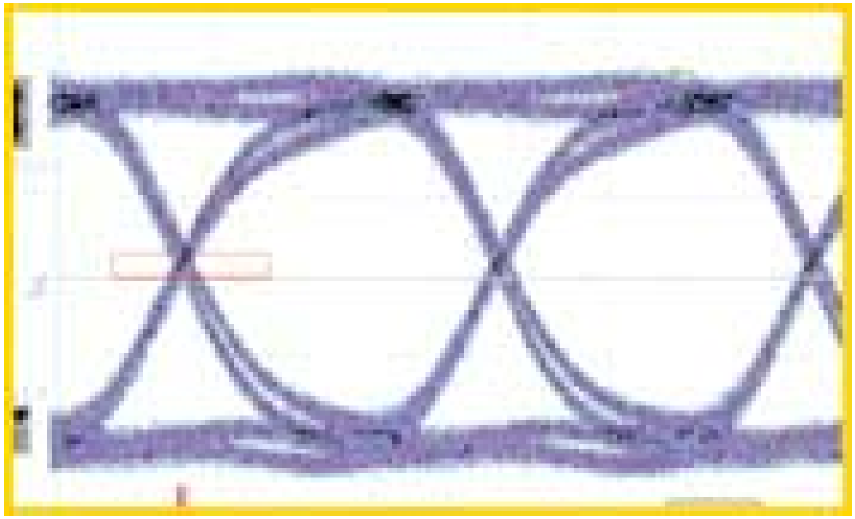
Eye Diagram



t_{UI}
300mV
V_{P-P}
t_{TJ}
t_{MJ}
t_{TJ} : Total Jitter
t_{MJ} : Marginal Jitter
t_{UI} : Symbol Duration
V_{P-P} : Differential Peak-to-Peak Voltage

Eye Pattern Analysis





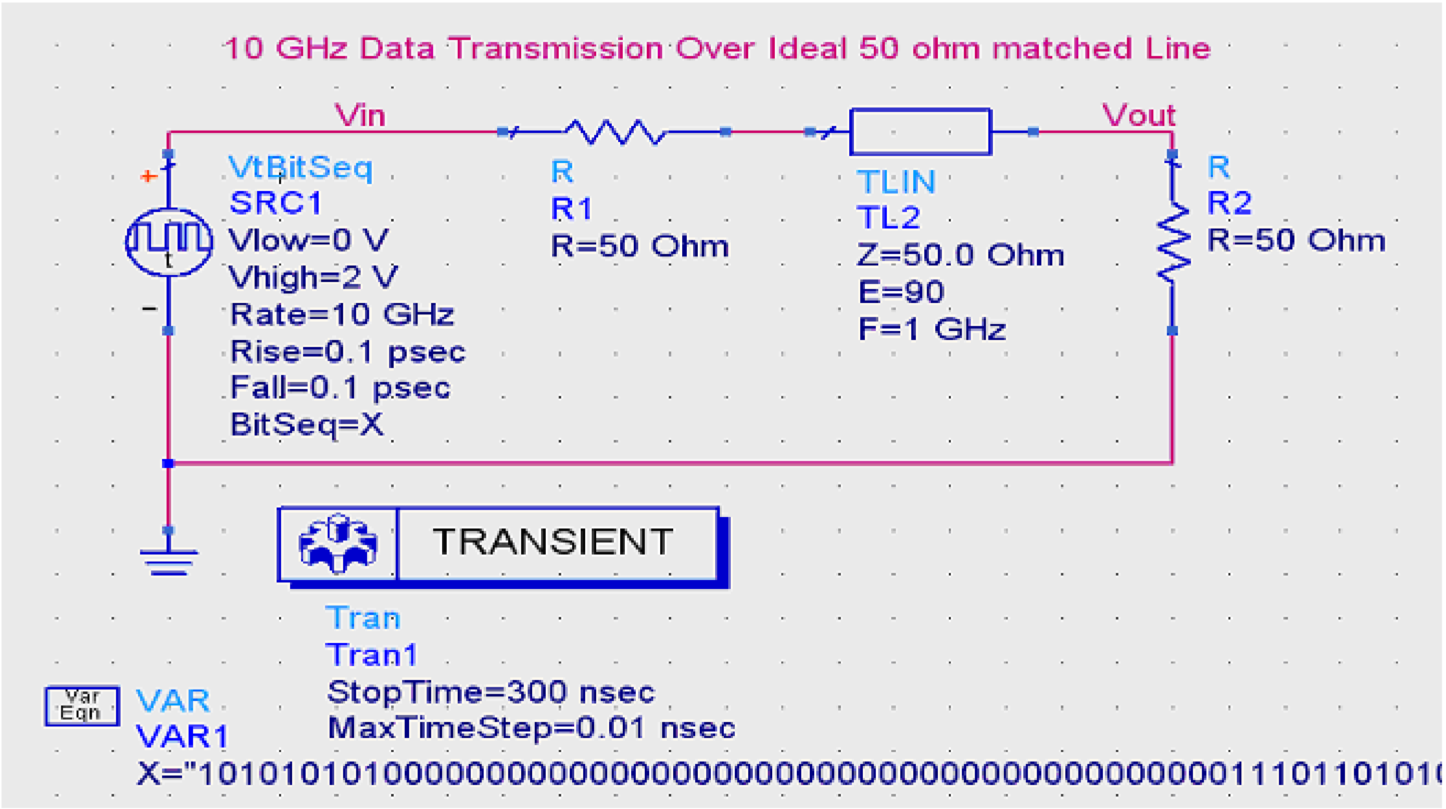
Jitter

- **Jitter is a signal timing deviation referenced to a recovered clock from the recovered bit stream**
- **Measured in Unit Intervals and captured visually with eye diagrams**
- **Two types of jitter**
  - **Deterministic (non Gaussian)**
  - **Random**
- **The total jitter (TJ) is the sum of the random (RJ) and deterministic jitter(DJ)**

Causes of Deterministic Jitter

- Crosstalk
  - Noisy neighboring signals
- Interference
- Reflections
  - Imperfect terminations
  - Discontinuities (e.g. multidrop buses, stubs)
- Simultaneous switching noise (SSN)
  - Noisy reference plane or power rail
  - Shift in threshold voltages

Eye Diagram - ADS Simulation

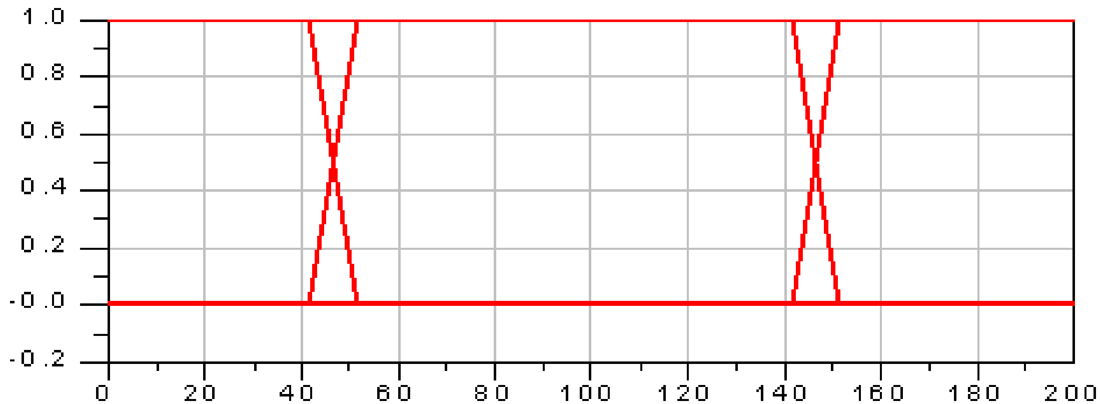


Eye Diagram - ADS Simulation
Ideal Matched Line

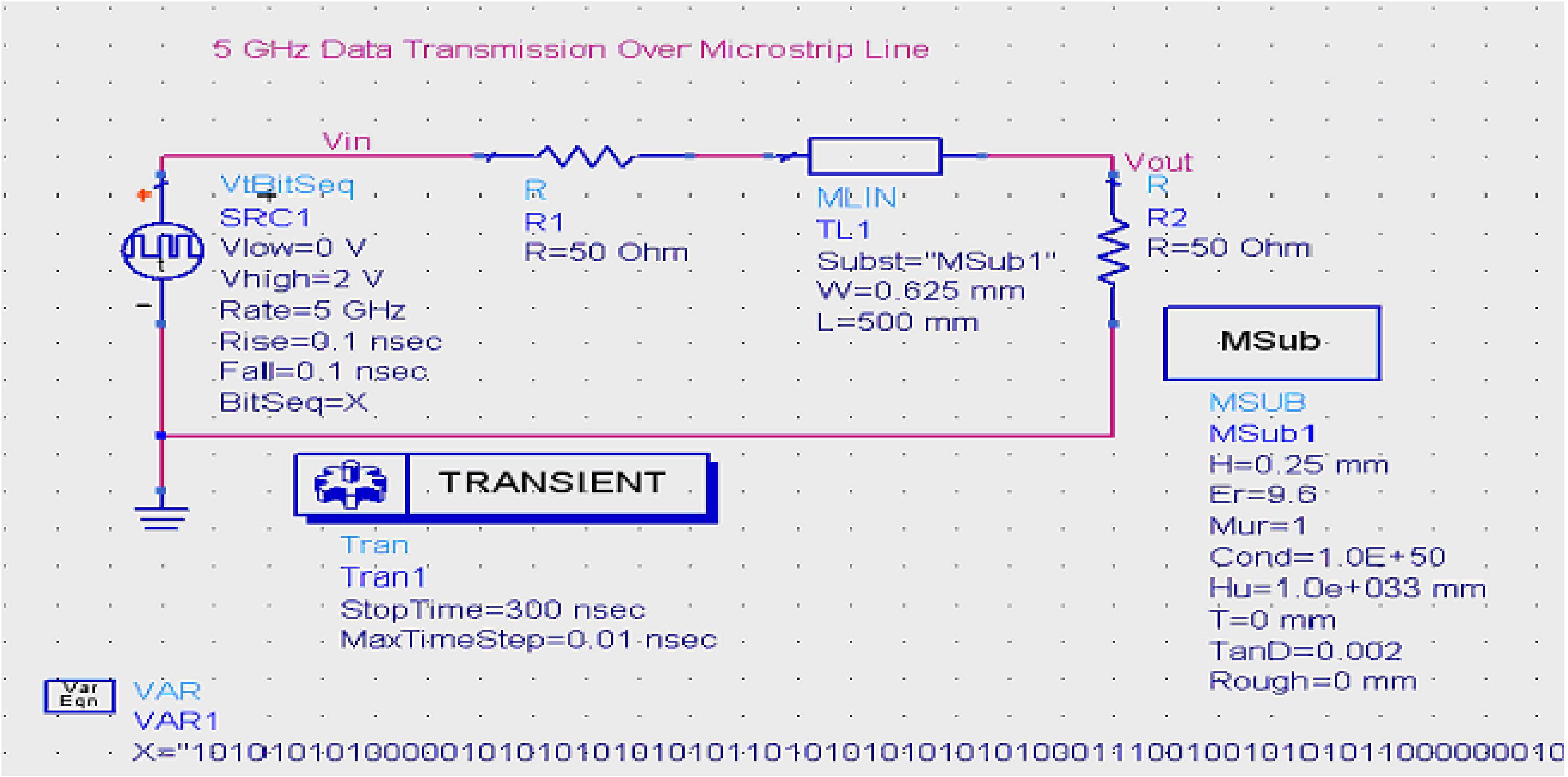
Eye Diagram of 10 GHz Data Transmission over an Ideal 50 ohm, matched Line

Bit Rate = 10 GHz
Rise time = 0.1 psec
Fall time = 0.1 psec

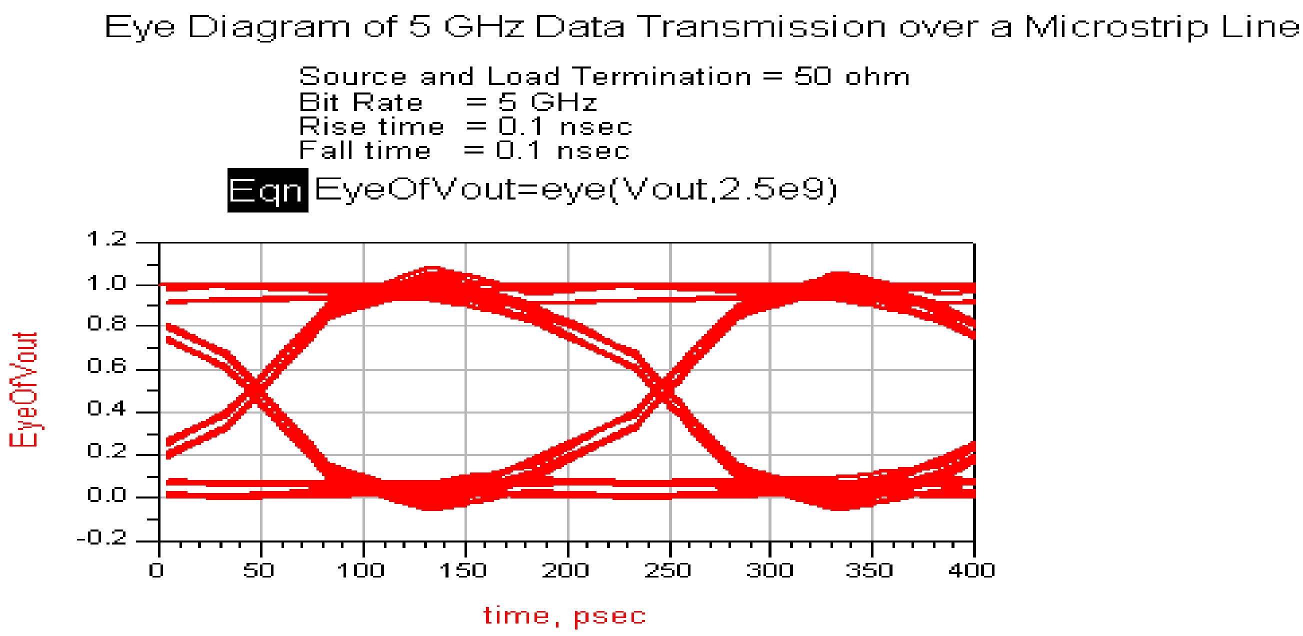
Eqn EyeOfVout=eye(Vout,5e9)



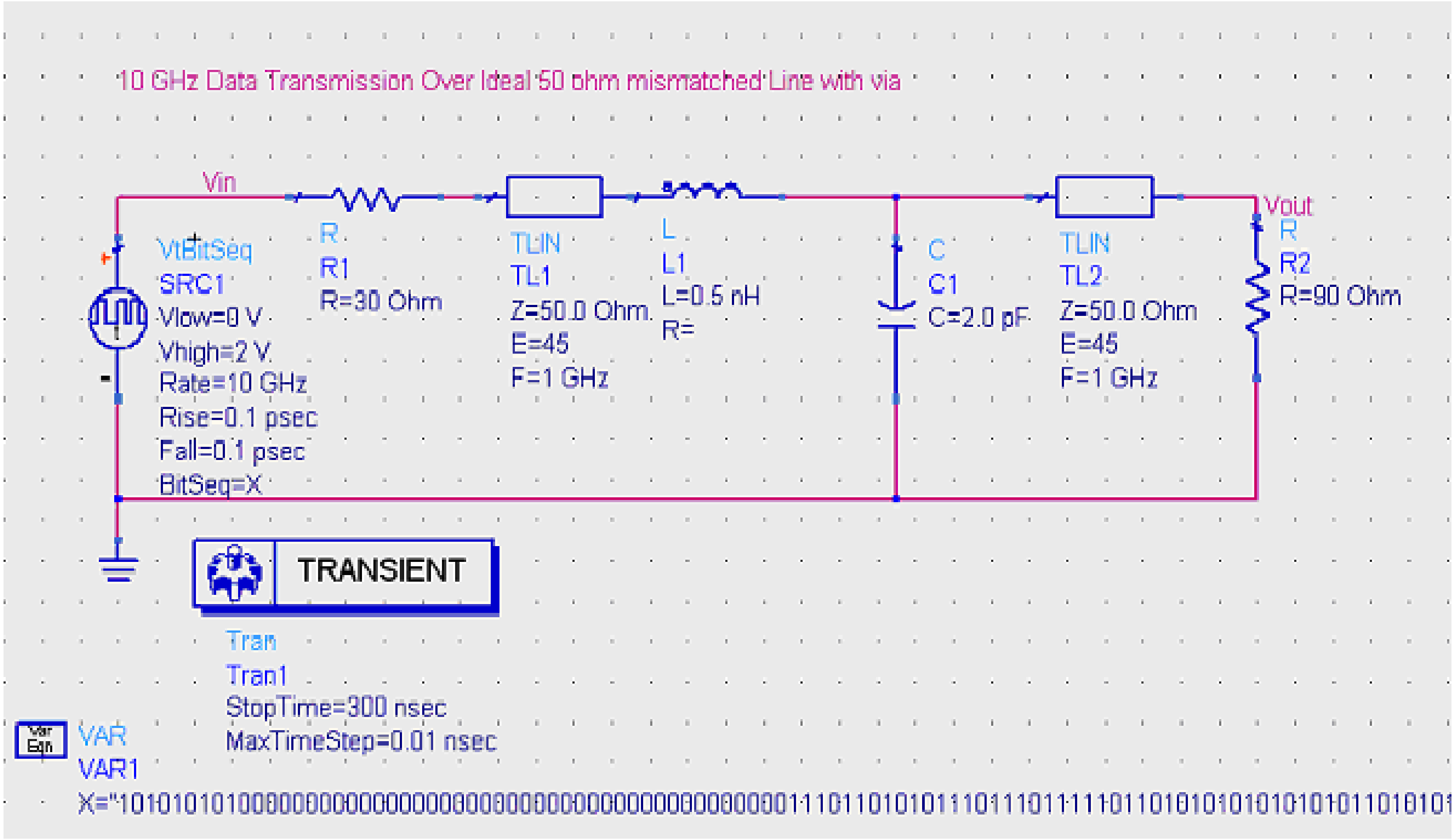
Eye Diagram - ADS Simulation
5 GHz Data Transmission



Eye Diagram - ADS Simulation
5 GHz Data Transmission



Eye Diagram - ADS Simulation
10 GHz Data Transmission

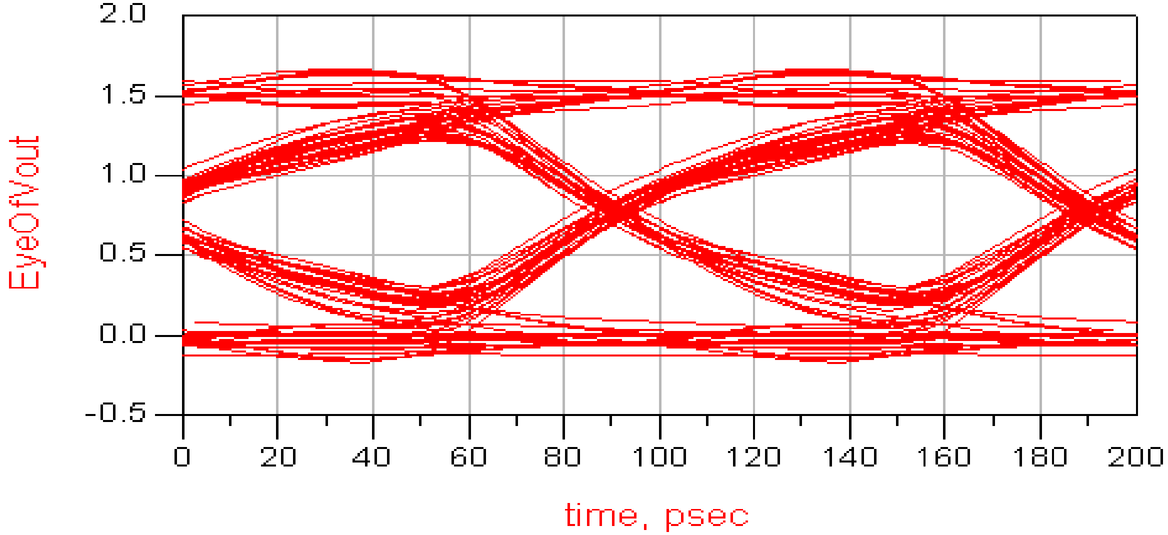


Eye Diagram - ADS Simulation

Eye Diagram of 10 GHz Data Transmition over
an Ideal 50 ohm, mismatched Line with via

Source termination = 30 ohm
Load termination = 90 ohm
Bit Rate = 10 GHz
Rise time = 0.1 psec
Fall time = 0.1 psec

Eqn EyeOfVout=eye(Vout,5e9)



Bit-Error Rate

- **The Bit-error rate (BER) quantifies the likelihood of a bit being interpreted at the receiver incorrectly due to jitter- or amplitude-induce degradation on the received signal**

- **No higer than a 10-16 BER is tolerable => no more than 1 error out of 1016 bits.**

- **BER can be measured directly or quantified with statistical calculations**

- **Deterministic jitter(DJ) can be easily measured via S-parameters obtained in the frequency domain**