ECE 451
Advanced Microwave Measurements

Signal Integrity

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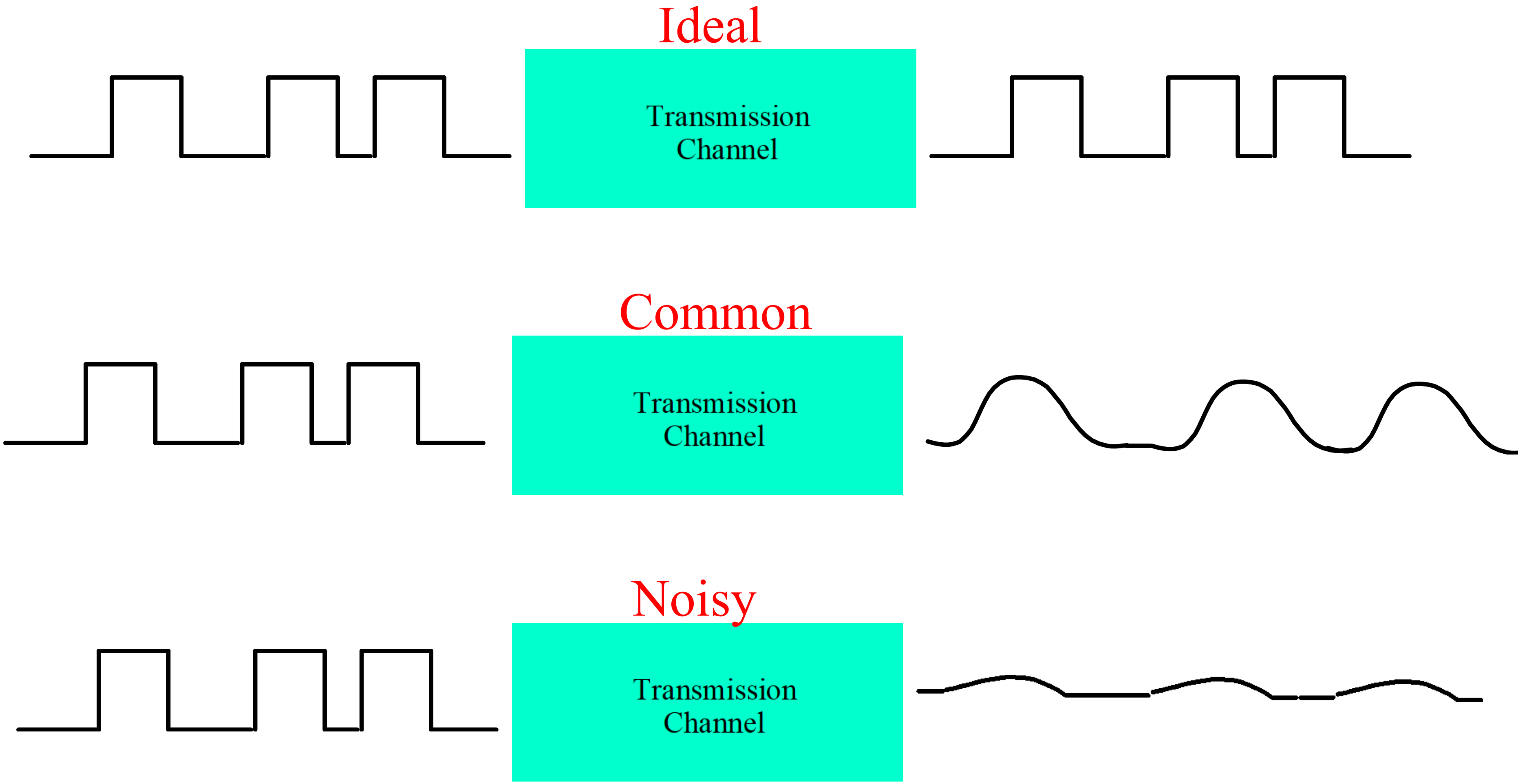
Signal Integrity



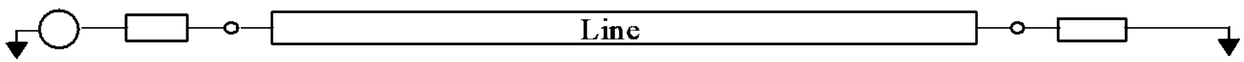
Signal Integrity

- **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

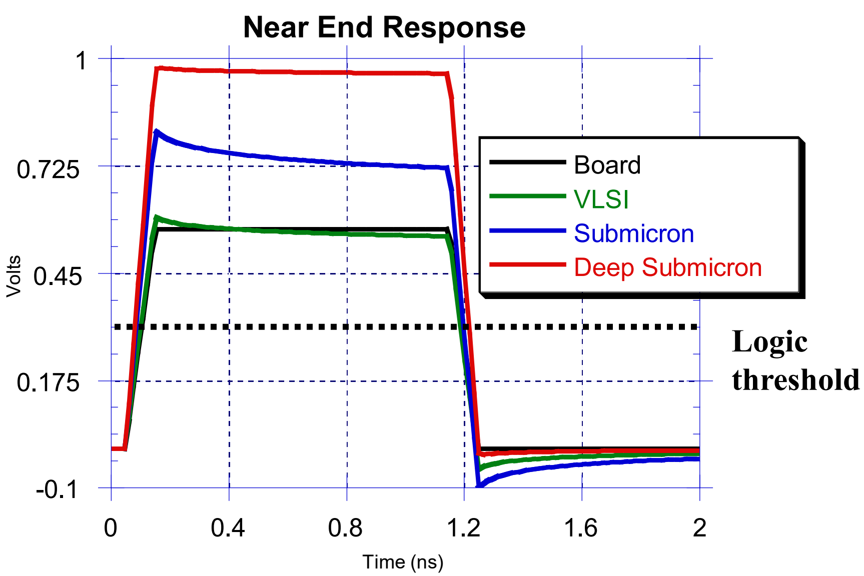


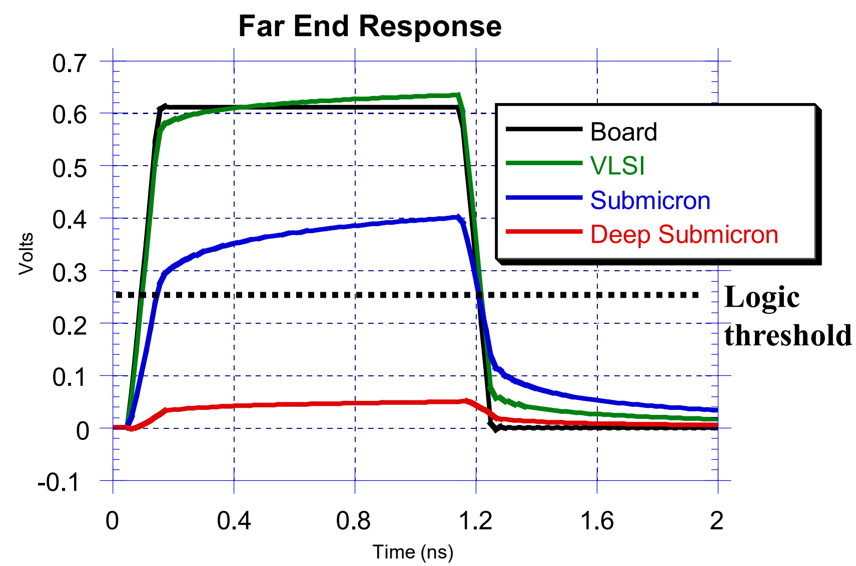
Pulse Characteristics:

- 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

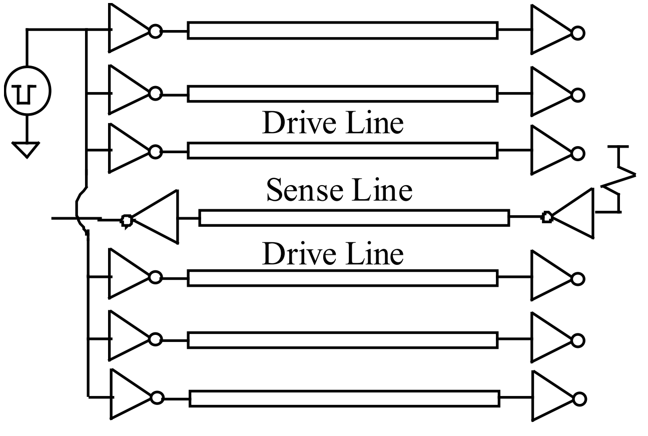


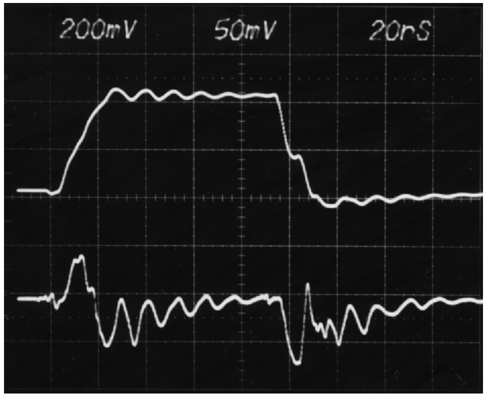


Interconnect Bottleneck

Signal Integrity

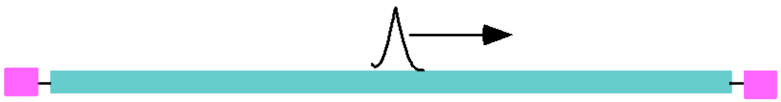
Crosstalk	**Dispersion**	**Attenuation**
Reflection	**Distortion**	**Loss**
Delta I Noise	**Ground Bounce**	**Radiation**





Reflection in Transmission Lines

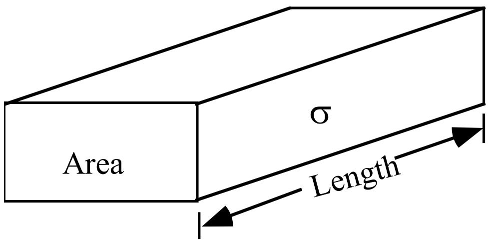
1.



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:

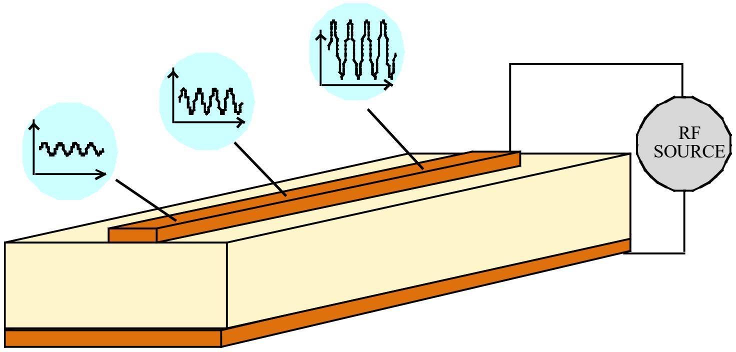
W=0.25 microns

R=422 Ω/mm

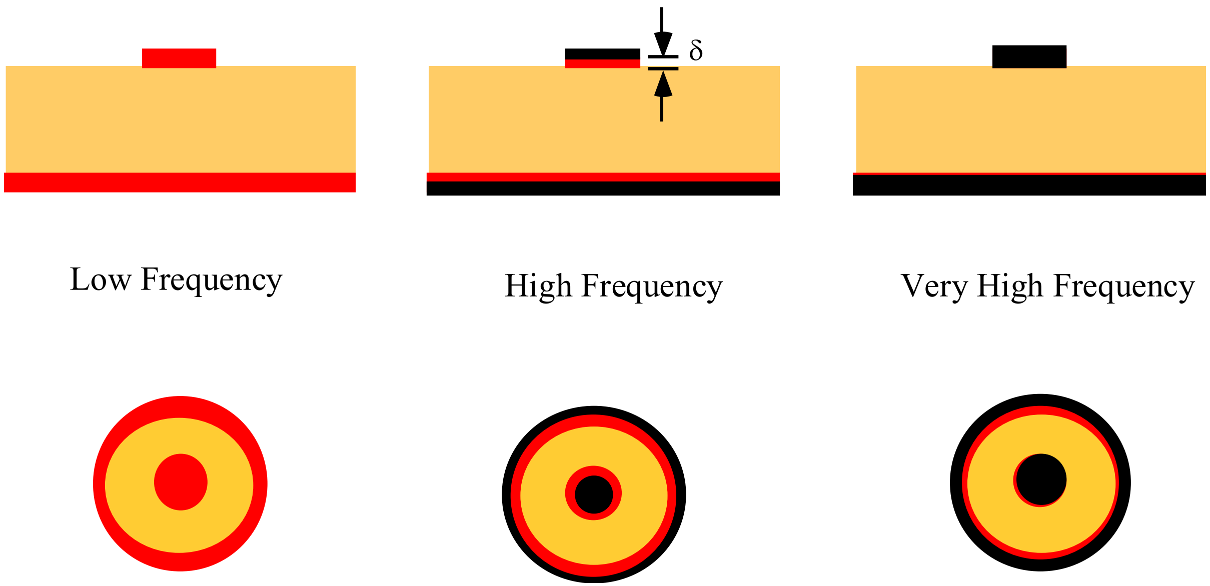
Metallic Conductors

Metal	Conductivity σ (Ω^{-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

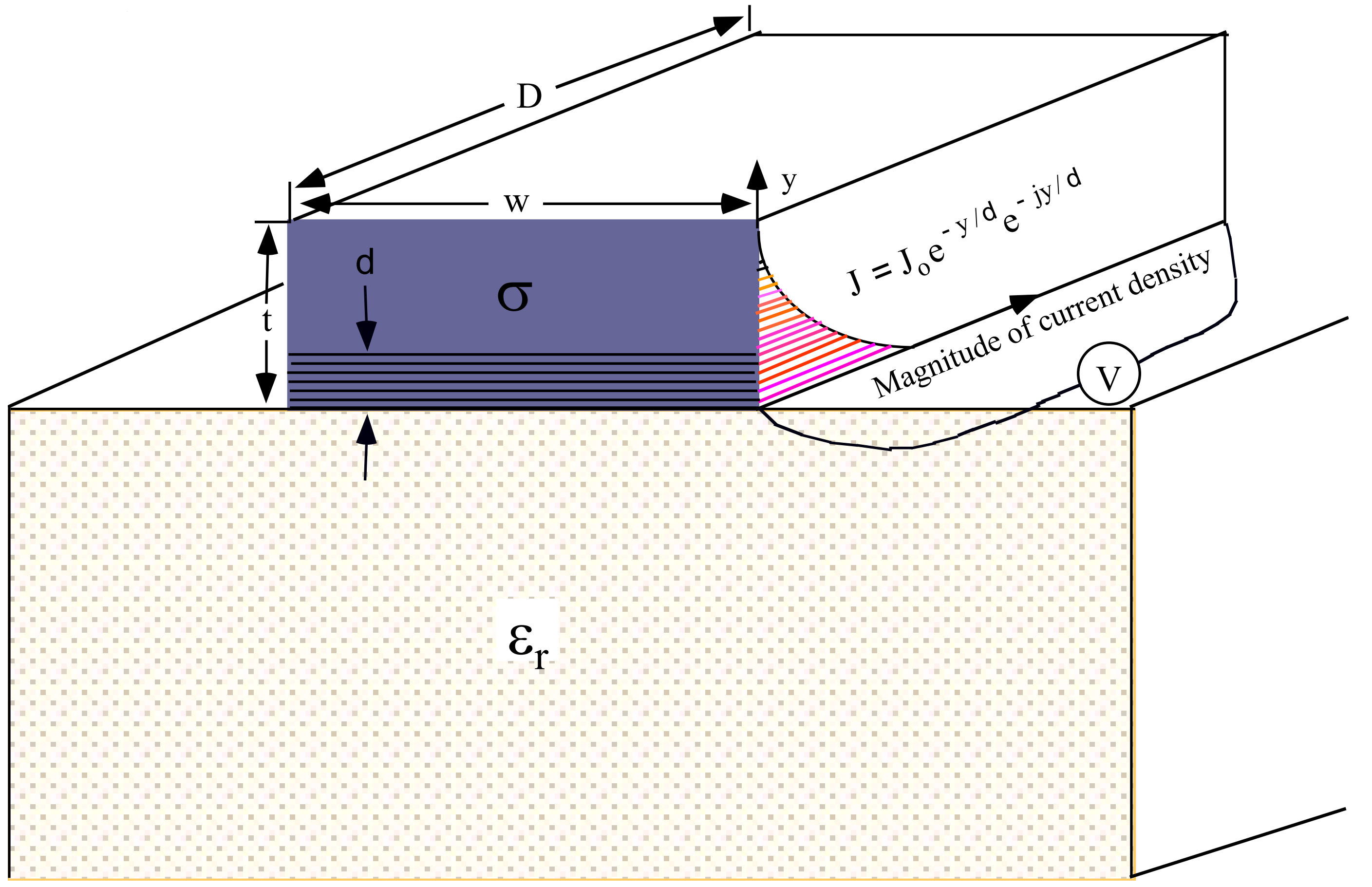
Loss in Transmission Lines



Skin Effect in Transmission Lines

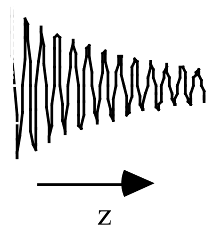


Skin Effect in Microstrip



Skin Effect

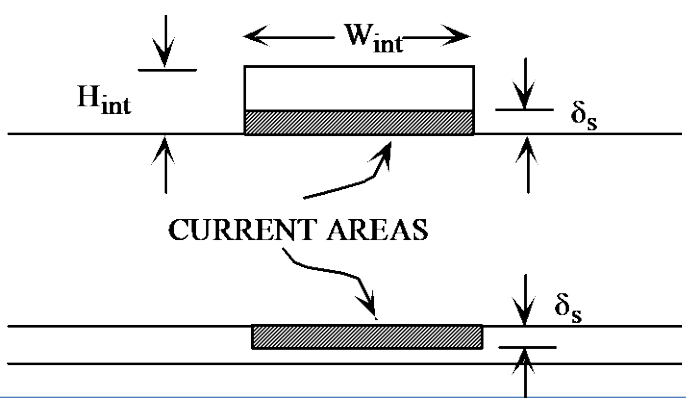
The electric field in a material medium propagates as



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

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

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

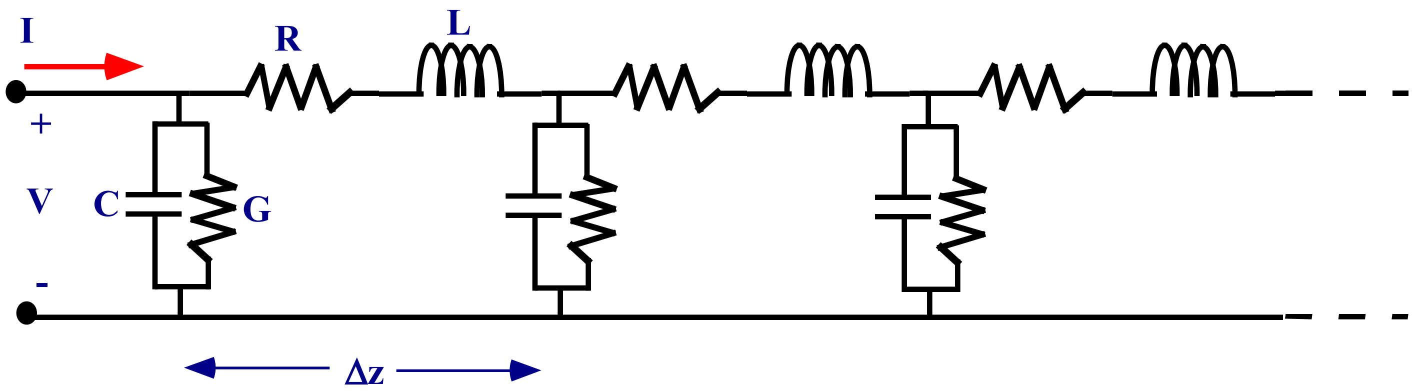
where $\rho = \dfrac{1}{\sigma}$ is the bulk resistivity of the conductor

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

with

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

Lossy Transmission Line

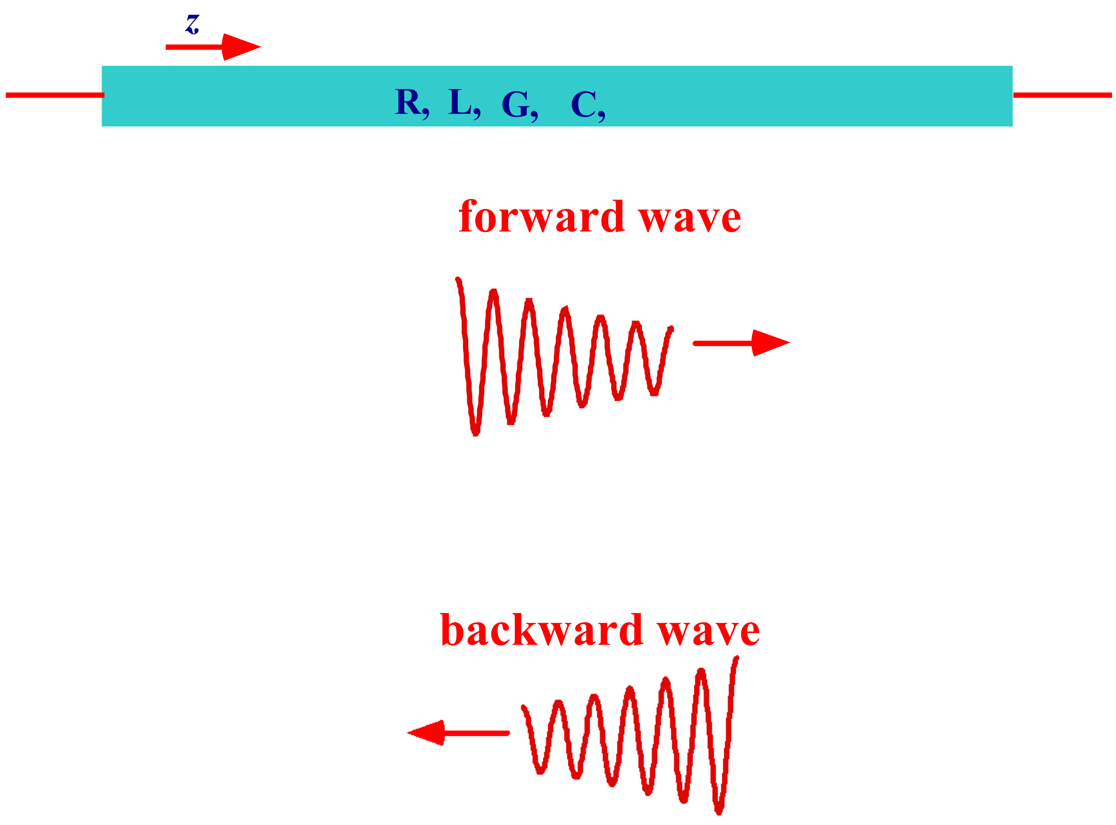


Telegraphers Equation

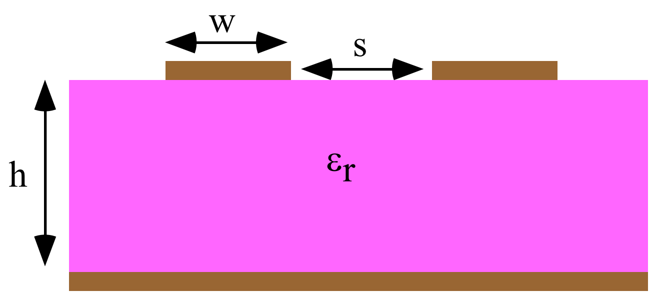
$$-\frac{\partial V}{\partial z} = (R + j\omega L)I = ZI$$

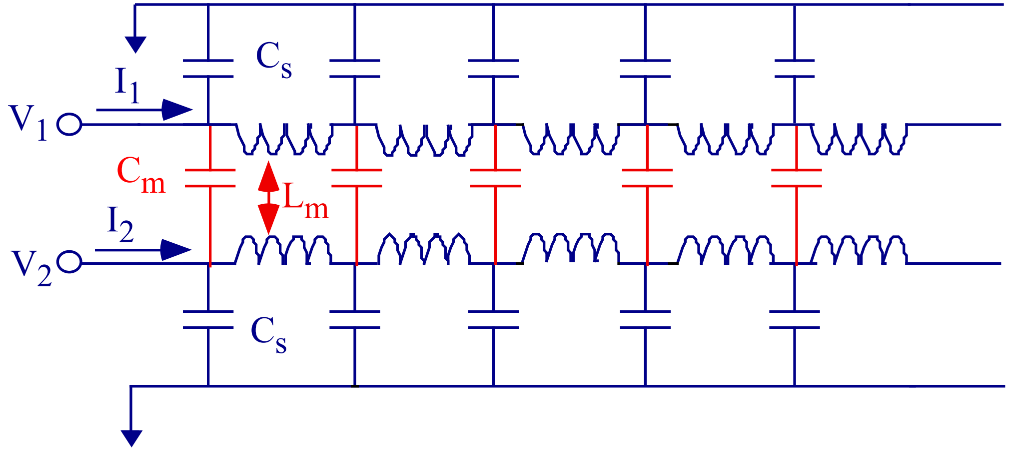
$$-\frac{\partial I}{\partial z} = (G + j\omega C)V = YV$$

Lossy Transmission Line

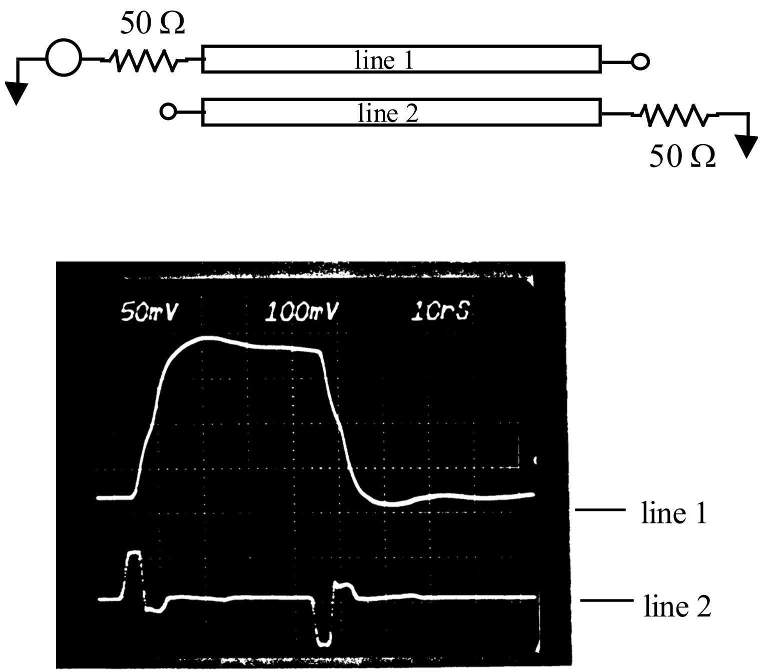


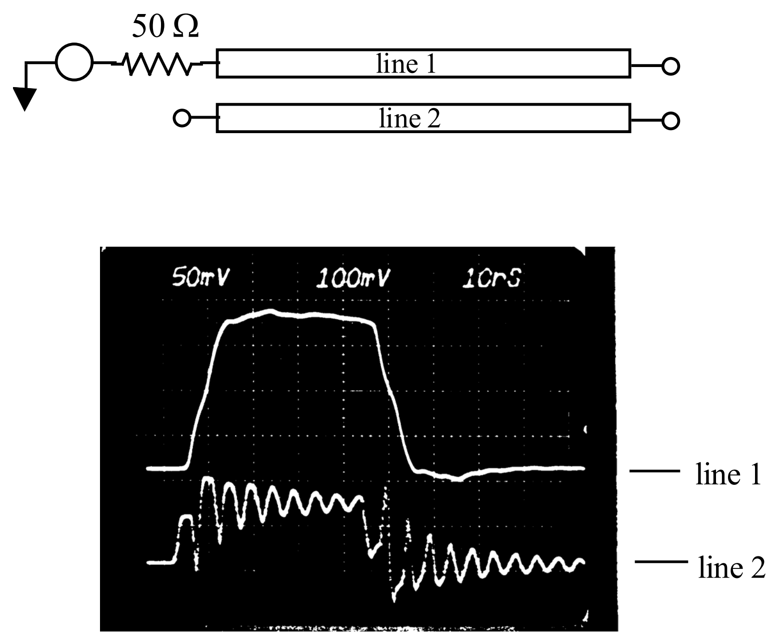
Coupled Lines and Crosstalk



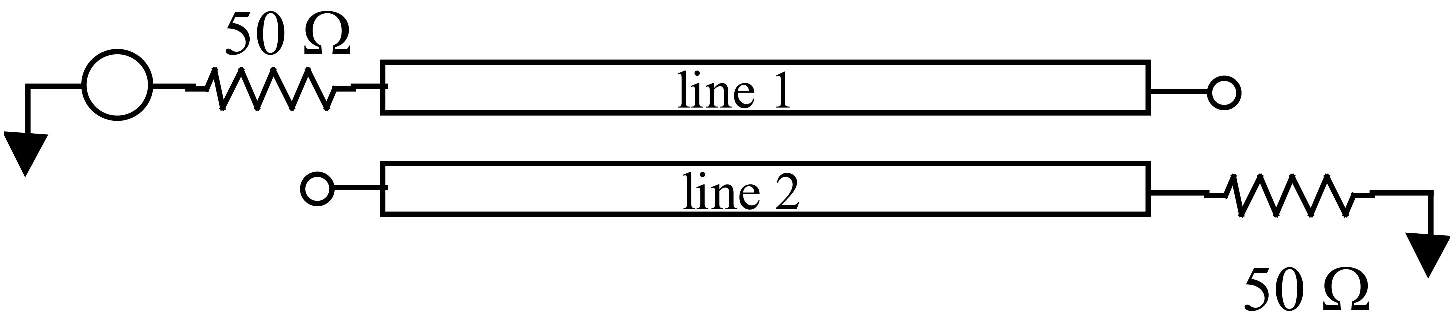


Crosstalk noise depends on termination

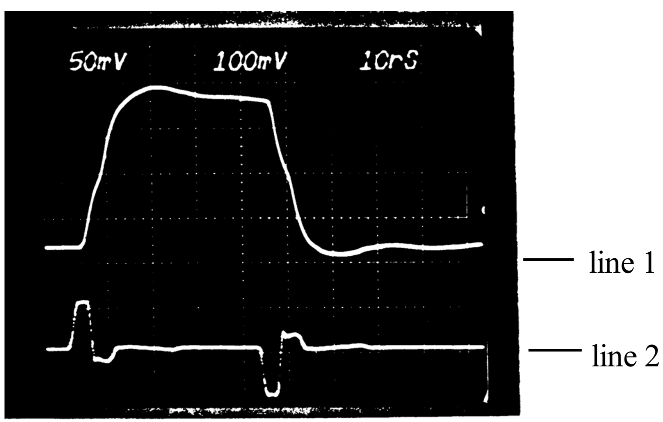




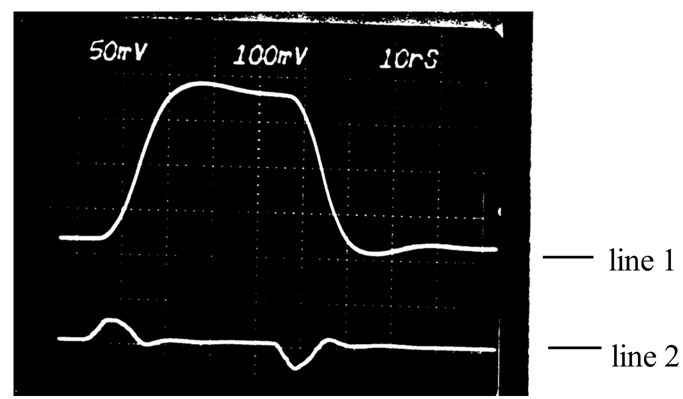
Crosstalk depends on signal rise time



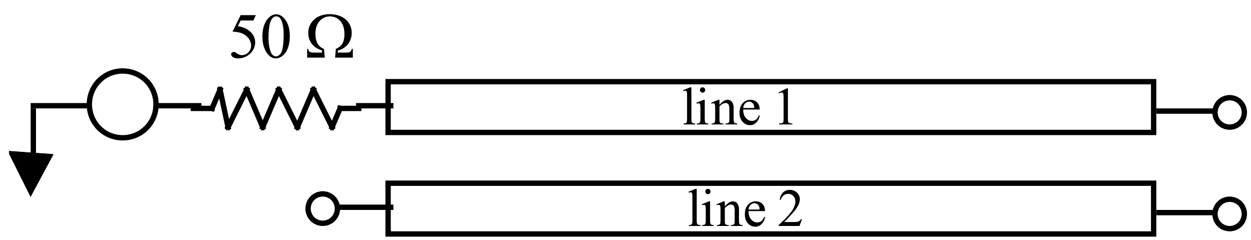
t_r = 1 ns



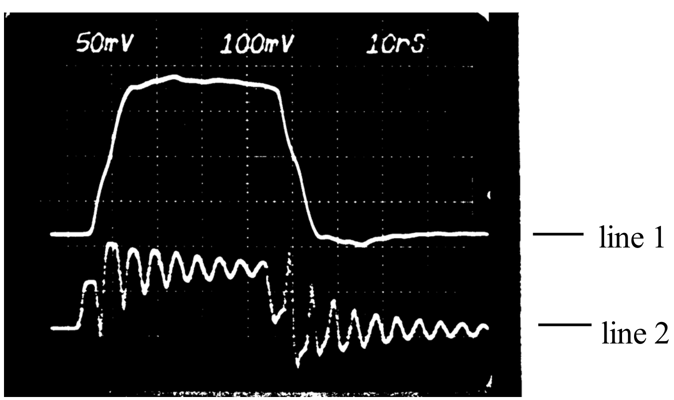
t_r = 7 ns



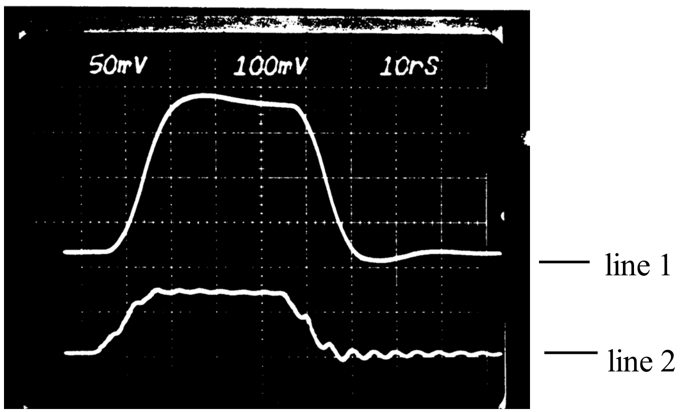
Crosstalk depends on signal rise time

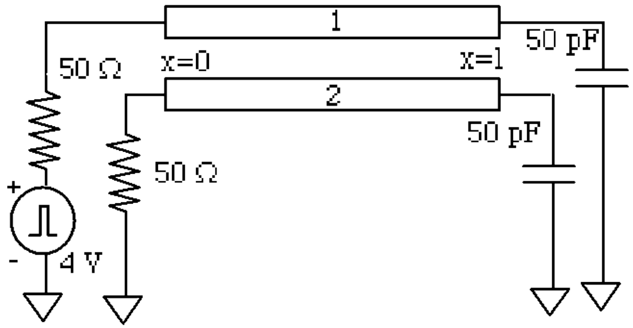


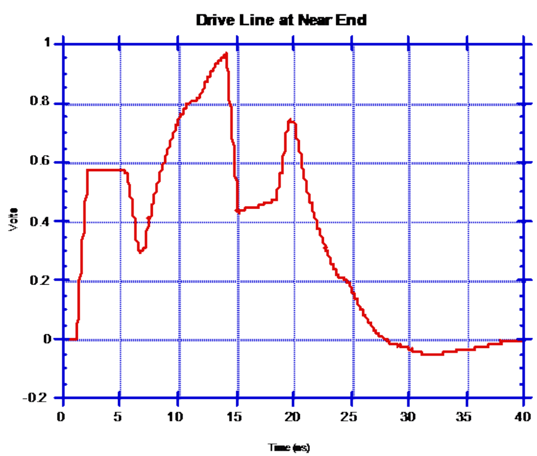
t_r = 1 ns

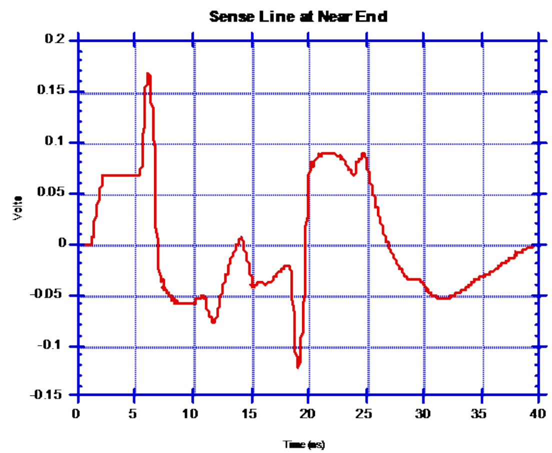


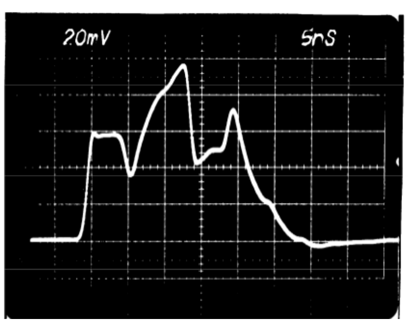
t_r = 7 ns

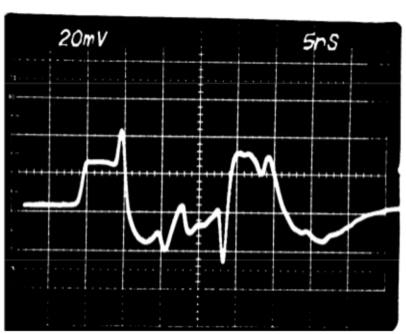



1
2
50 pF
50 Ω
x=0
x=1
50 pF
50 Ω
+
-
4 V

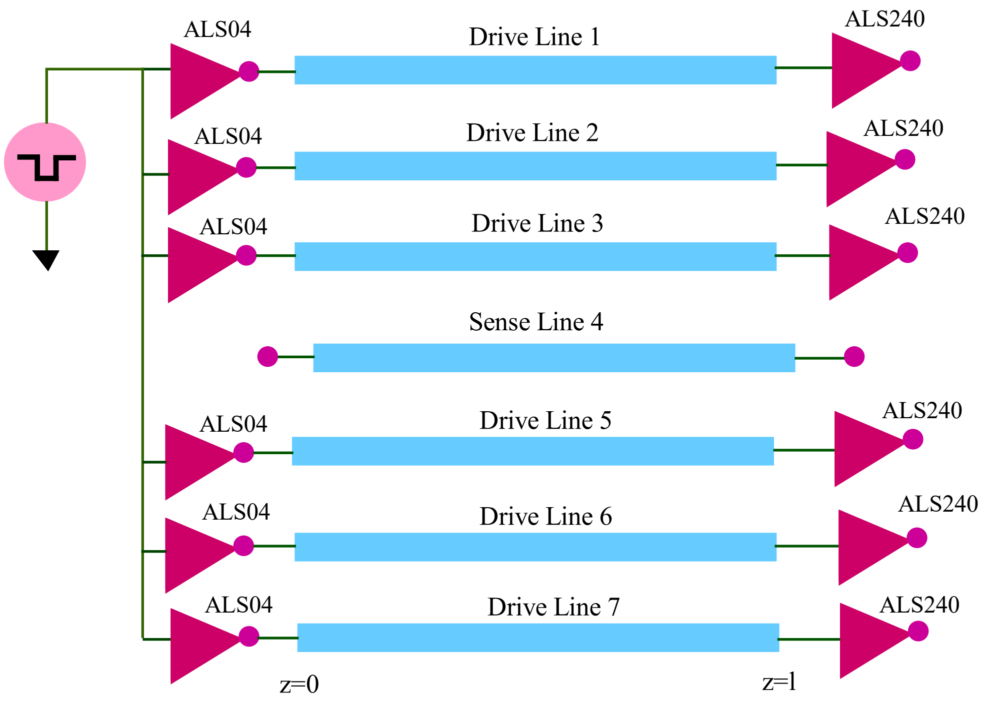

Drive Line at Near End
Volts
Time (ns)
1
0.8
0.6
0.4
0.2
0
-0.2
0 5 10 15 20 25 30 35 40


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

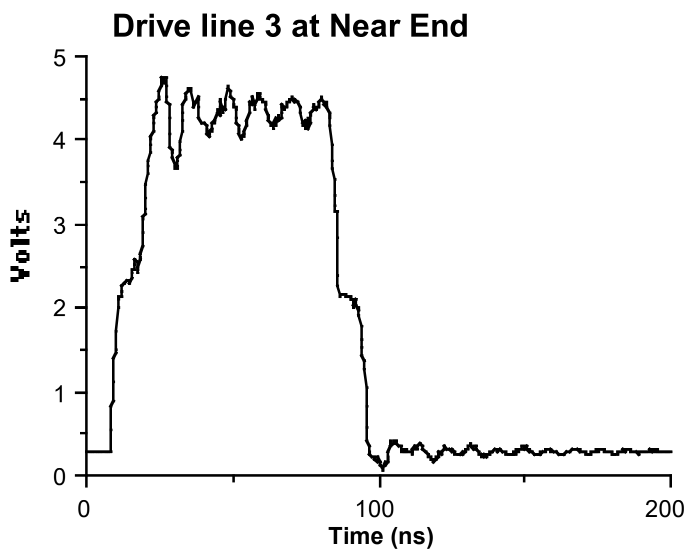
7-Line Coupled-Microstrip System

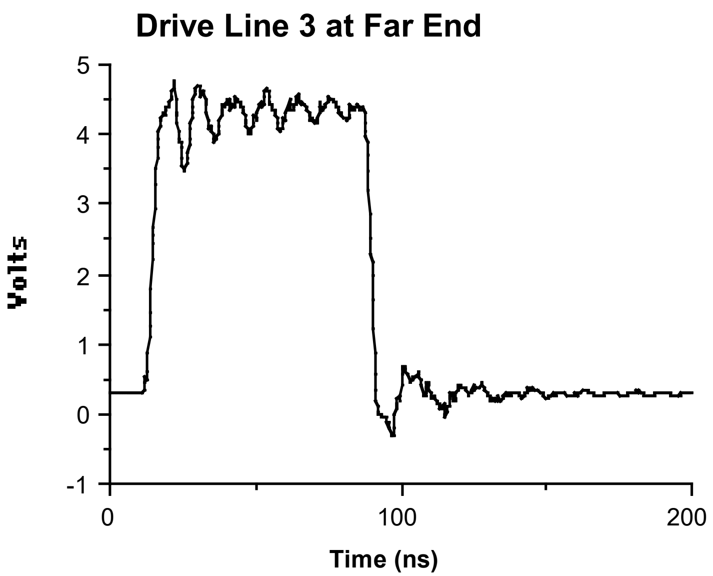


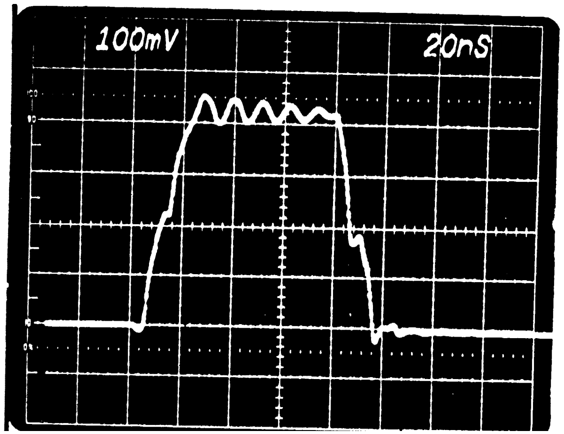
$L_s = 312$ nH/m; $C_s = 100$ pF/m;

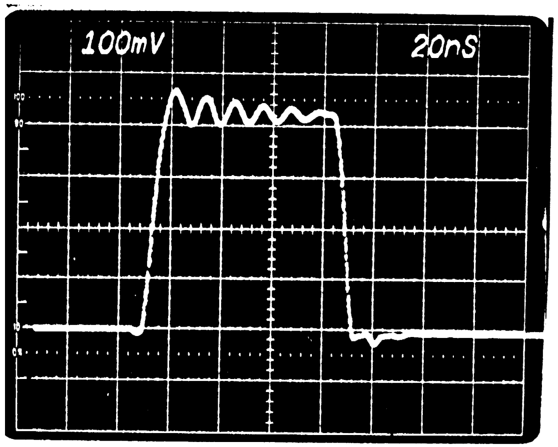
$L_m = 85$ nH/m; $C_m = 12$ pF/m.

Drive Line 3

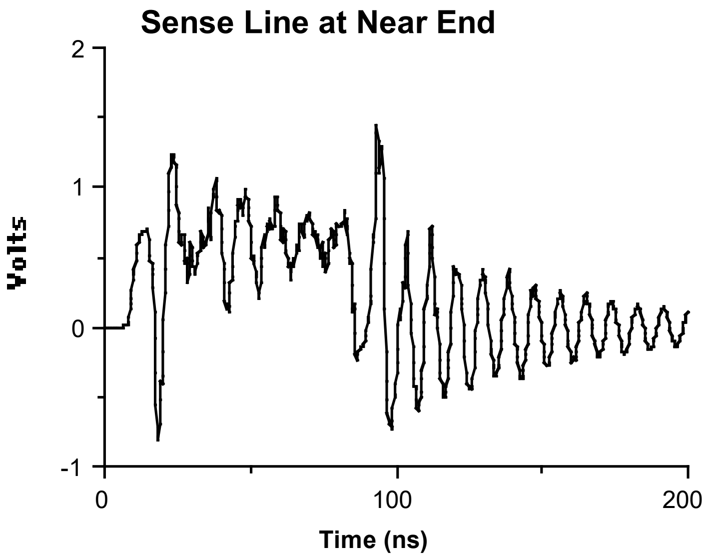

Drive line 3 at Near End
Volts
0
1
2
3
4
5
0
100
200
Time (ns)

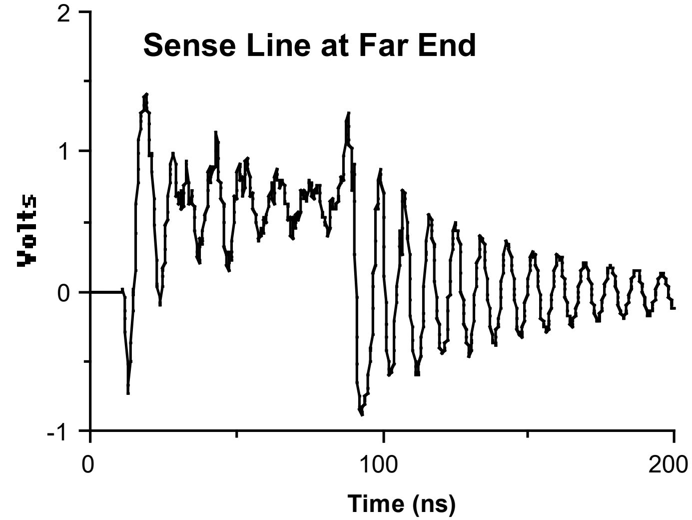

Drive Line 3 at Far End
Volts
-1
0
1
2
3
4
5
0
100
200
Time (ns)

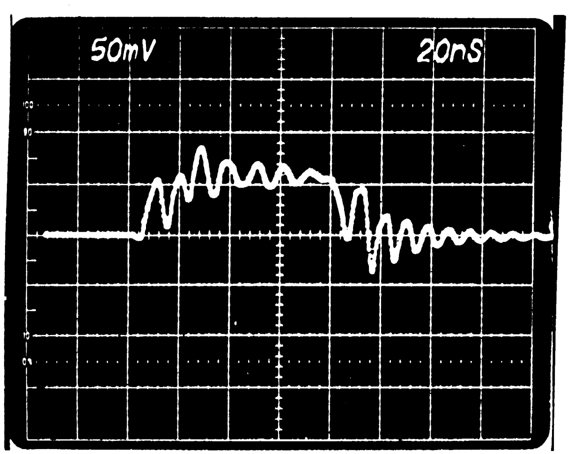

100mV
20nS

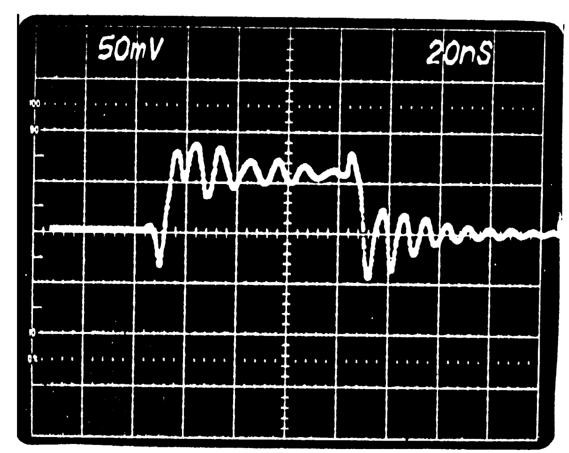

100mV
20nS

Sense Line

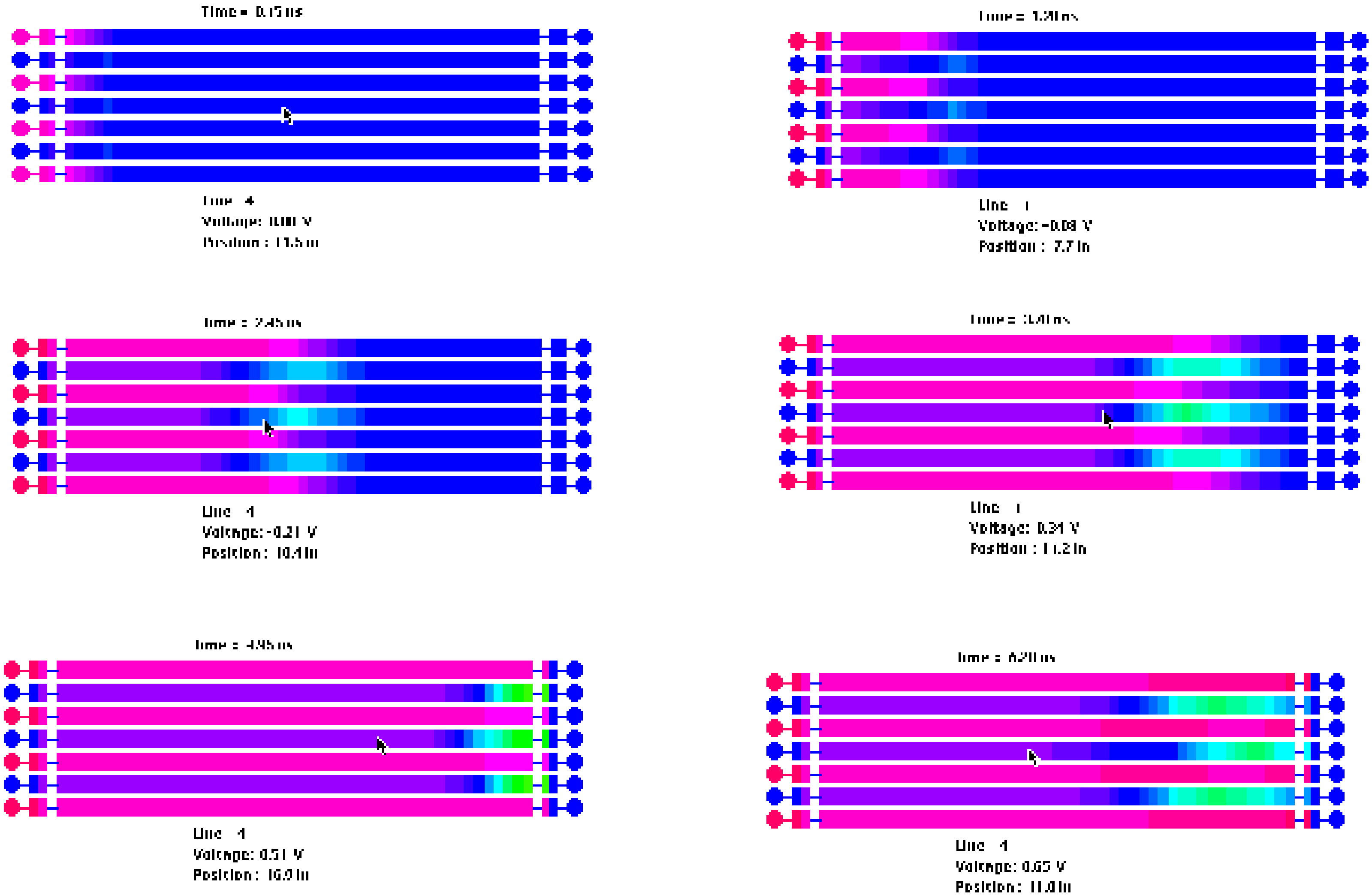

Sense Line at Near End
2
1
0
-1
Volts
0
100
200
Time (ns)


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


50mV
20nS


50mV
20nS

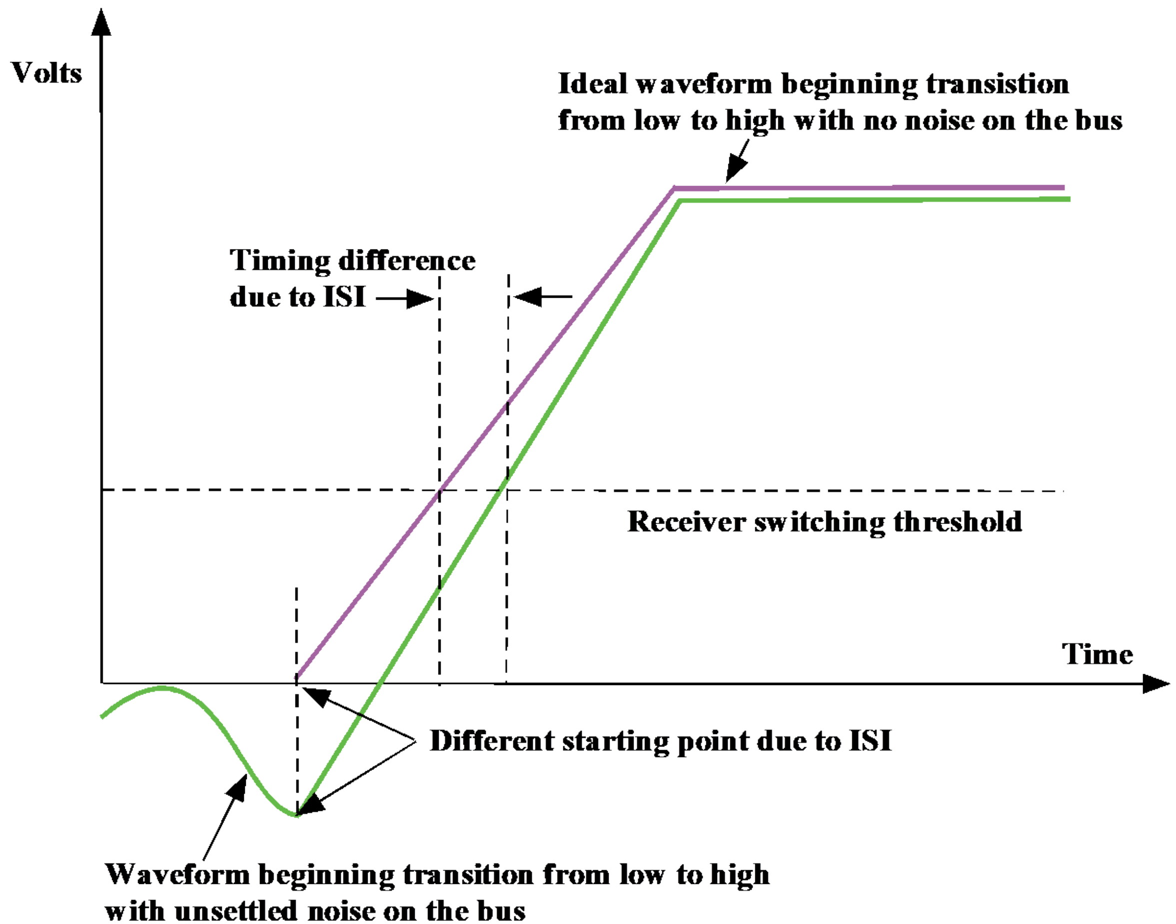
Multiconductor Simulation



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



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

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

- **Timing uncertainties in digital transmission systems**
- **Utmost importance because timing uncertainties cause bit errors**
- **There are different types of jitter**

Jitter Characteristics

- 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)

Types of Jitter

- Deterministic Jitter (DDJ)
  - Data-Dependent Jitter (DDJ)
  - Periodic Jitter (PJ)
  - Bounded Uncorrelated Jitter (BUJ)

- Random Jitter (RJ)
  - Gaussian Jitter
  - $f^{-\alpha}$ Higher-Order Jitter

Jitter Effects

Bandwidth Limitations

- Cause intersymbol interference (ISI)
- ISI occurs if time required by signal to completely charge is longer than bit interval
- Amount of ISI is function of channel and data content of signal

Oscillator Phase Noise

- Present in reference clocks or high-speed clocks
- In PLL based clocks, phase noise can be amplified

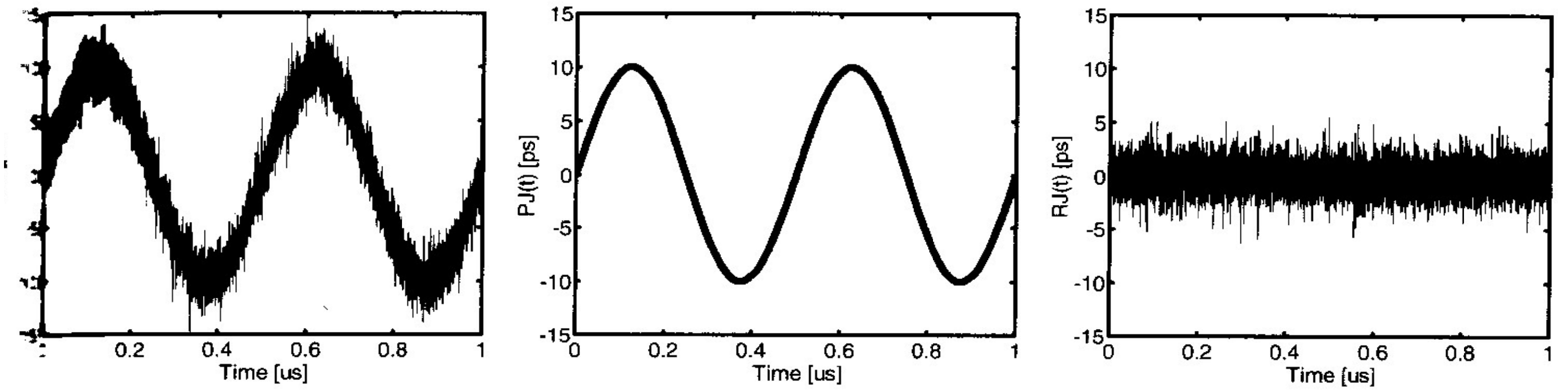
Jitter Statistics

- Most common way to look at jitter is in statistical domain
- Because one can observe jitter histograms directly on oscilloscopes
- No instruments to measure jitter time waveform or frequency spectrum directly

Jitter Histograms and Probability Density Functions (PDF)

- Built directly from time waveforms
- Frequency information is lost
- Peak-to-peak value depends on observation time

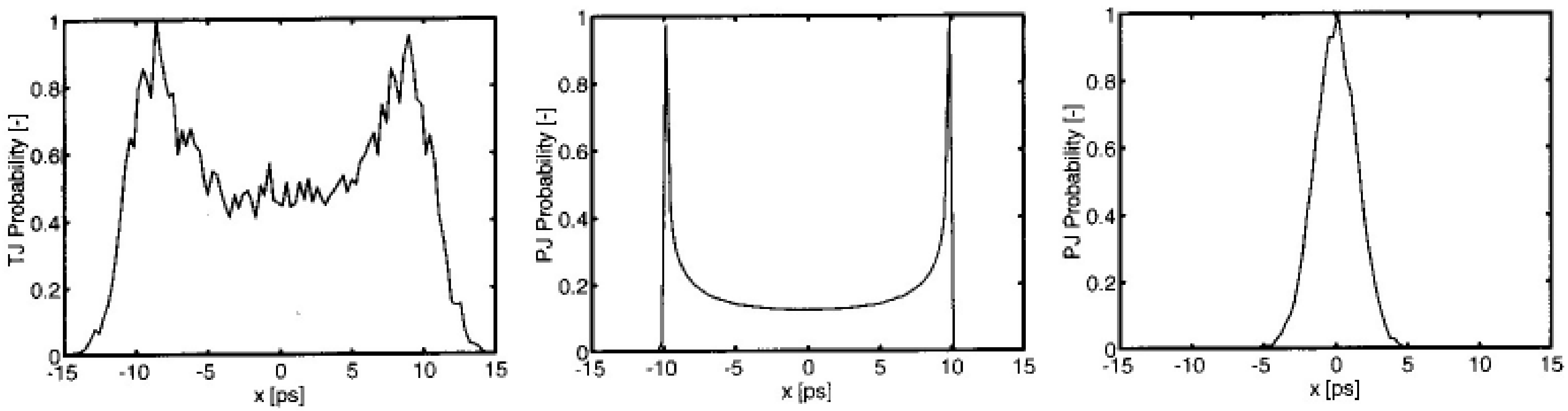
Total Jitter Time Waveform



$$TJ(t) = PJ(t) + RJ(t)$$

The total jitter waveform is the sum of individual components

Jitter Statistics

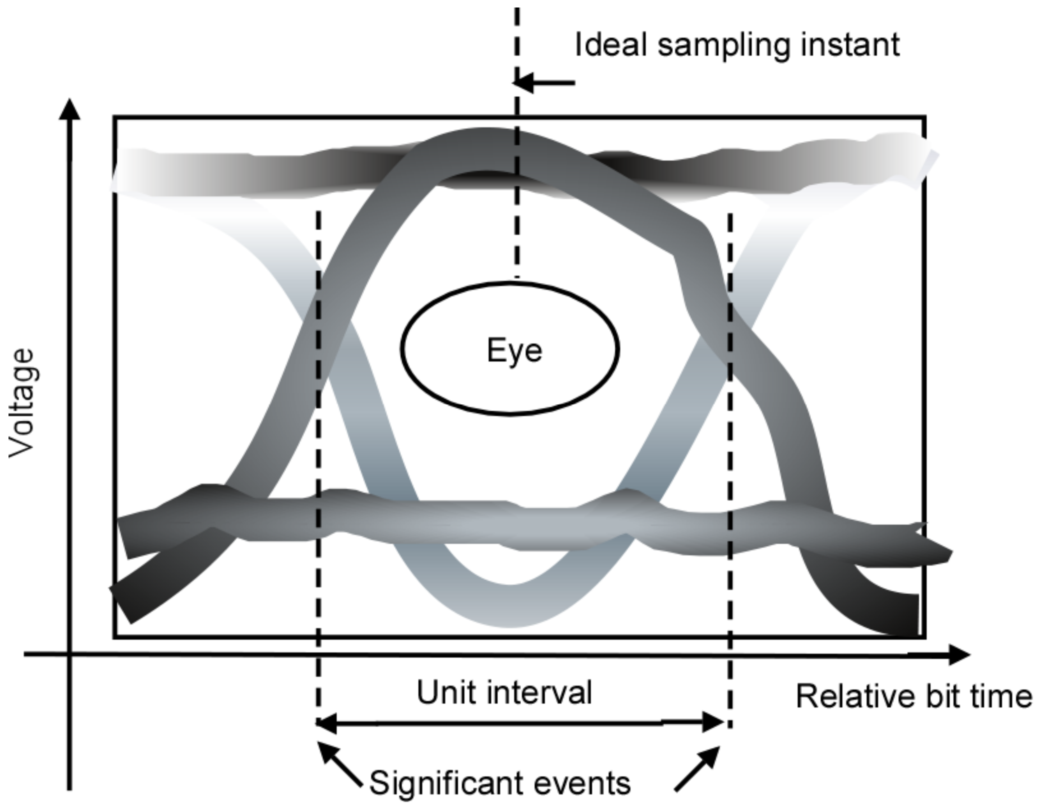


$$TJ(x) = PJ(x) * RJ(x)$$

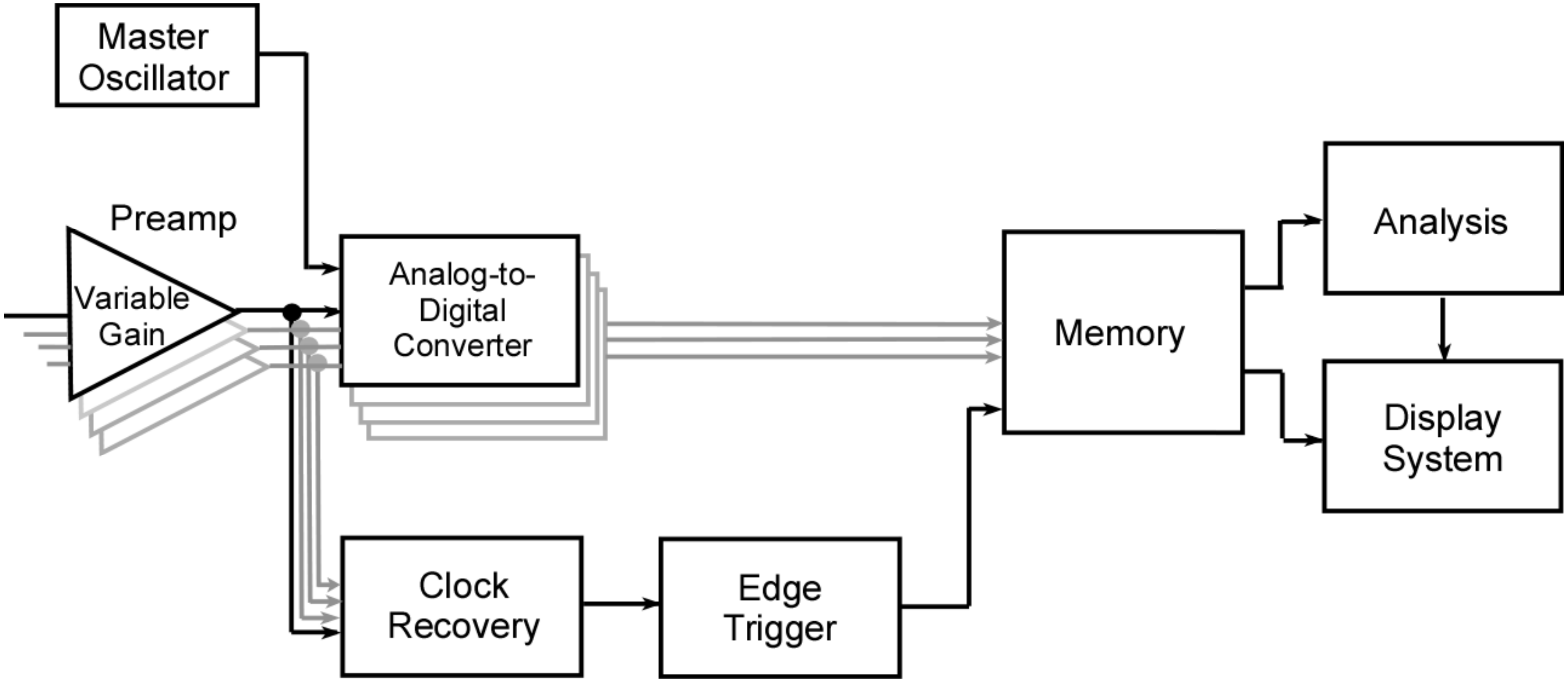
The total jitter PDF is the convolution of individual components

Eye Diagram

An eye diagram is a time-folded representation of a signal that carries digital information

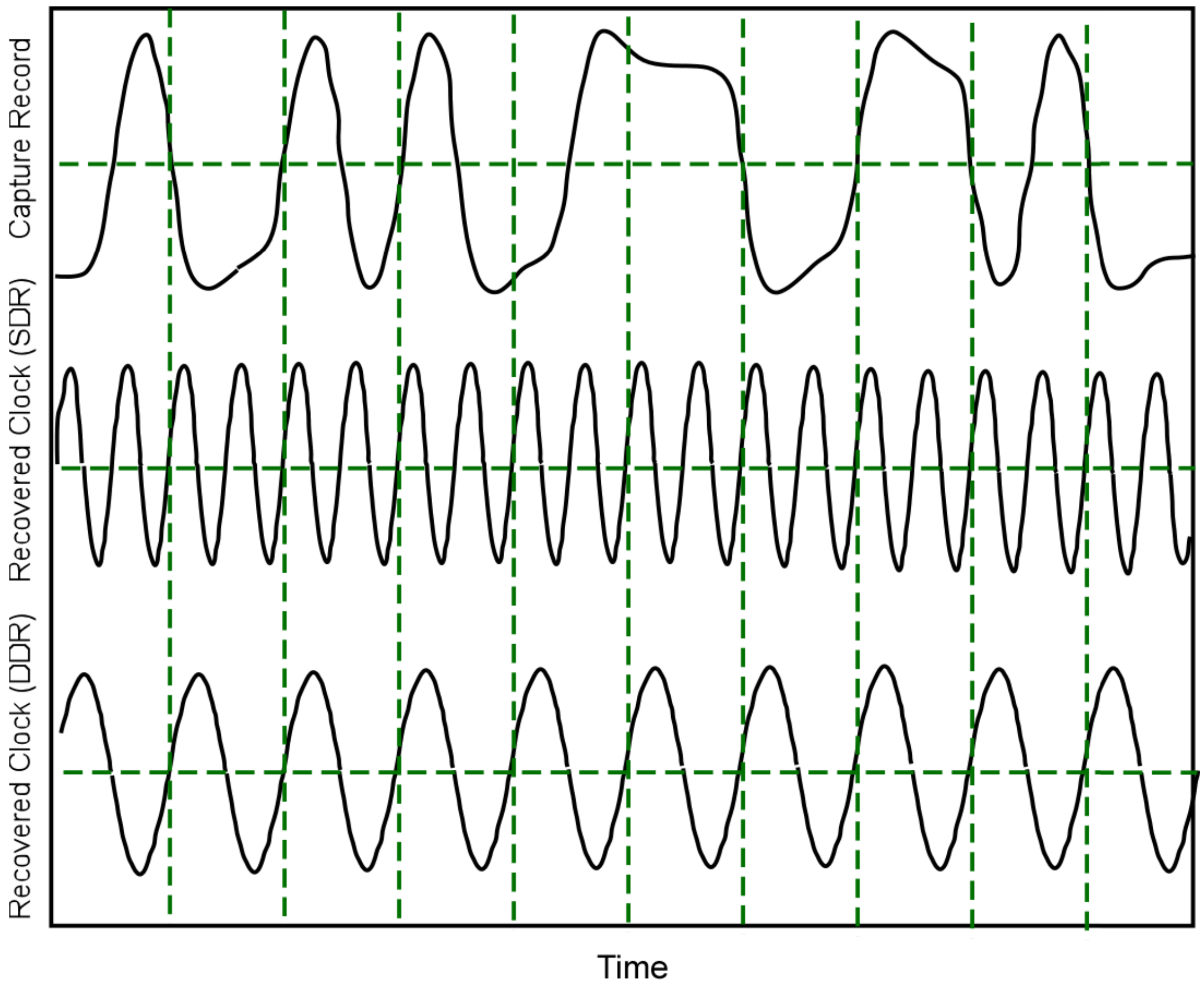


Eye Diagram Construction

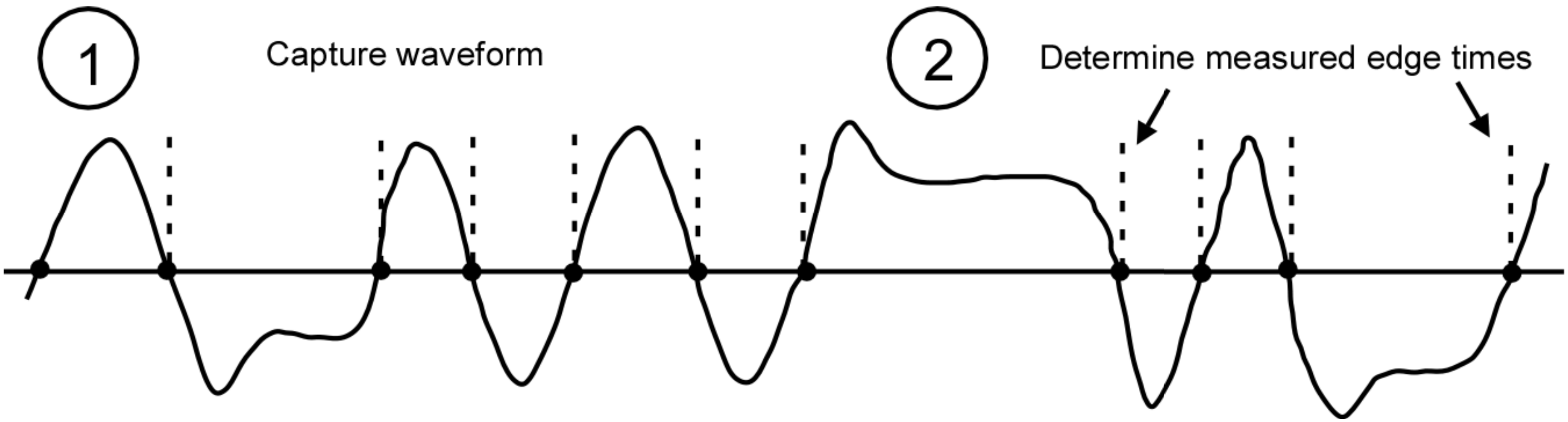


Eye diagram construction in real-time oscilloscope is based on hardware clock recovery and trigger circuitry

Eye Diagram Construction



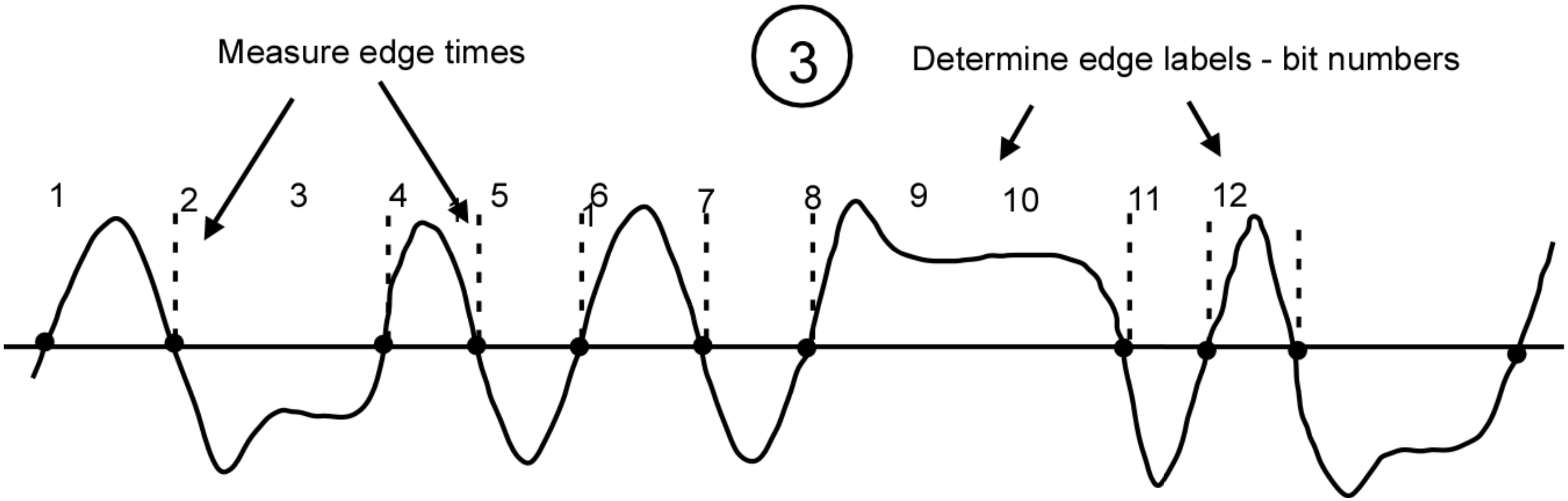
Eye Diagram Construction



1. Capture of the Waveform Record

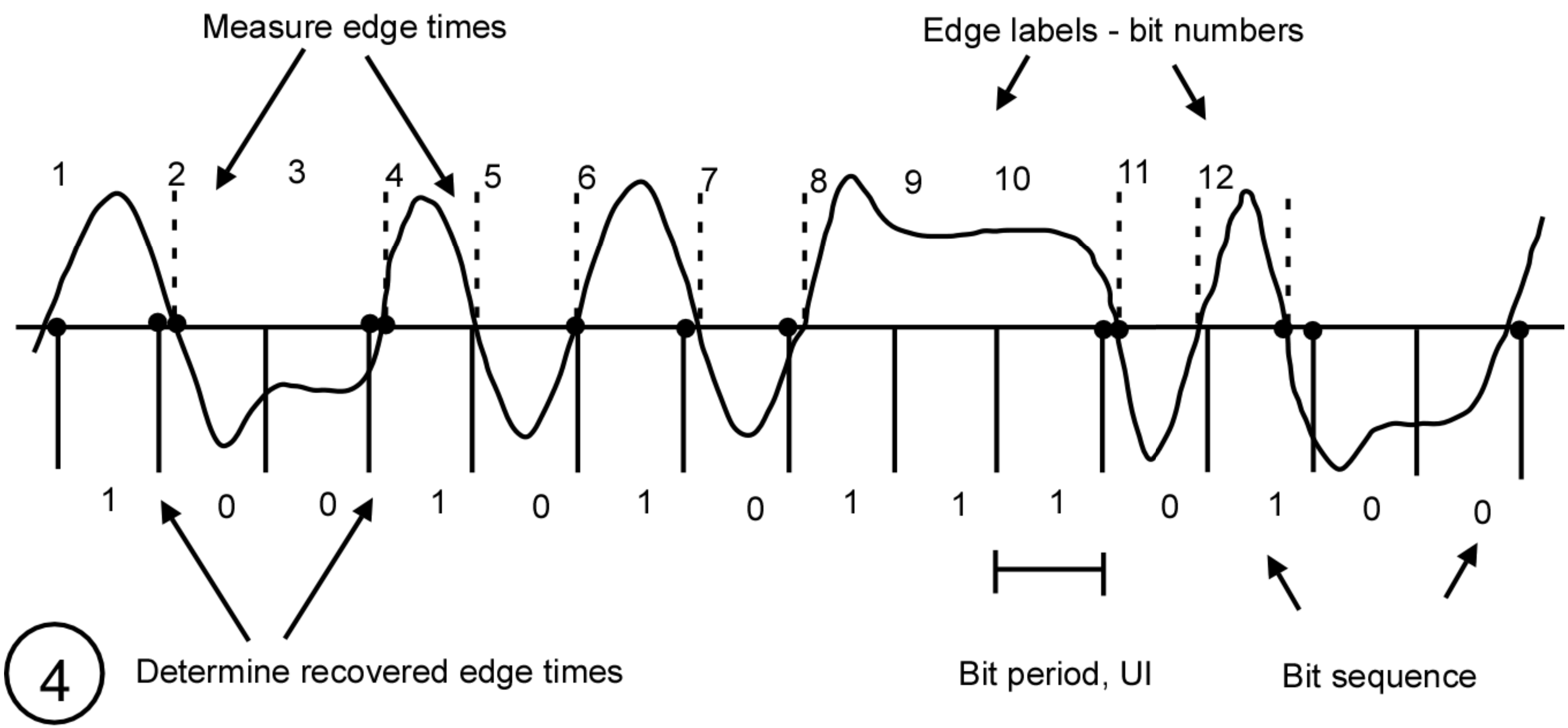
2. Determine the Edge Times

Eye Diagram Construction



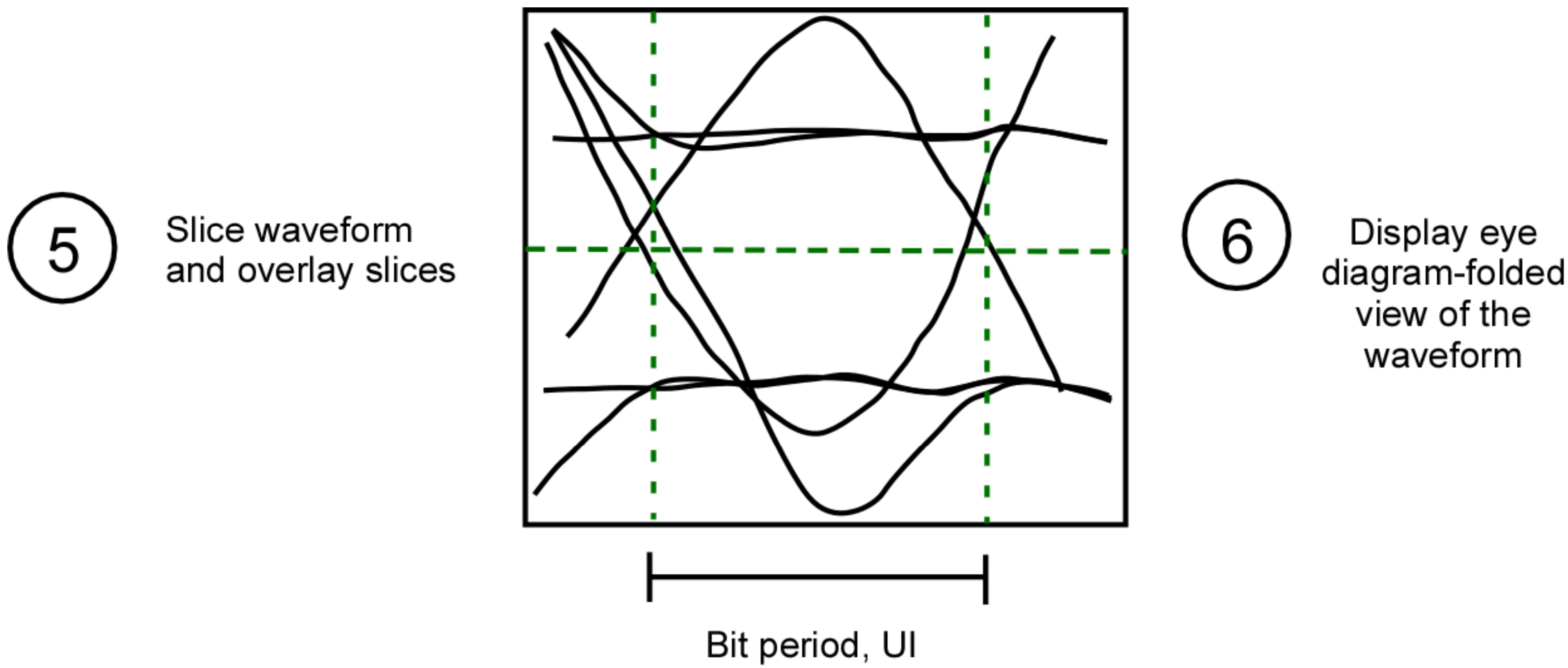
3. Determine the Bit Labels

Eye Diagram Construction



4. Clock Recovery

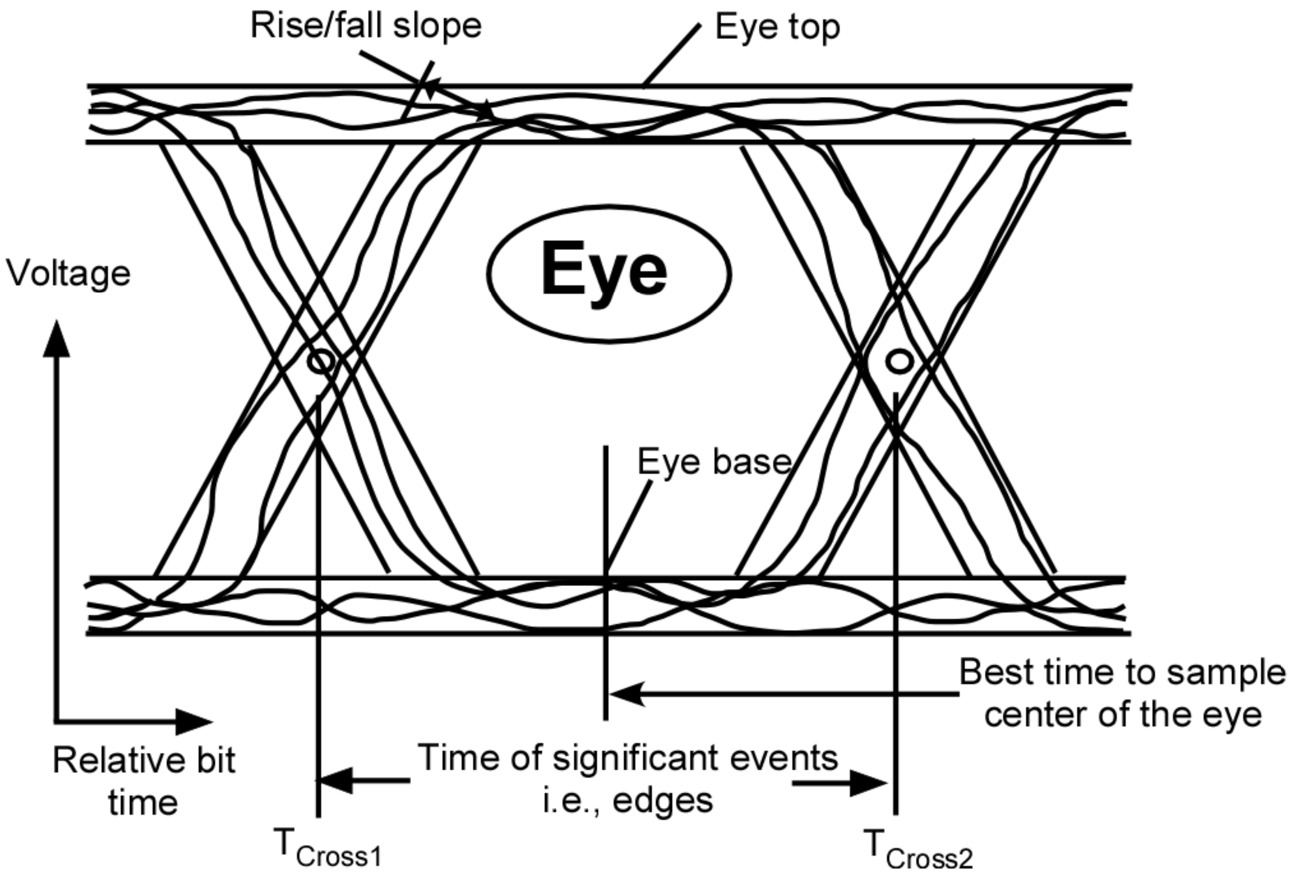
Eye Diagram Construction



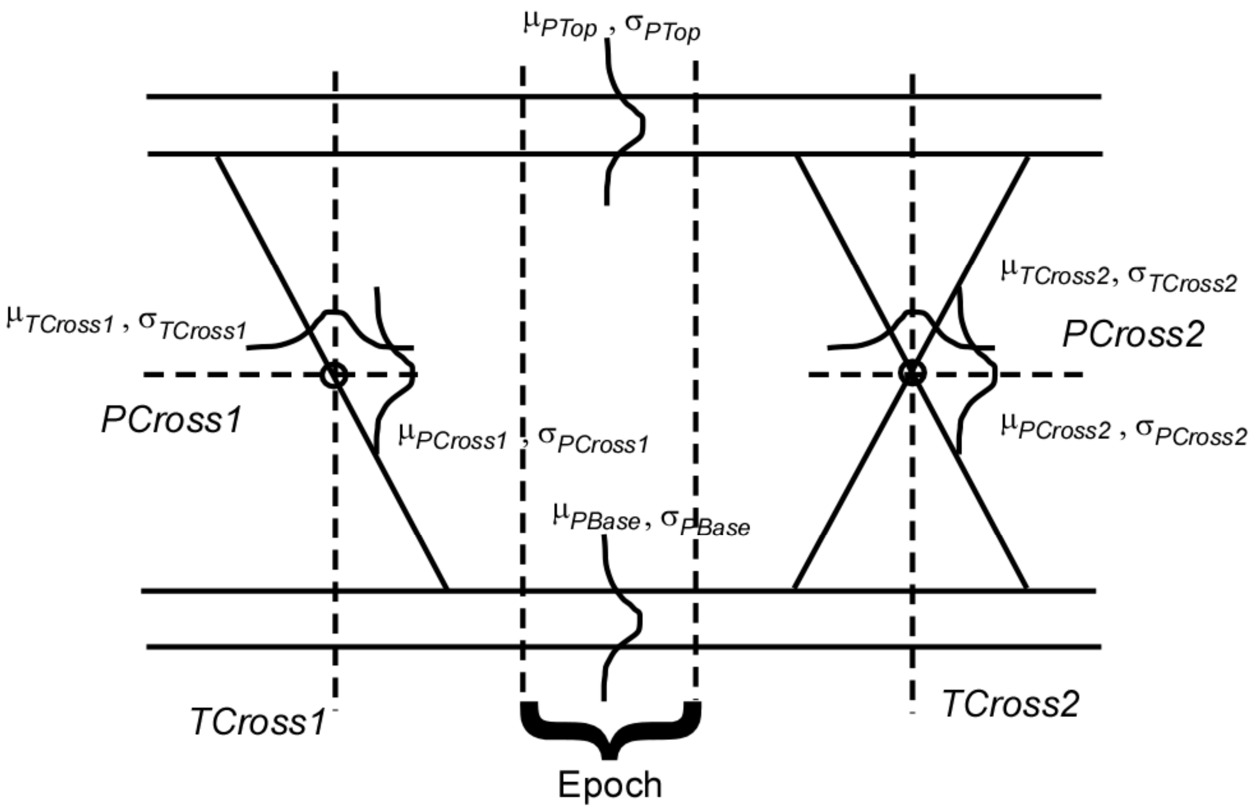
5. Slice Overlay

6. Display

Eye Diagram Measurements



Reference Levels



Eye Height

Eye Height is the measuremnt of the eye height in volts

$$Eye\ Height = \left(\mu_{PTop} - 3\sigma_{PTop}\right) - \left(\mu_{PBase} + 3\sigma_{PBase}\right)$$

μ_{PTop} : mean value of eye top

σ_{PTop} : standard deviation of eye top

μ_{PBase} : mean value of eye base

σ_{PBase} : standard deviation of eye base

Eye Width

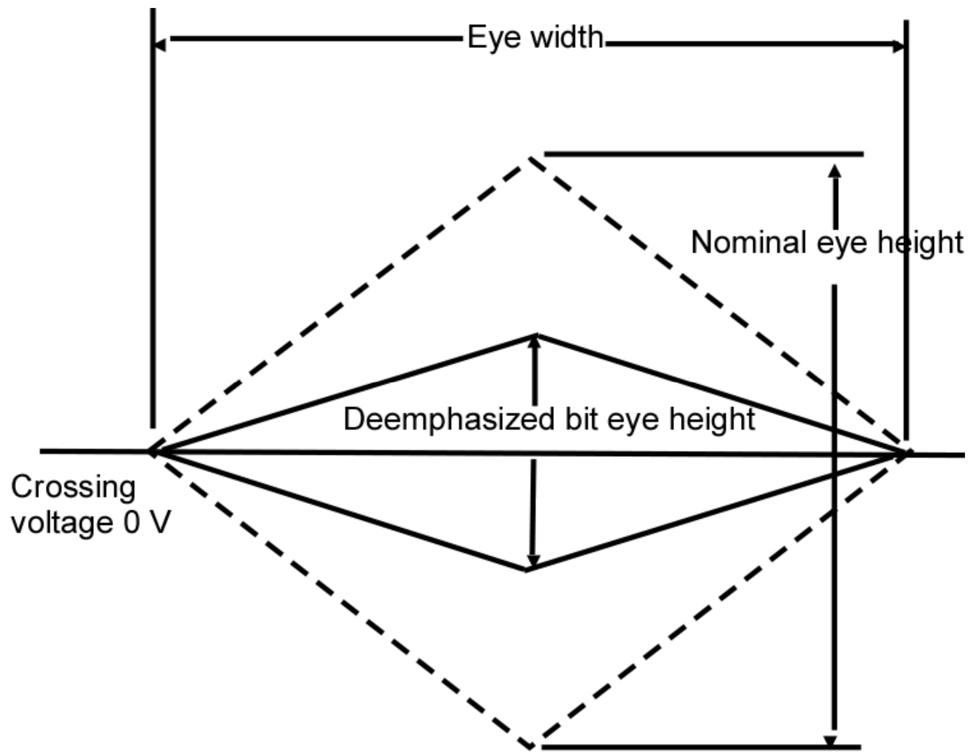
Eye Width **is the measuremnt of the eye width in seconds**

$$Eye\,Width = \left(\mu_{TCross\,2} - 3\sigma_{TCross\,2}\right) - \left(\mu_{TCross\,1} + 3\sigma_{TCross\,1}\right)$$

Crossing percent **measurement is the eye crossing point expressed as a percentage of the eye height**

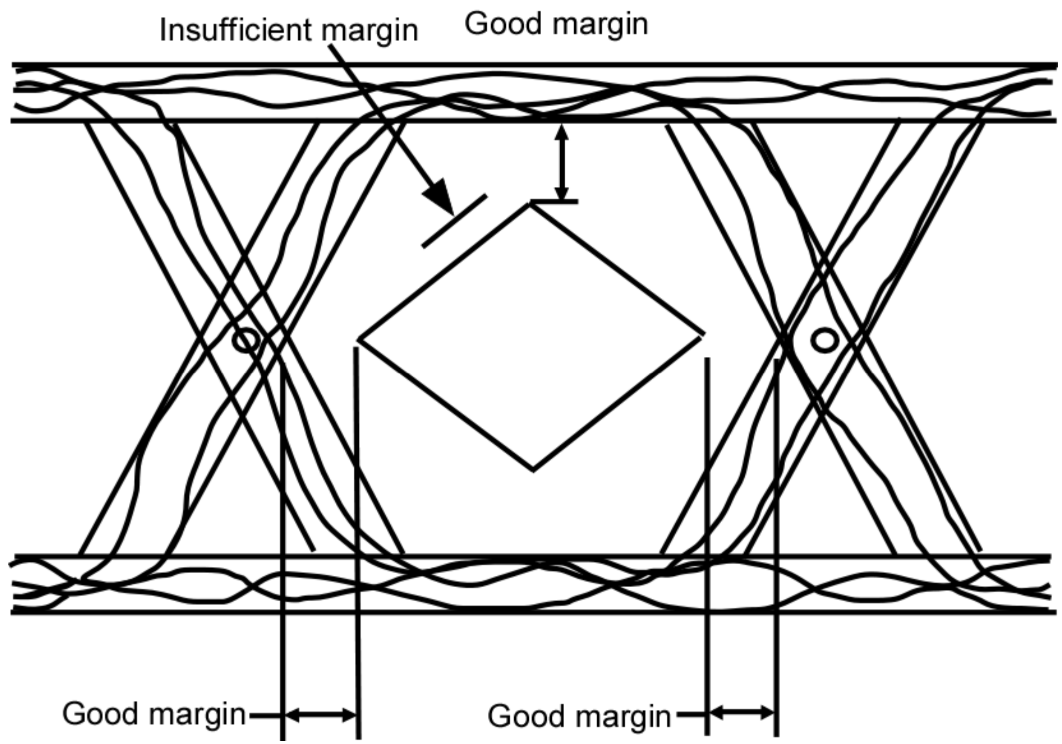
$$\text{Crossing Percent} = \frac{\left(\mu_{PCross\,1} - \mu_{PBase}\right)}{\left(\mu_{PTop} - \mu_{PBase}\right)} \times 100\%$$

Eye Diagram Specifications



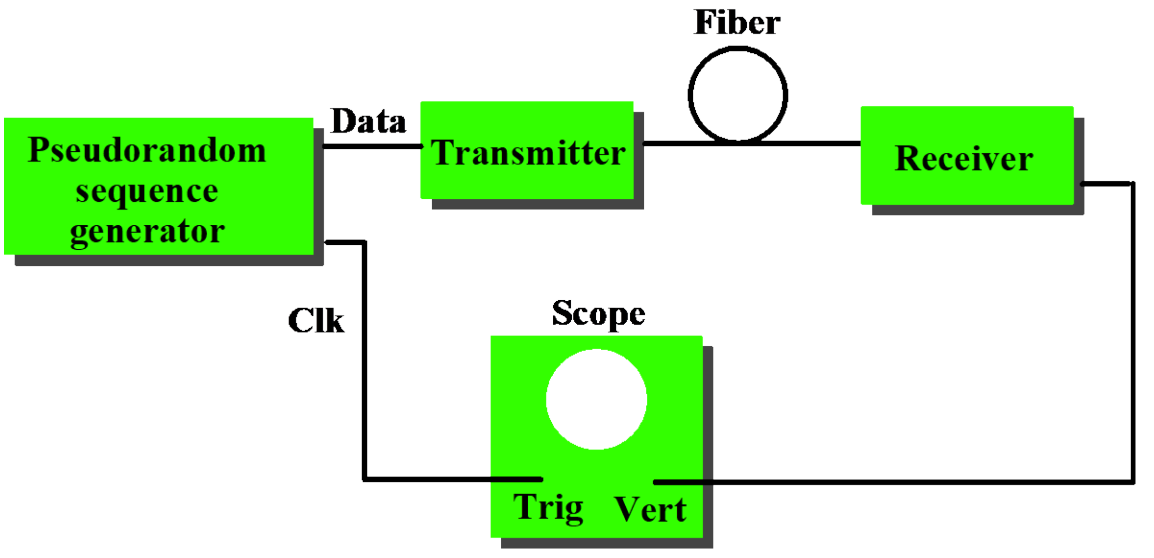
PCI Express 2.0 eye diagram specification for full and deemphasized signals

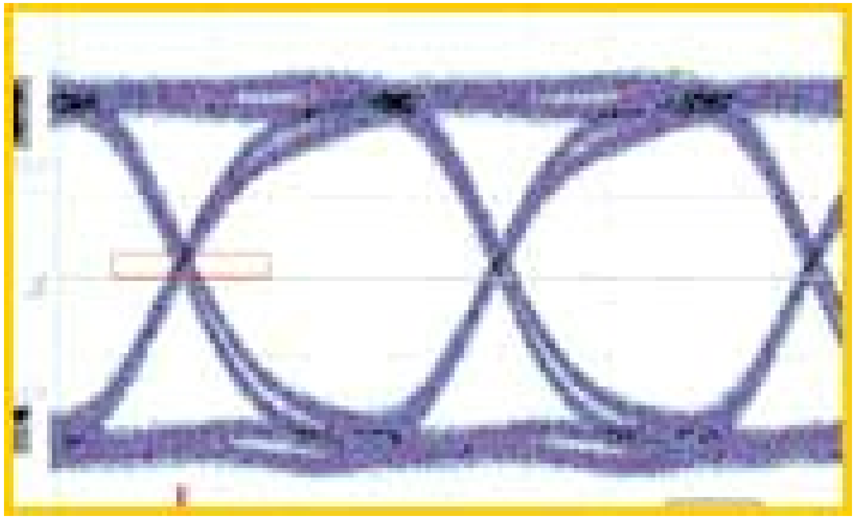
Margin Testing



Eye diagram with low margin

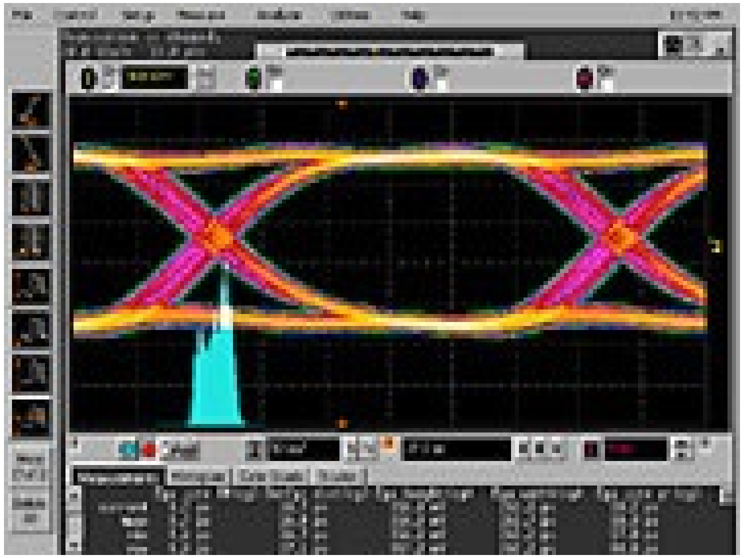
Eye Pattern Analysis

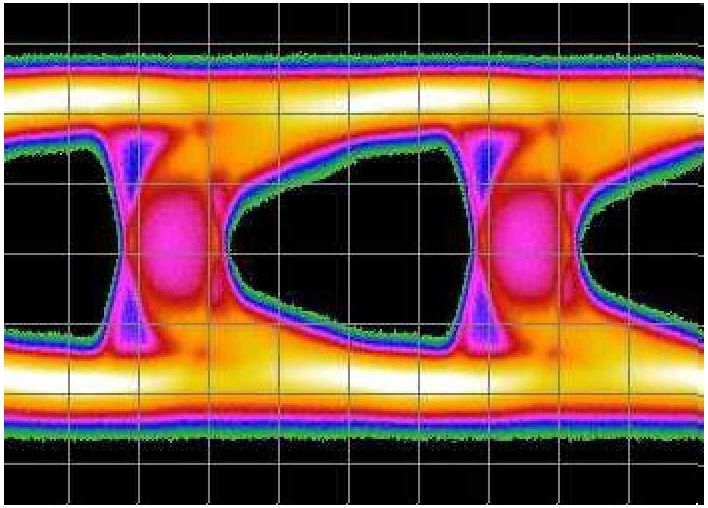




Eye Diagram

Typical Eye Diagrams





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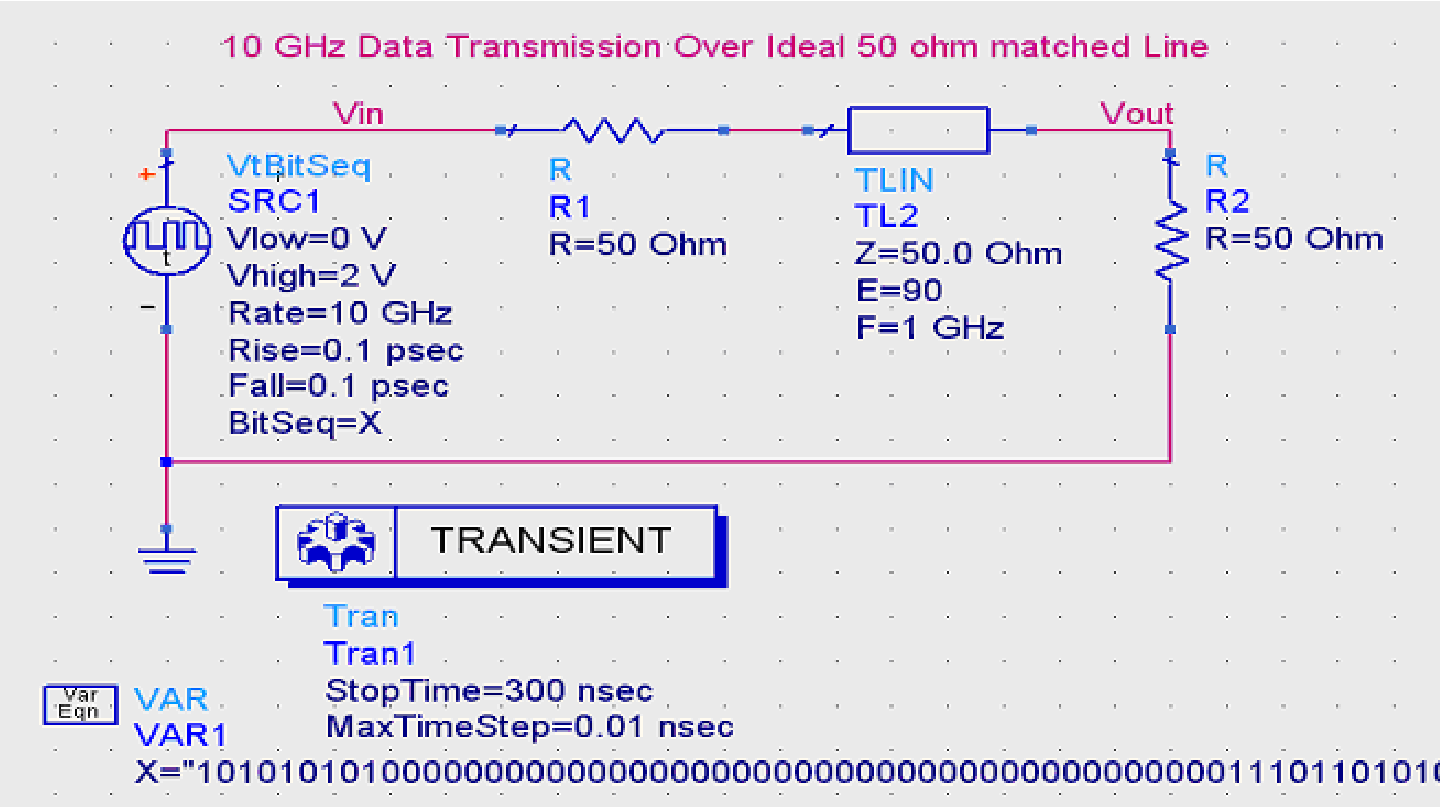
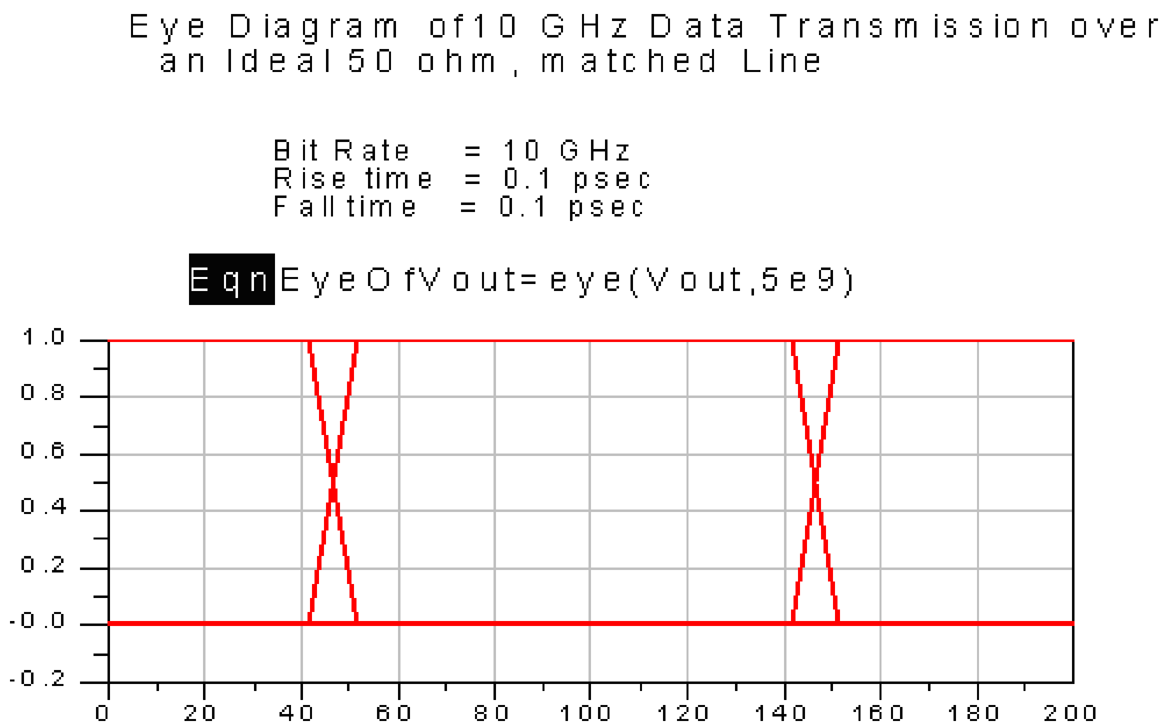
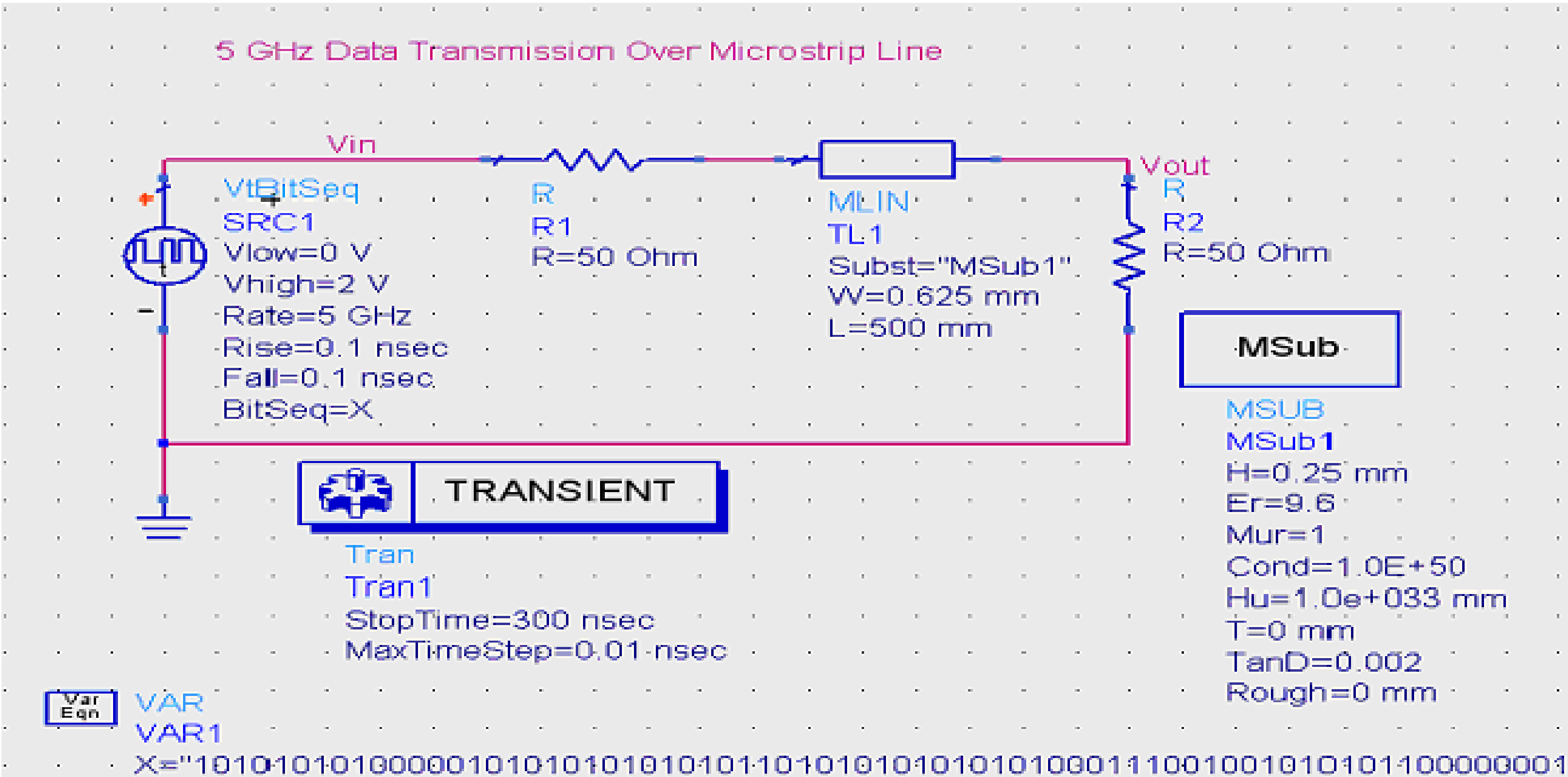
Eye Diagram - ADS Simulation



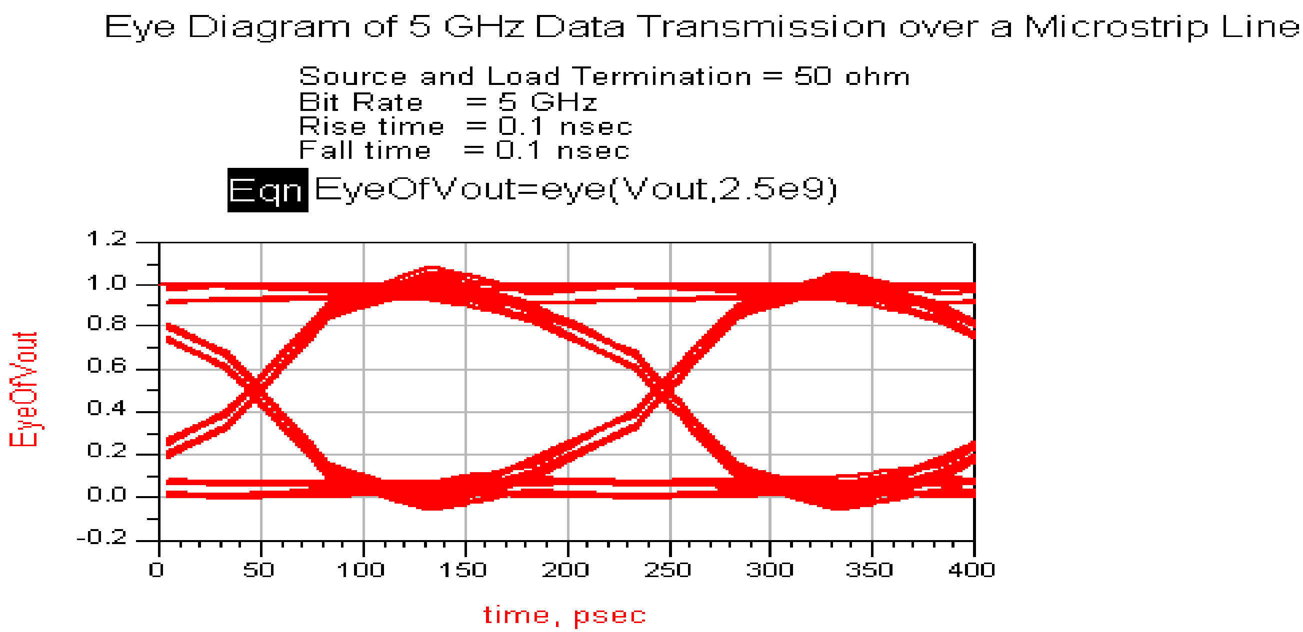
Eye Diagram - ADS Simulation
Ideal Matched Line



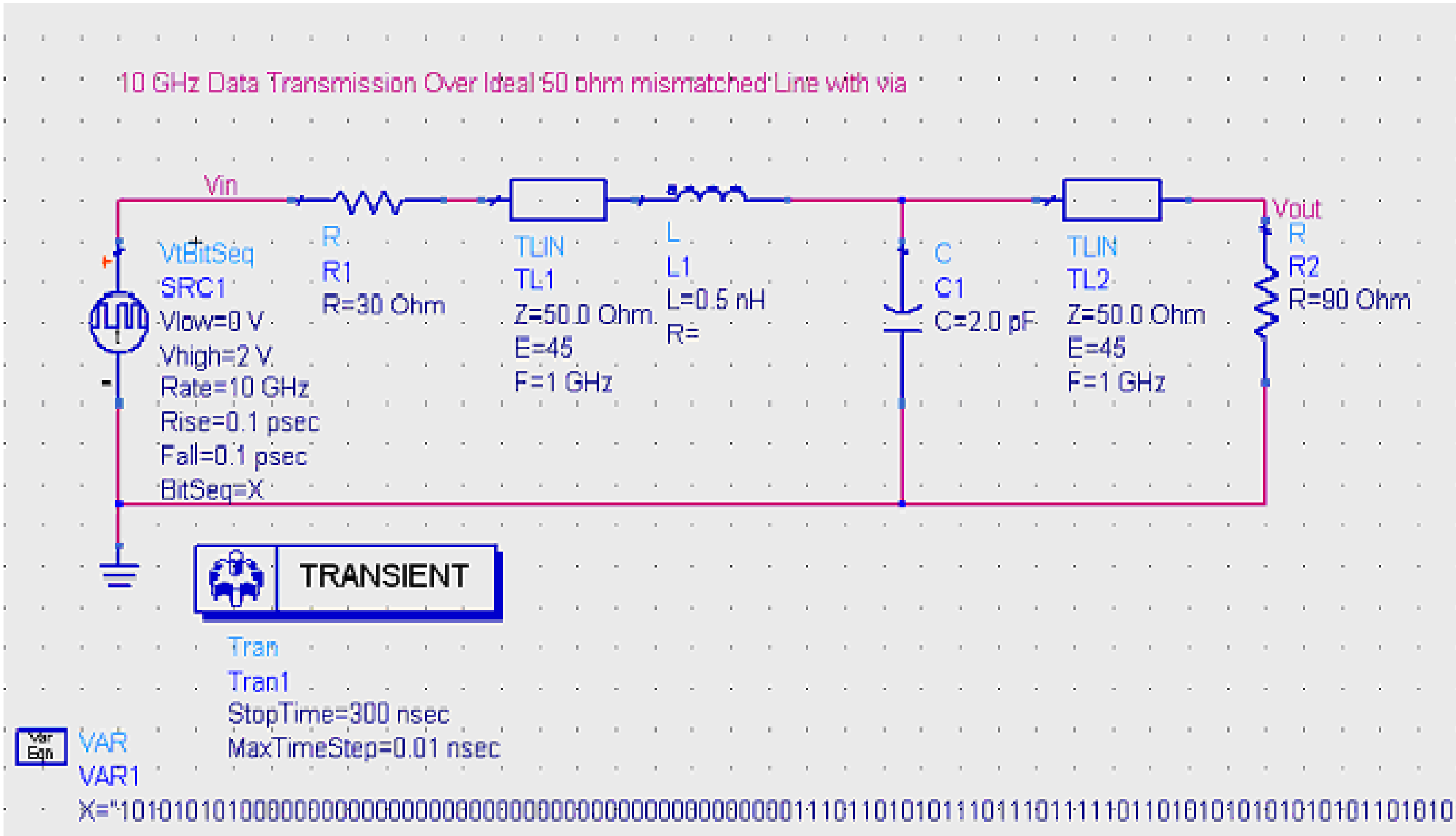
Eye Diagram - ADS Simulation
5 GHz Data Transmission



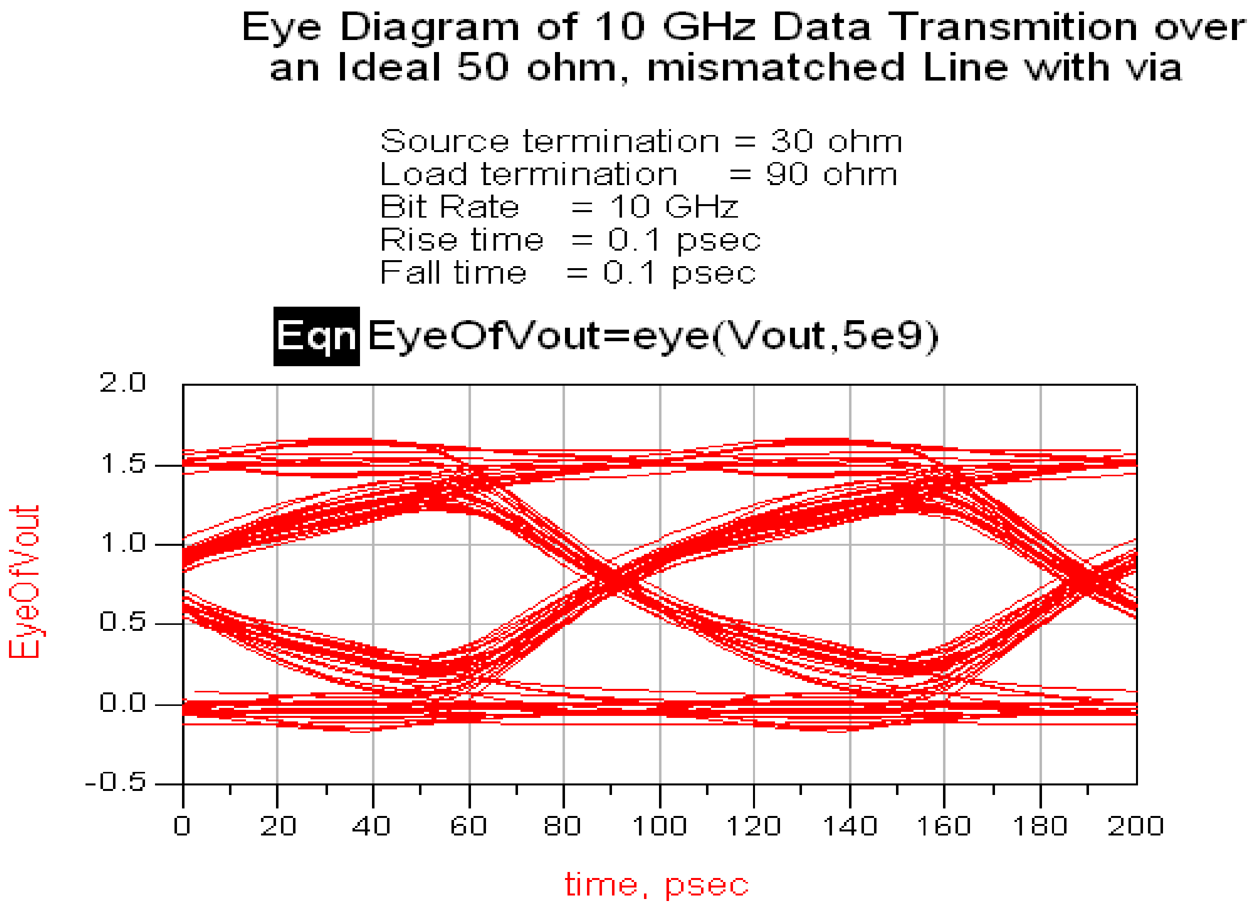
Eye Diagram - ADS Simulation
5 GHz Data Transmission



Eye Diagram - ADS Simulation
10 GHz Data Transmission



Eye Diagram - ADS Simulation



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-induced degradation on the received signal

- No higher than a 10^{-16} BER is tolerable → no more than 1 error out of 10^{16} 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