Novel Crosstalk mitigation solutions for high-speed interconnects to maximize bus band-width and density

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by
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Agenda

- Problem/Goal of this research
- Motivation: Effects of cross-talk
- Decoupling of a Multi-conductor Transmission Lines
- Modal decomposition
- Modal composition
- Crosstalk Harnessed Signaling
- Measurement Validation
- Summary
- References

Problem: As form factors shrink (i.e., tablets), increased routing density in motherboards & packages induce crosstalk noise that prevents bus performance from scaling with Moore's Law.

- Historical techniques to scale bus performance become problematic due to power, density & cost

Research Goal: Remove the crosstalk roadblock, allowing very dense routing on packages & PCBs so maximum computational performance can be designed into the smallest possible volume

- Increase max bus BW per unit Vol
- Find a viable alternative to traditional binary signaling to make tradeoffs between bandwidth, density and power

The focus of this research is to increase platform bus BW/Vol especially for small form factor high performance systems

Fundamental I/O limiting factors

Moore's law is the observation that over the history of computing hardware, the number of transistors on integrated circuits doubles approximately every two years.

Fundamental signaling BW/Vol limiting factors that that prevents bus performance from scaling with Moore's Law are:

- Losses (function of material properties)
- Cross talk (electric and magnetic field intensity coupling)
- Reflections (Impedance mismatch)
- ISI etc.

Crosstalk is the limiting factor that impacts both the data rate (how fast the bus can run) and density of the channel (how dense the channel can be laid out)

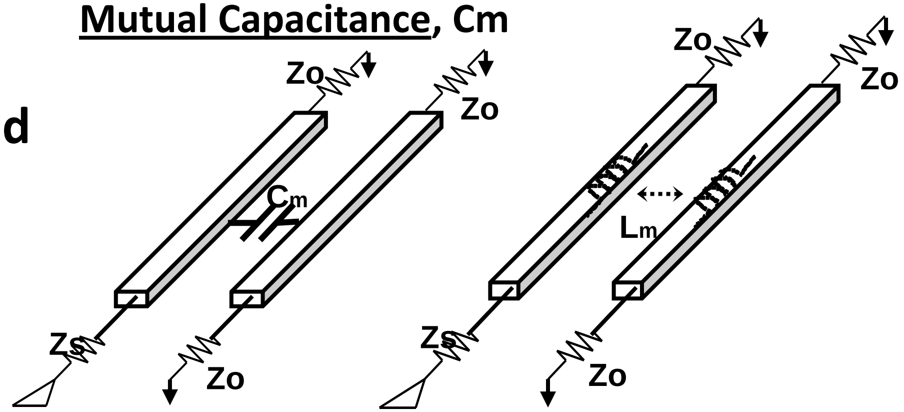
What is Crosstalk

Crosstalk: is an unwanted coupling of energy from one line to another via:

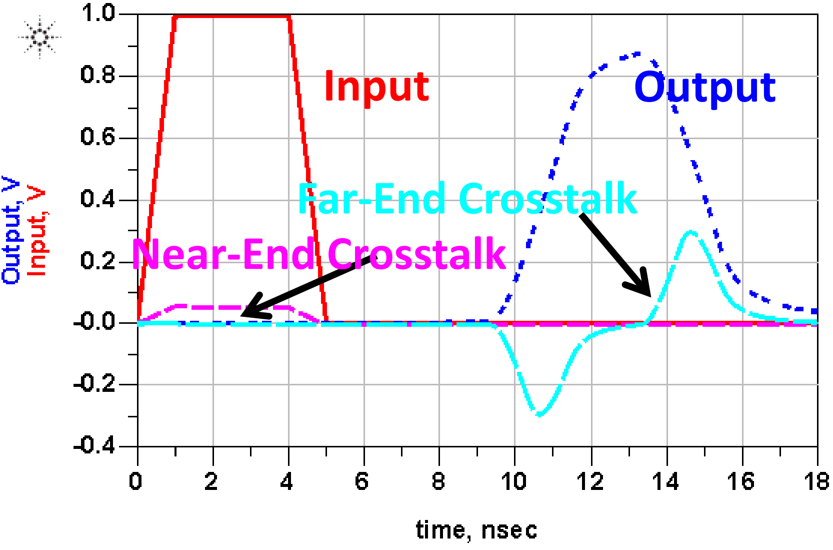
- **Mutual capacitance (electric field Intensity)**
- **Mutual inductance (magnetic field Intensity)**

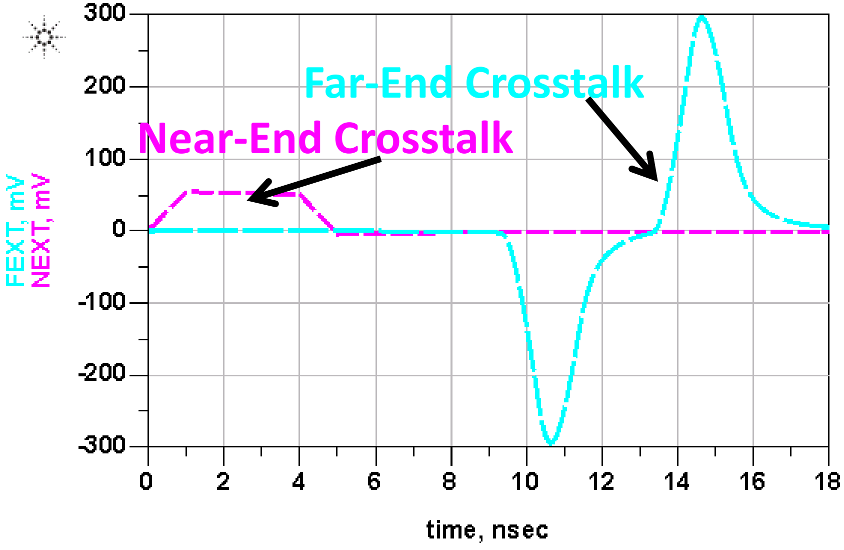
Both mutual capacitance and inductance are a function of transmission line layout/physical geometry, material characteristics, and frequency of operation.

Mutual Capacitance, Cm



Mutual Inductance, Lm

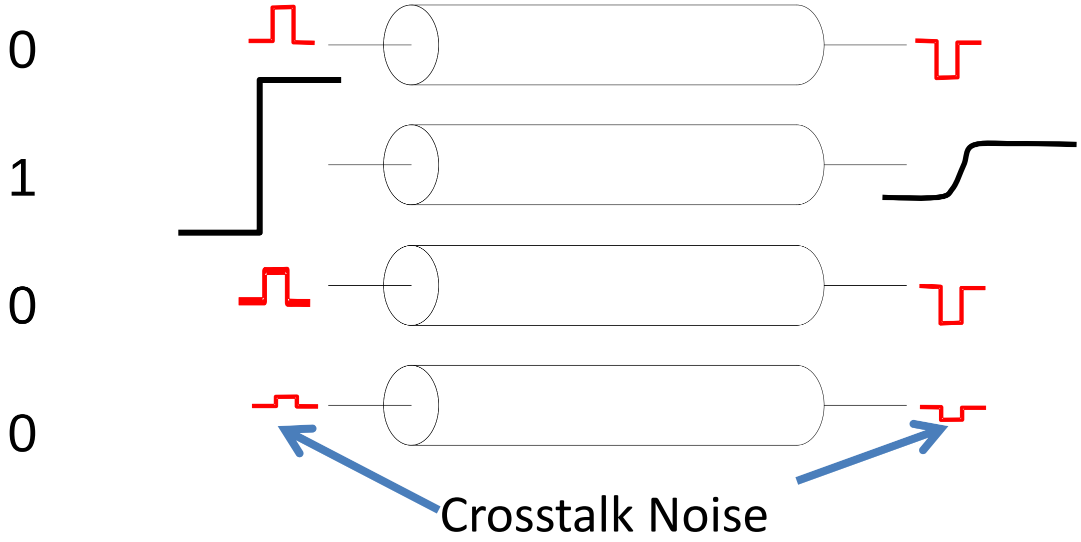




Binary Signaling and Crosstalk

Binary signaling: Buses send data in discrete voltage pulses where each transmission line carries 1 bit.

Crosstalk is a limiter of bus performance → Energy "leaks" between signals, increasing the noise & reducing BW

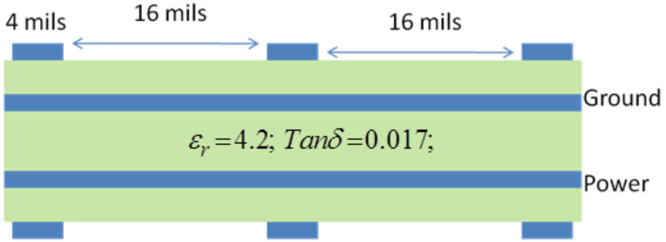


Conventional Methods to mitigate crosstalk noise are expensive

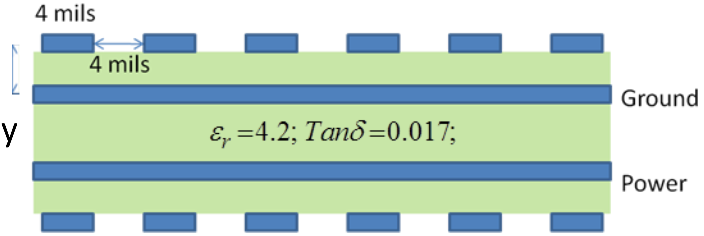
- More space to spread out signals → increased board cost
- Add ground shield traces → reduces density
- Crosstalk equalization → Power hungry
- Reducing the dielectric height → increased fabrication cost

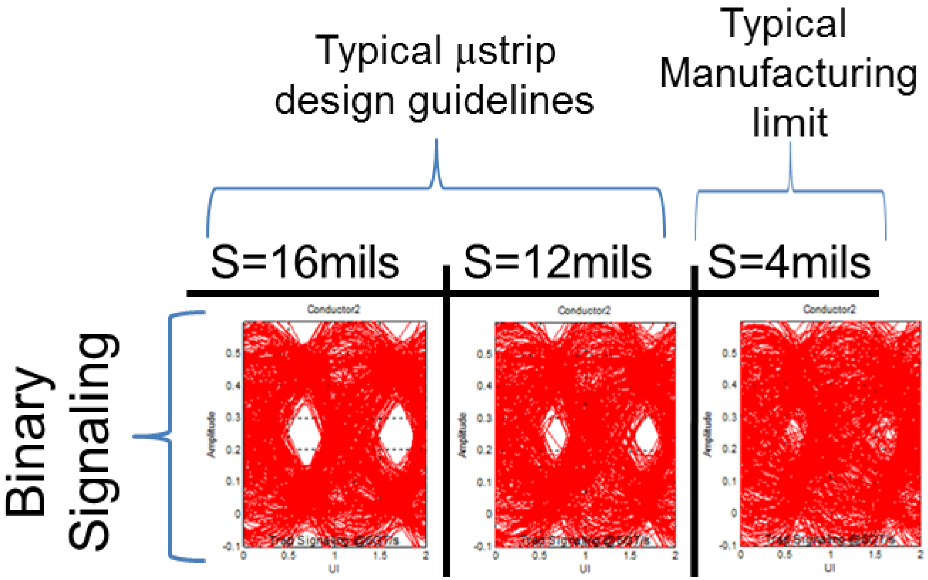
Motivation

Pitch 4-16-4
(Typical DDR type Density on PCB)



Pitch 4-4-4
(Maximum HVM density on PCB)

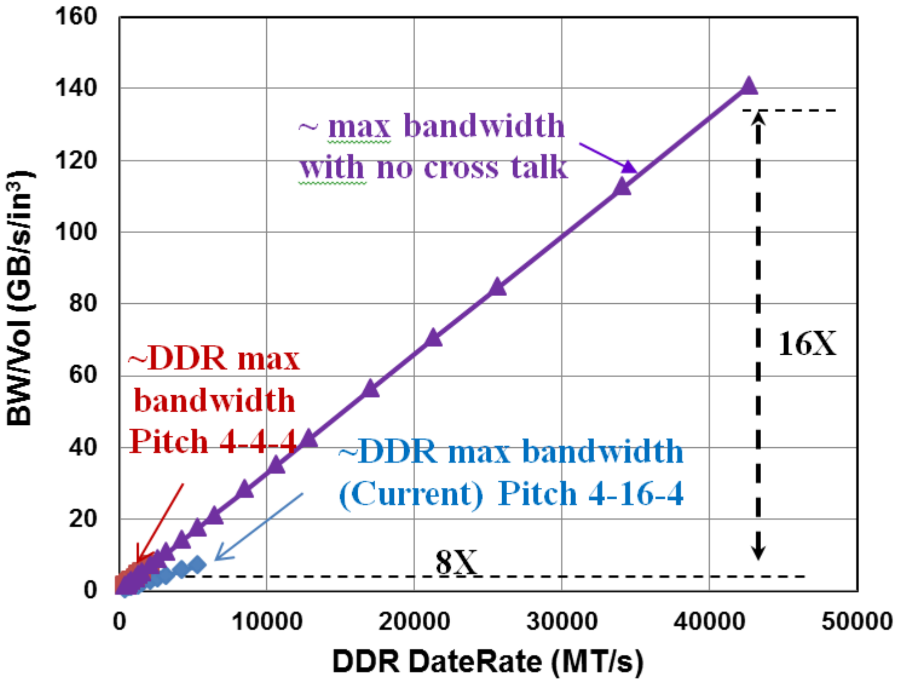



Typical µstrip design guidelines

Typical Manufacturing limit

S=16mils | S=12mils | S=4mils

Binary Signaling



- **Mitigating Cross talk has a theoretical potential to increase memory bus BW/Vol by ~16X with no crosstalk for dense routing over conventional routing methods**
- **Paves the way to explore some novel layout structures that can maximize the channel BW/Vol further**

Initial Approach

<u>Idea:</u> Modal signaling to use the inherent coupled energy to our benefit

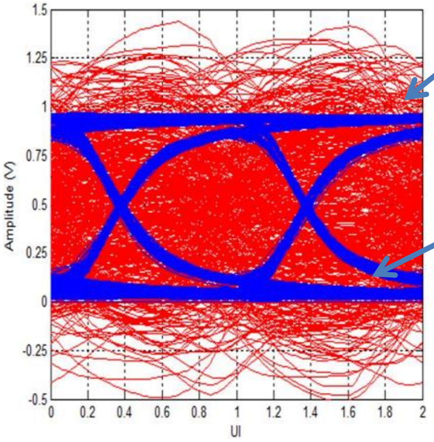
<u>Concept:</u> Eigen modes are independent (i.e., they do not interact with each other)

- i.e., A 64 bit channel would have 64 *uncoupled* Eigen modes

<u>We partially take advantage of this today:</u>

- Differential signaling, which uses 2-conductor to transmit data only in one mode (the odd mode), takes advantage of this principle to minimize cross-talk within a pair.

<u>Theoretical advantage:</u>
Utilizing all propagation modes can dramatically increase signal density <u>and</u> max bus speed



Conventional signaling eye

Same structure with Modal signaling eye

Example: 4 t-lines, 15” long at minimum spacing (2 mils) @ 2 GT/s (1024 Bits)

Decoupling of Multi-conductor Transmission Lines (MTL)

Enables one to mathematically represent N coupled transmission lines as N decoupled or distinct propagating modes, each of which is a function of its coupled transmission line characteristics.

$$\frac{\partial}{\partial z}\mathbf{V}(z,t) = -\mathbf{R}\mathbf{I}(z,t) - \mathbf{L}\frac{\partial}{\partial t}\mathbf{I}(z,t)$$

$$\frac{\partial}{\partial z}\mathbf{I}(z,t) = -\mathbf{G}\mathbf{V}(z,t) - \mathbf{C}\frac{\partial}{\partial t}\mathbf{V}(z,t)$$

where, z is the transmission line length.

If a sinusoidal signal is assumed, then

$$\frac{\partial e^{j\omega t}}{\partial t} = j\omega e^{j\omega t}$$

Subsequently:

$$\frac{\partial}{\partial z}\hat{\mathbf{V}}(z) = -\hat{\mathbf{Z}}\hat{\mathbf{I}}(z)$$

$$\frac{\partial}{\partial z}\hat{\mathbf{I}}(z) = -\hat{\mathbf{Y}}\hat{\mathbf{V}}(z)$$

where,

$$\hat{\mathbf{Z}} = \mathbf{R} + j\omega\mathbf{L}$$

$$\hat{\mathbf{Y}} = \mathbf{G} + j\omega\mathbf{C}$$

Reference: Analysis of Multiconductor Lines book by Clayton Paul

Decoupling of MTL (cont.)

The coupled first-order equations can be represented as uncoupled second-order differential equations

Voltage equation:

$$\frac{\partial^2}{\partial z^2}\hat{\mathbf{V}}(z) = -\hat{\mathbf{Z}}\frac{\partial}{\partial z}\hat{\mathbf{I}}(z) = \hat{\mathbf{Z}}\hat{\mathbf{Y}}\hat{\mathbf{V}}(z)$$

Current Equation:

$$\frac{\partial^2}{\partial z^2}\hat{\mathbf{I}}(z) = -\hat{\mathbf{Y}}\frac{\partial}{\partial z}\hat{\mathbf{V}}(z) = \hat{\mathbf{Y}}\hat{\mathbf{Z}}\hat{\mathbf{I}}(z)$$

we can represent the product of $\hat{\mathbf{Z}}\hat{\mathbf{Y}}$ and $\hat{\mathbf{Y}}\hat{\mathbf{Z}}$ in terms of its eigenvalues and eigenvectors using matrix diagonalization or matrix decomposition or Eigen decomposition

$$\hat{\mathbf{Z}}\hat{\mathbf{Y}} = \hat{\mathbf{T}}_{\mathbf{V}}{}^{-1}[\hat{\boldsymbol{\gamma}}_{\mathbf{m}}{}^{2}]\hat{\mathbf{T}}_{\mathbf{V}}$$

$$\hat{\mathbf{Y}}\hat{\mathbf{Z}} = \hat{\mathbf{T}}_{\mathbf{I}}{}^{-1}[\hat{\boldsymbol{\gamma}}_{\mathbf{m}}{}^{2}]\hat{\mathbf{T}}_{\mathbf{I}}$$

where,

$$\hat{\mathbf{T}}_{\mathbf{V}} = Eigenvector\left(\hat{\mathbf{Z}}\hat{\mathbf{Y}}\right)$$

$$\hat{\mathbf{T}}_{\mathbf{I}} = Eigenvector\left(\hat{\mathbf{Y}}\hat{\mathbf{Z}}\right)$$

$$\hat{\boldsymbol{\gamma}}_{\mathbf{m}}{}^{2} = Eigenvalue\left(\hat{\mathbf{Y}}\hat{\mathbf{Z}}\right) = Eigenvalue\left(\hat{\mathbf{Z}}\hat{\mathbf{Y}}\right)$$

Decoupling of MTL (cont.)

To solve equations as uncoupled second-order differential equations, we can use the transformations to transform the line voltages and currents into modal quantities

$$\hat{\mathbf{V}}(z) = \hat{\mathbf{T}}_{\mathbf{V}} \hat{\mathbf{V}}_{\mathbf{m}} \qquad \hat{\mathbf{I}}(z) = \hat{\mathbf{T}}_{\mathbf{I}} \hat{\mathbf{I}}_{\mathbf{m}}$$

Such that the left-hand double derivative term will be equal to a diagonal matrix times itself.

$$\frac{d^2}{dz^2}\left(\hat{\mathbf{T}}_{\mathbf{V}} \hat{\mathbf{V}}_{\mathbf{m}}\right) = \hat{\mathbf{T}}_{\mathbf{V}} \hat{\boldsymbol{\gamma}}_{\mathbf{m}}{}^2 \hat{\mathbf{V}}_{\mathbf{m}} \Leftrightarrow \frac{d^2}{dz^2} \hat{\mathbf{V}}_{\mathbf{m}} = \hat{\mathbf{T}}_{\mathbf{V}}{}^{-1} \hat{\mathbf{T}}_{\mathbf{V}} \hat{\boldsymbol{\gamma}}_{\mathbf{m}}{}^2 \hat{\mathbf{V}}_{\mathbf{m}} = \hat{\boldsymbol{\gamma}}_{\mathbf{m}}{}^2 \hat{\mathbf{V}}_{\mathbf{m}}$$

$$\frac{d^2}{dz^2}\left(\hat{\mathbf{T}}_{\mathbf{I}} \hat{\mathbf{I}}_{\mathbf{m}}\right) = \hat{\mathbf{T}}_{\mathbf{I}} \hat{\boldsymbol{\gamma}}_{\mathbf{m}}{}^2 \hat{\mathbf{I}}_{\mathbf{m}} \Leftrightarrow \frac{d^2}{dz^2} \hat{\mathbf{I}}_{\mathbf{m}} = \hat{\mathbf{T}}_{\mathbf{I}}{}^{-1} \hat{\mathbf{T}}_{\mathbf{I}} \hat{\boldsymbol{\gamma}}_{\mathbf{m}}{}^2 \hat{\mathbf{I}}_{\mathbf{m}} = \hat{\boldsymbol{\gamma}}_{\mathbf{m}}{}^2 \hat{\mathbf{I}}_{\mathbf{m}}$$

This method of using the transformation matrix for solving the multiconductor transmission line equations is also widely known as a similarity transformation [4], [5]

Thus, the equations governing the voltage mode and current modes are decoupled and have the following simple solutions:

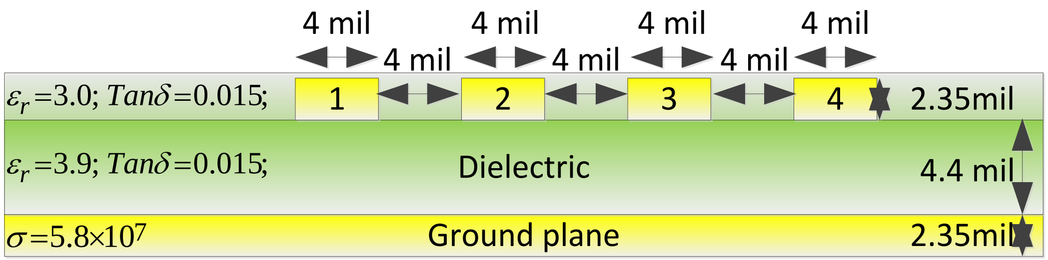
$$\hat{\mathbf{V}}_{\mathbf{m}}(z) = \mathbf{e}^{-\hat{\gamma}_{\mathbf{m}} z} \hat{\mathbf{V}}_{\mathbf{m}}^{+} + \mathbf{e}^{\hat{\gamma}_{\mathbf{m}} z} \hat{\mathbf{V}}_{\mathbf{m}}^{-}$$

$$\hat{\mathbf{I}}_{\mathbf{m}}(z) = \mathbf{e}^{-\hat{\gamma}_{m} z} \hat{\mathbf{I}}_{\mathbf{m}}^{+} - \mathbf{e}^{\hat{\gamma}_{\mathbf{m}} z} \hat{\mathbf{I}}_{\mathbf{m}}^{-}$$

Example

$$\hat{\gamma}_{\mathbf{m}} = 1\times10^{2} \begin{array}{cccc} \text{Mode 1} & \text{Mode 2} & \text{Mode 3} & \text{Mode 4} \\ \left[\begin{matrix} 0.0174 + 1.2341i & 0.0000 + 0.0000i & 0.0000 + 0.0000i & 0.0000 + 0.0000i \\ 0.0000 + 0.0000i & 0.0179 + 1.1449i & 0.0000 + 0.0000i & 0.0000 + 0.0000i \\ 0.0000 + 0.0000i & 0.0000 + 0.0000i & 0.0204 + 1.1141i & 0.0000 + 0.0000i \\ 0.0000 + 0.0000i & 0.0000 + 0.0000i & 0.0000 + 0.0000i & 0.0227 + 1.1069i \end{matrix}\right. & & & \left.\right] \end{array}$$

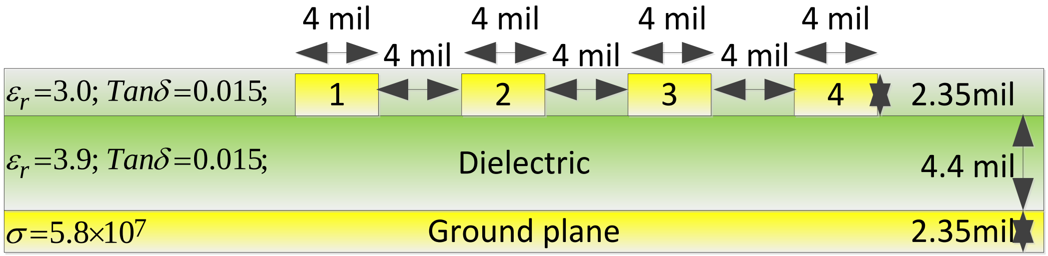
$$eig(\hat{\mathbf{Y}}\hat{\mathbf{Z}}) = \begin{array}{cccc} \text{Mode 1} & \text{Mode 2} & \text{Mode 3} & \text{Mode 4} \\ \left[\begin{matrix} 0.4637 - 0.0010i & -0.6465 - 0.0000i & 0.5038 + 0.0000i & 0.2553 + 0.0061i \\ 0.5339 + 0.0000i & -0.2861 - 0.0035i & -0.4975 + 0.0021i & -0.6582 - 0.0006i \\ 0.5338 + 0.0000i & 0.2859 + 0.0036i & -0.4960 + 0.0014i & 0.6600 + 0.0000i \\ 0.4637 - 0.0010i & 0.6468 + 0.0000i & 0.5026 + 0.0003i & -0.2568 - 0.0055i \end{matrix}\right. & & & \left.\right] \end{array}$$



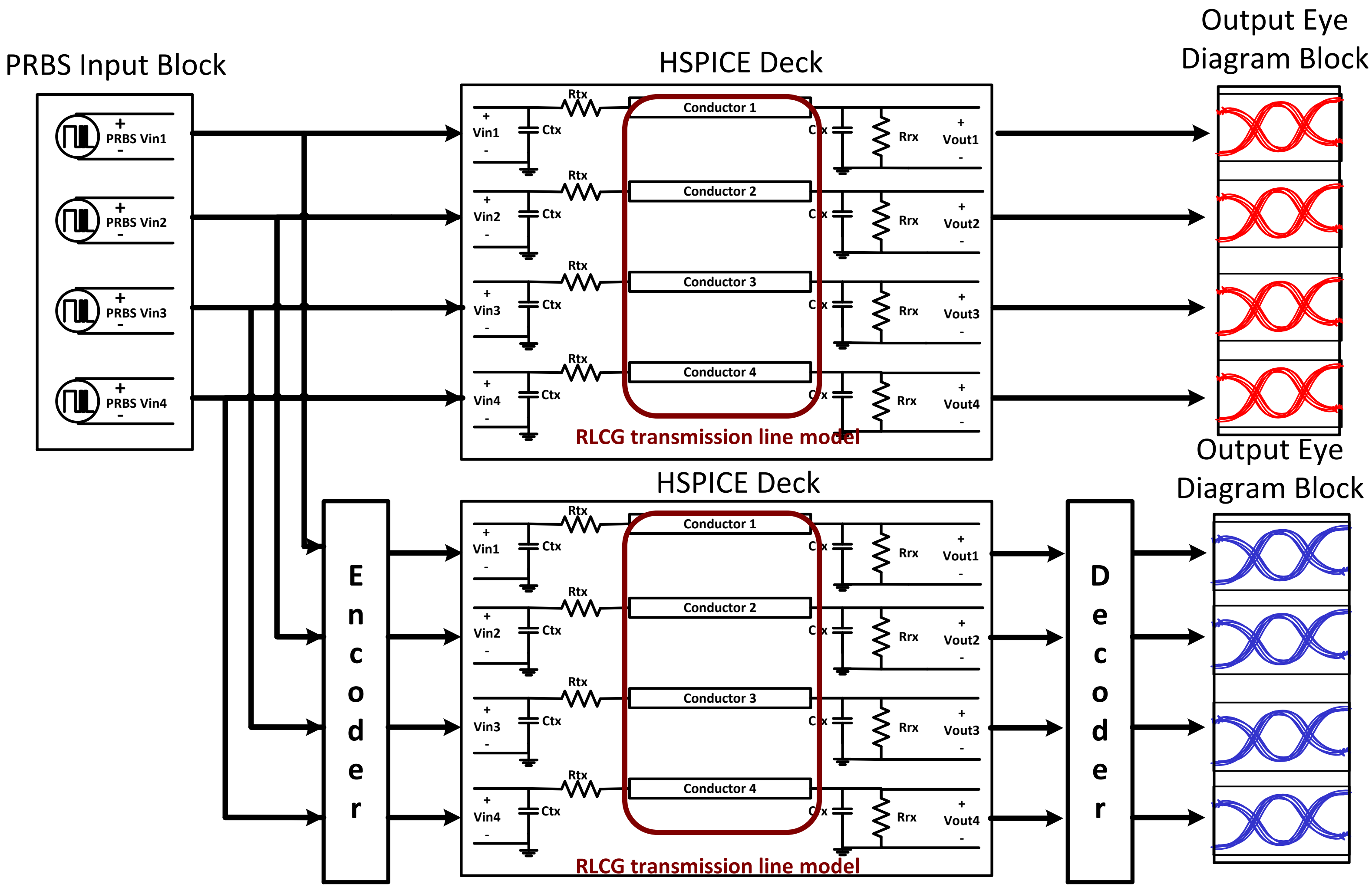
Example

$$\boldsymbol{\upsilon}_{\mathbf{m}} = 1\times10^{8}\begin{array}{cccc} \text{Mode 1} & \text{Mode 2} & \text{Mode 3} & \text{Mode 4} \\ \hline 1.5273 & 0 & 0 & 0 \\ 0 & 1.6464 & 0 & 0 \\ 0 & 0 & 1.6920 & 0 \\ 0 & 0 & 0 & 1.7030 \end{array}\left(m/s\right)$$

$$\hat{\mathbf{Z}}_{\mathbf{modal}} = \begin{array}{cccc} \text{Mode 1} & \text{Mode 2} & \text{Mode 3} & \text{Mode 4} \\ \hline 93.1417 - 0.0381i & 0.0002 + 0.0039i & 0.0000 - 0.0037i & 0.0033 - 0.0001i \\ 0.0040 - 0.0002i & 63.7736 - 0.0360i & 0.0004 + 0.0040i & 0.0030 + 0.0001i \\ 0.0043 + 0.0000i & 0.0033 - 0.0004i & 46.5609 - 0.1886i & 0.0016 + 0.0094i \\ 0.0002 + 0.0030i & 0.0001 - 0.0030i & 0.0092 - 0.0016i & 37.6638 - 0.3282i \end{array}\ \Omega$$



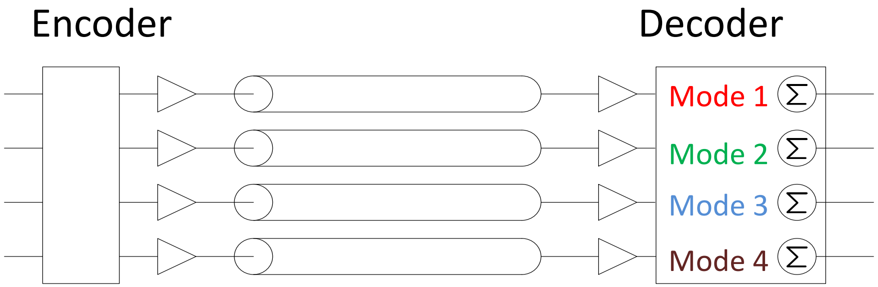
Simulation Framework



A common simulation framework is used throughout this dissertation to compare the effectiveness of various modal signaling techniques

Modal decomposition (Eigen Mode Signaling)

Eigen mode signaling - Encode the parallel signals as the linear combination of fundamental transmission modes. Due to linear independence of modes, the signals are decoupled; such signaling is theoretically free of crosstalk, and therefore could allow the data transfer at channel capacity.



- Requires a prior knowledge of the channel
  - **Issue: HVM layout variation**
- Tx uncertainty due to complex (Re/Im) math precision
  - **Issue: Cannot achieve full crosstalk cancellation**
- Unique termination & Modal propagation delay
  - **Issue: Active termination and delay adjustment**
- Tx/Rx complexity: >10 reference voltages required
  - **Issue: Power hungry**

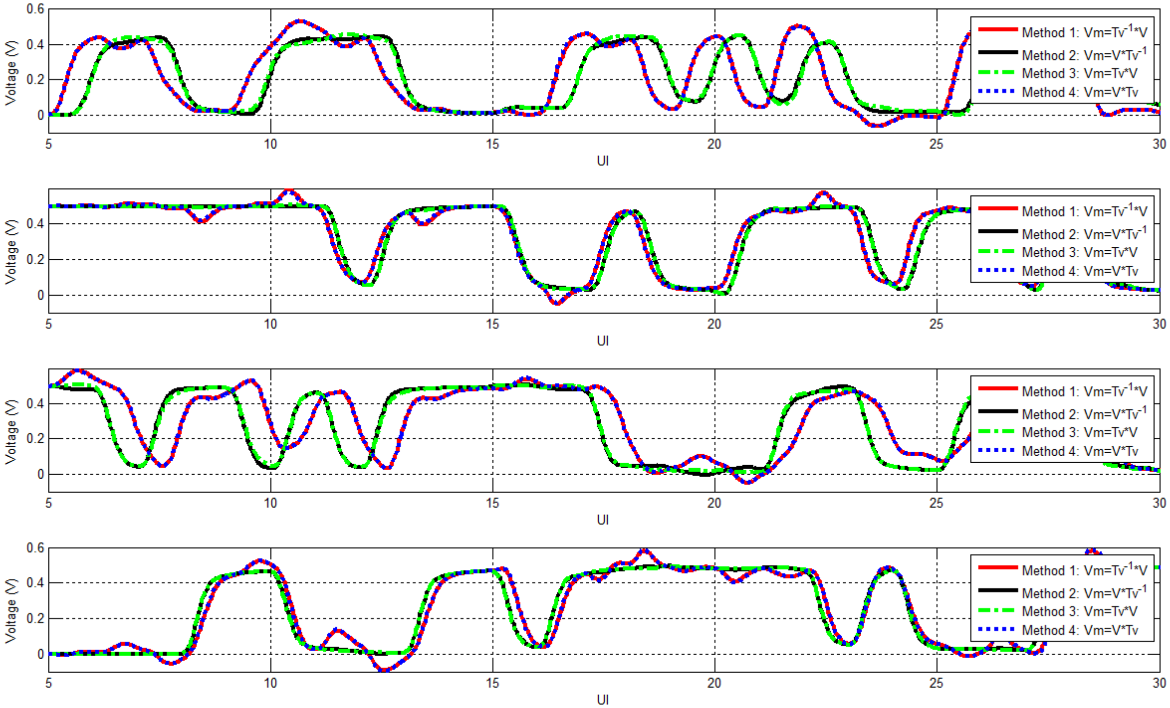
If both the rows and the columns are linearly independent /orthogonal, one can use the transformation matrix to encode and decode line voltages by maintaining the order of multiplication in four possible ways as shown below:

Method 1: $\left[\hat{\mathbf{V}}_{\mathbf{m}}\right]_{n\times1} = \left[\hat{\mathbf{T}}_{\mathbf{V}}^{-1}\right]_{n\times n}\cdot\left[\hat{\mathbf{V}}\right]_{n\times1}$

Method 2: $\left[\hat{\mathbf{V}}_{\mathbf{m}}\right]_{1\times n} = \left[\hat{\mathbf{V}}\right]_{1\times n}\cdot\left[\hat{\mathbf{T}}_{\mathbf{V}}^{-1}\right]_{n\times n}$

Method 3: $\left[\hat{\mathbf{V}}_{\mathbf{m}}\right]_{n\times1} = \left[\hat{\mathbf{T}}_{\mathbf{V}}\right]_{n\times n}\cdot\left[\hat{\mathbf{V}}\right]_{n\times1}$

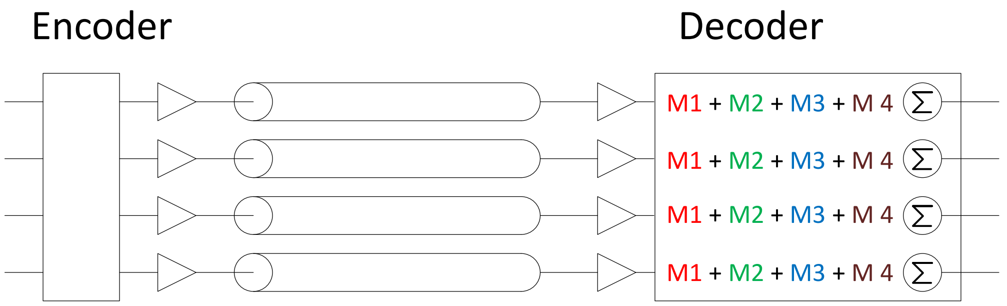
Method 4: $\left[\hat{\mathbf{V}}_{\mathbf{m}}\right]_{1\times n} = \left[\hat{\mathbf{V}}\right]_{1\times n}\cdot\left[\hat{\mathbf{T}}_{\mathbf{V}}\right]_{n\times n}$



After decode, methods 1 and 4 (Modal decomposition) yield one type of output, while methods 2 and 3 (Modal Composition) yield another

Modal composition

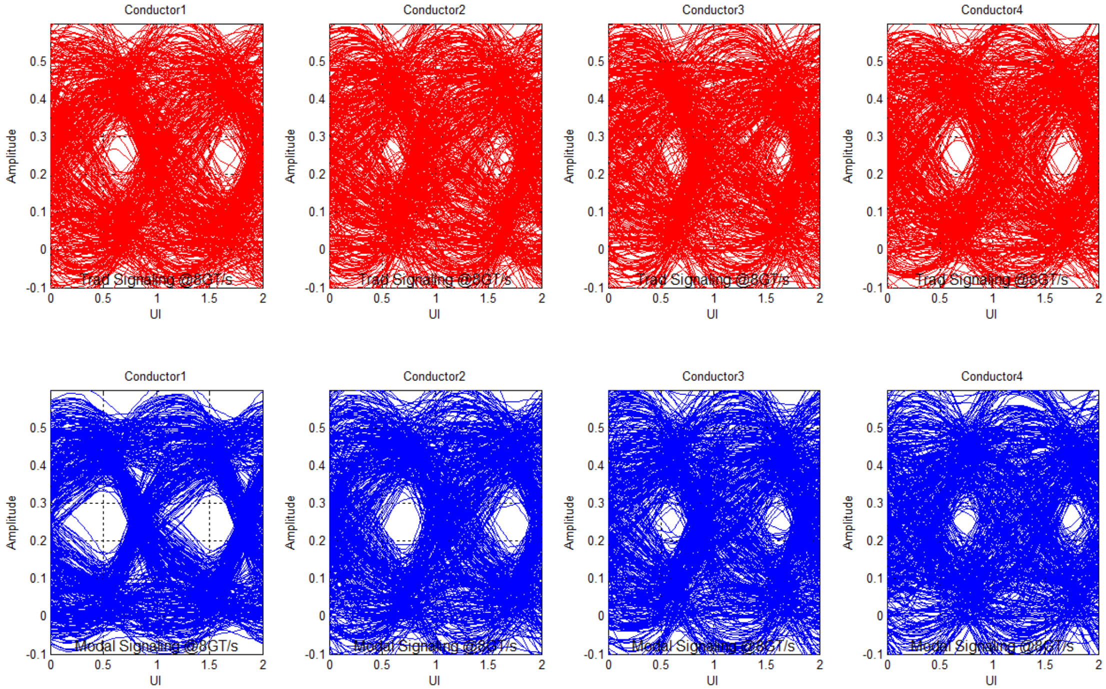
Sends data as a linear combination of orthogonal Eigen modes, where each conductor caries a contribution of an independent mode so that each bit is spread across multiple conductors where the crosstalk becomes part of the signal & can be removed during decode



- Requires a prior knowledge of the channel
  - **Issue: HVM layout variation**
- Tx uncertainty due to complex (Re/Im) math precision
  - **Issue: Cannot achieve full crosstalk compensation**
- Static termination & Modal propagation delay
  - **Issue: some delay adjustment might be required**.
- Tx/Rx complexity: >10 reference voltages required
  - **Issue: Power hungry**

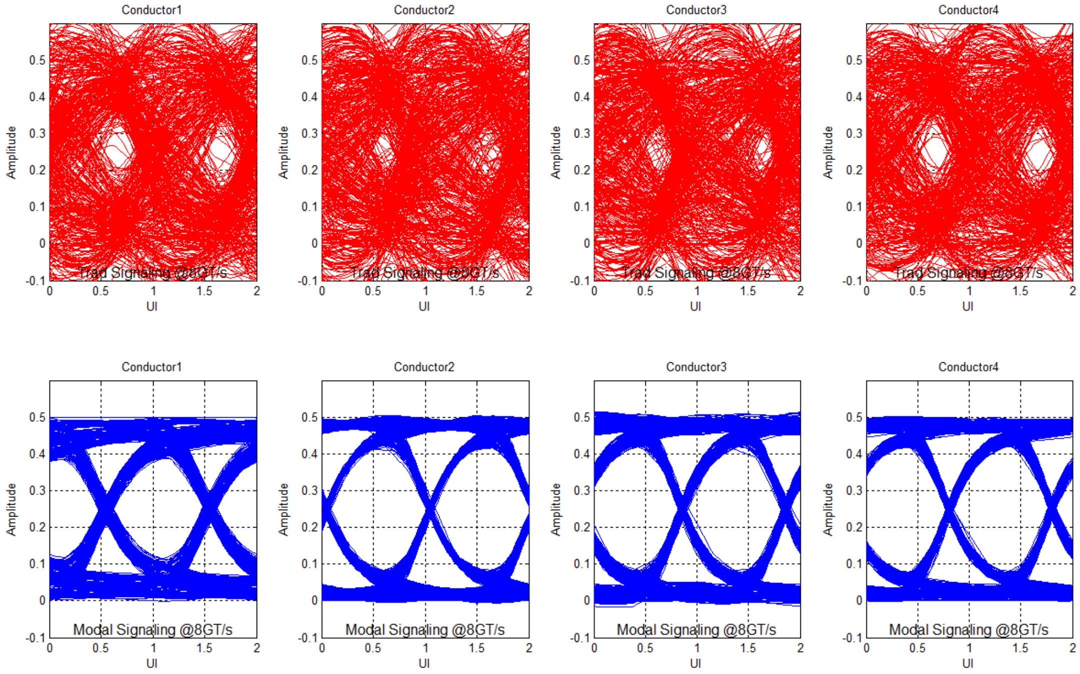
Modal Decomposition

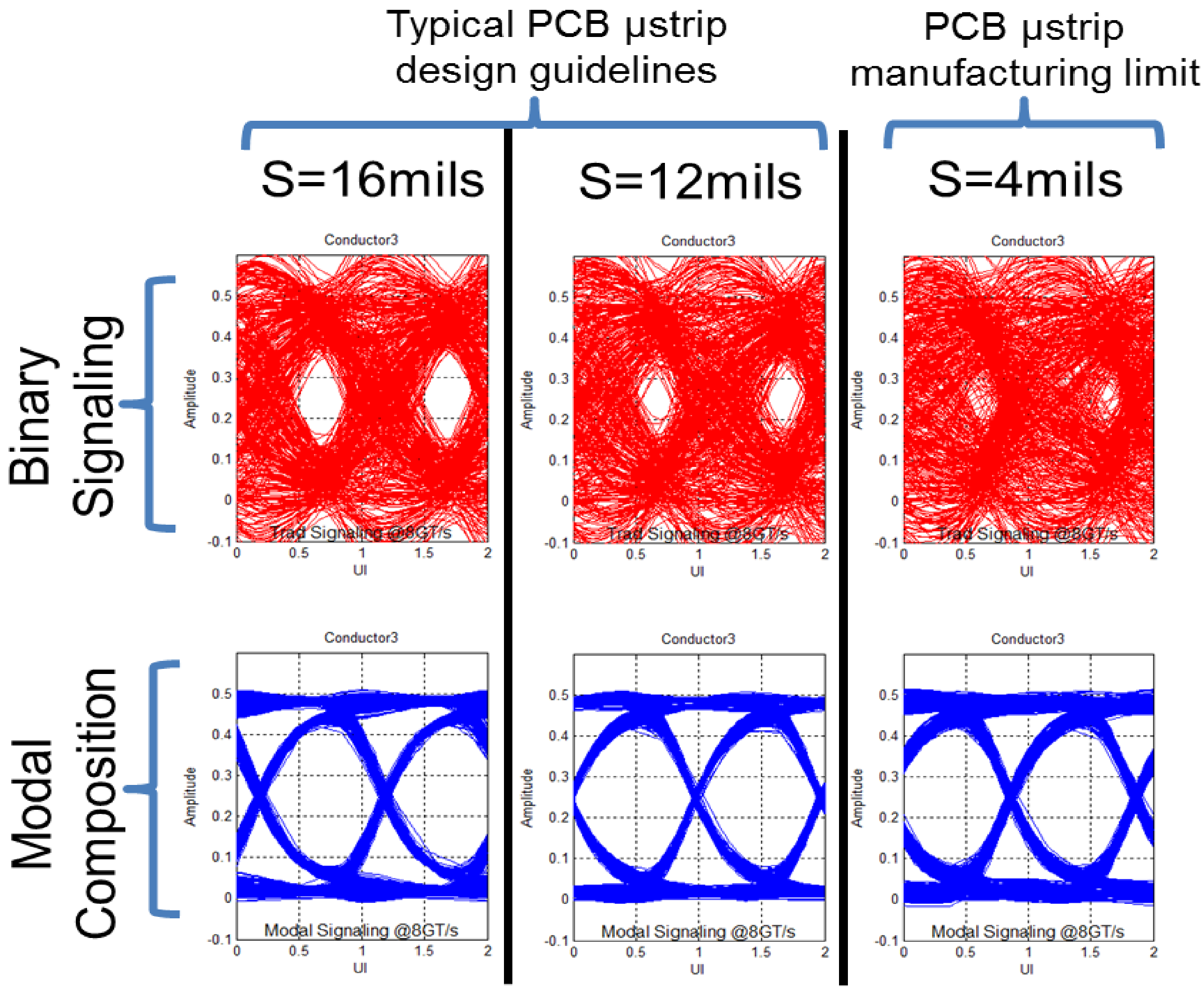
Eye diagrams of traditional binary signaling compared to modal signaling for the 5” long channel in at 8 GT/s.



Modal Composition

Eye diagrams of traditional binary signaling compared to modal composition for 5” long channel at 8 GT/s.





Typical PCB μstrip design guidelines

PCB μstrip manufacturing limit

S=16mils

S=12mils

S=4mils

Binary Signaling

Modal Composition

Eyes due to modal composition technique are independent of trace spacing, thus allowing higher routing density.

Its dependence on channel characteristics for transformation matrix computation and requirement of complex/power-hungry encoding/decoding circuitry remains its biggest drawback.

How do these Modal Signaling methods compare?

Modal Decomposition : Send data in independent Eigen modes

- **Pros:** Theoretically, this would minimize crosstalk → each mode is independent & decoupled
- **Cons:** Requires a prior knowledge of the channel, power hungry circuitry, complex training algorithms, difficult interconnect characterization & complex termination schemes

Modal Composition: Send data as a combination of Eigen modes

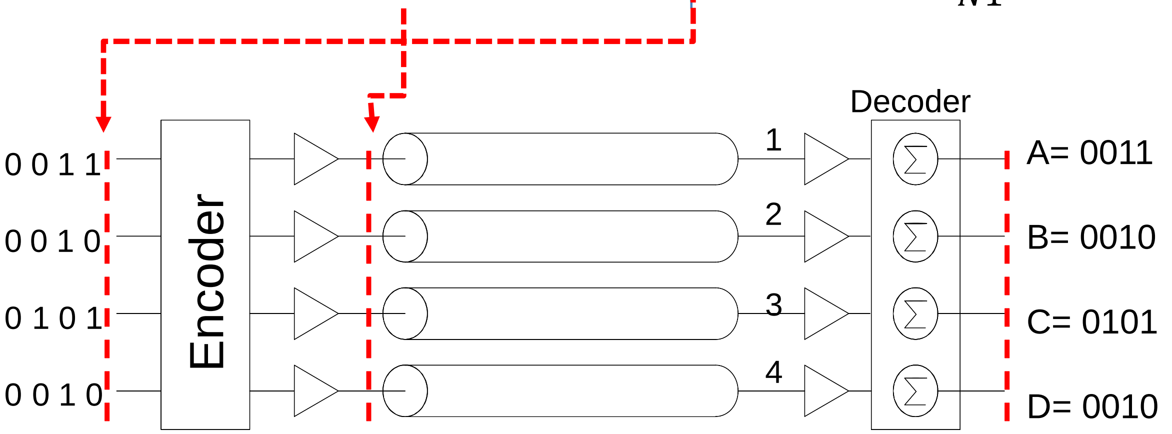
- **Pros:** Better results that modal decomposition. Does not require complex termination schemes and is less susceptible to modal delays compared to the previous approach.
- **Cons:** Requires a prior knowledge of the channel, power hungry circuitry, complex training algorithms, and difficult interconnect characterization.

Crosstalk Harnessed Signaling (CHS)

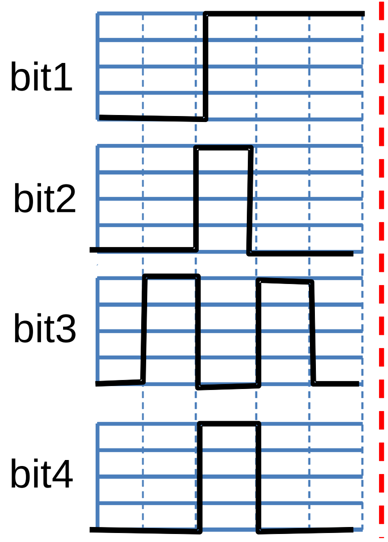
A new signaling strategy: Send the data sent in a way so crosstalk noise is not detrimental

Encoding sequence: →

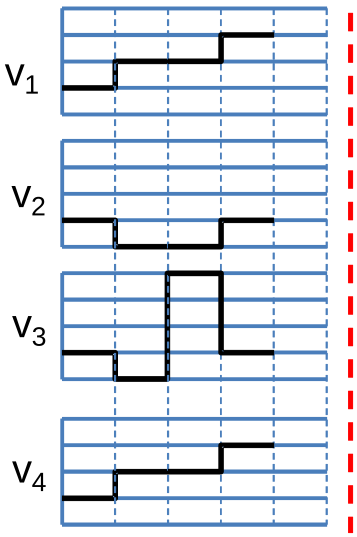
$$\overset{\text{Encoded voltages}}{[V_1 \quad \cdots \quad V_N]} = \overset{\text{Input binary bits}}{\underbrace{[V_{bit1} \quad \cdots \quad V_{bitN}]}} \begin{bmatrix} W_{11} & \cdots & W_{1N} \\ \vdots & \ddots & \vdots \\ W_{N1} & \cdots & W_{NN} \end{bmatrix} \ \text{Encoding matrix}$$

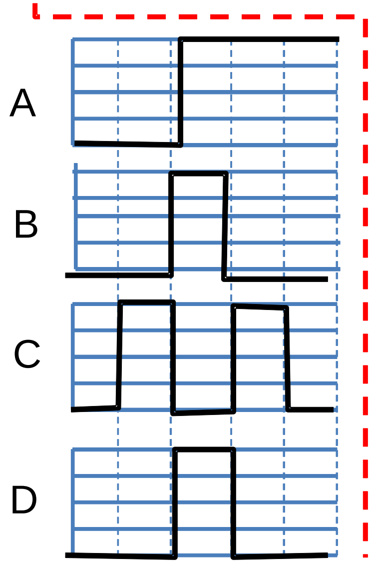


Decoded Output (recovered bit stream)



Binary data is Encoded into 4 voltage levels & driven onto the bus (quardary)





But … Why Does it Work?

Decoding sequence

$$\underbrace{[V_{bit1\_recover} \quad \cdots \quad V_{binN\_recover}]}_{\text{Recovered binary bit stream}} = \underbrace{[V_{rx1} \quad \cdots \quad V_{rxN}]}_{\text{Sampled encoded data at receiver}} \begin{bmatrix} W_{11} & \cdots & W_{1N} \\ \vdots & \ddots & \vdots \\ W_{N1} & \cdots & W_{NN} \end{bmatrix}^{-1}$$

Example: Decoding bit 1 for a 4 bit wide bus:

$$\begin{aligned} V_{bit1\_recover} & \\ &= V_{rx1}\,(W_{11}^2 + W_{21}^2 + W_{31}^2 + W_{41}^2) \\ &\quad + V_{rx2}(W_{11}W_{12} + W_{21}W_{22} + W_{31}W_{32} + W_{41}W_{42}) \\ &\quad + V_{rx3}(W_{13}W_{11} + W_{23}W_{21} + W_{31}W_{33} + W_{41}W_{43}) \\ &\quad + V_{rx4}(W_{11}W_{14} + W_{21}W_{24} + W_{31}W_{34} + W_{41}W_{44}) \end{aligned}$$

Sum of squares for column 1 in W = constant

$W_{column1} \cdot W_{column2} = 0$

$W_{column1} \cdot W_{column3} = 0$

$W_{column1} \cdot W_{column4} = 0$

Theoretically, noise from all other conductors is zero!

For the crosstalk to cancel, the encoding matrix [W] must be chosen so that

- **The sum of squares for each row/column is an integer**
- **The dot product between any 2 row/columns is zero**

Encoding matrix for a 4 bit bus (any configuration)

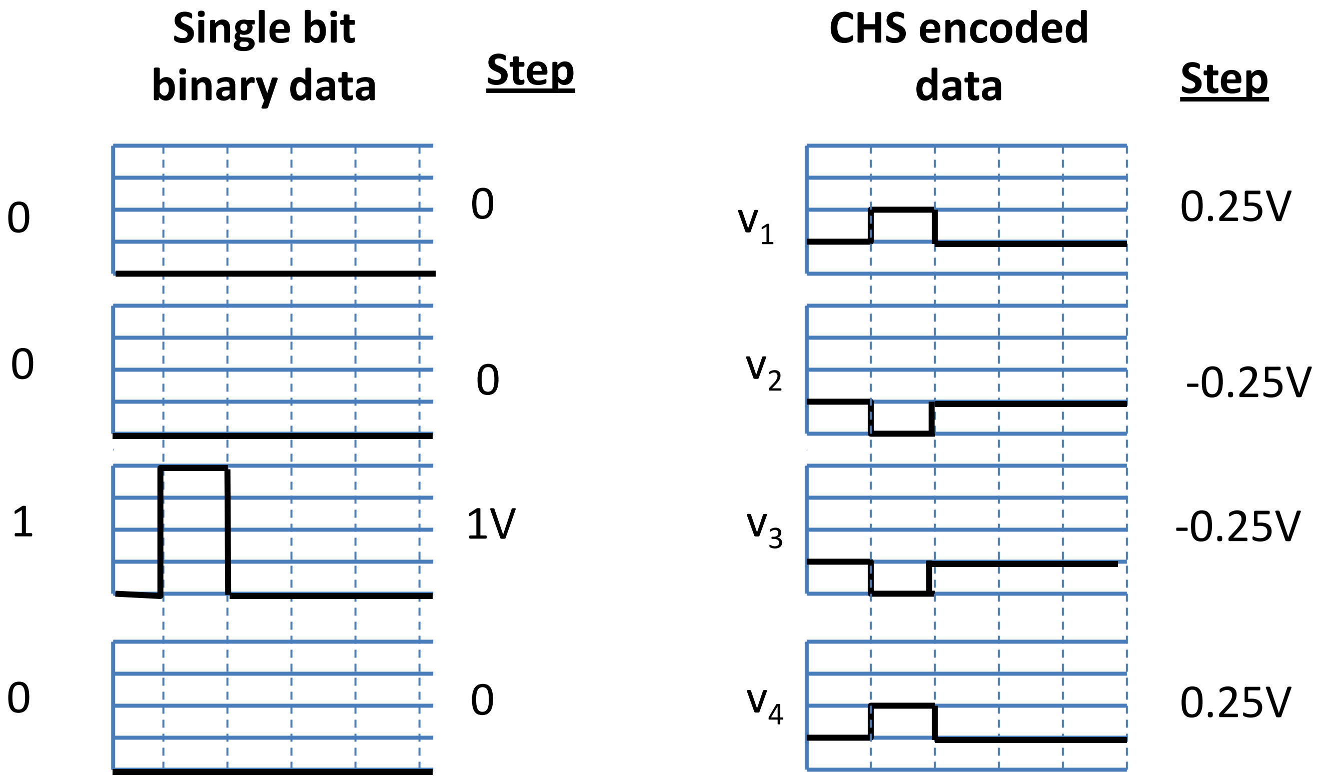
$$W = \begin{bmatrix} 1 & 1 & 1 & 1 \\ -1 & -1 & 1 & 1 \\ 1 & -1 & -1 & 1 \\ 1 & -1 & 1 & -1 \end{bmatrix}$$

(Intel patent pending)

Spreading out the energy

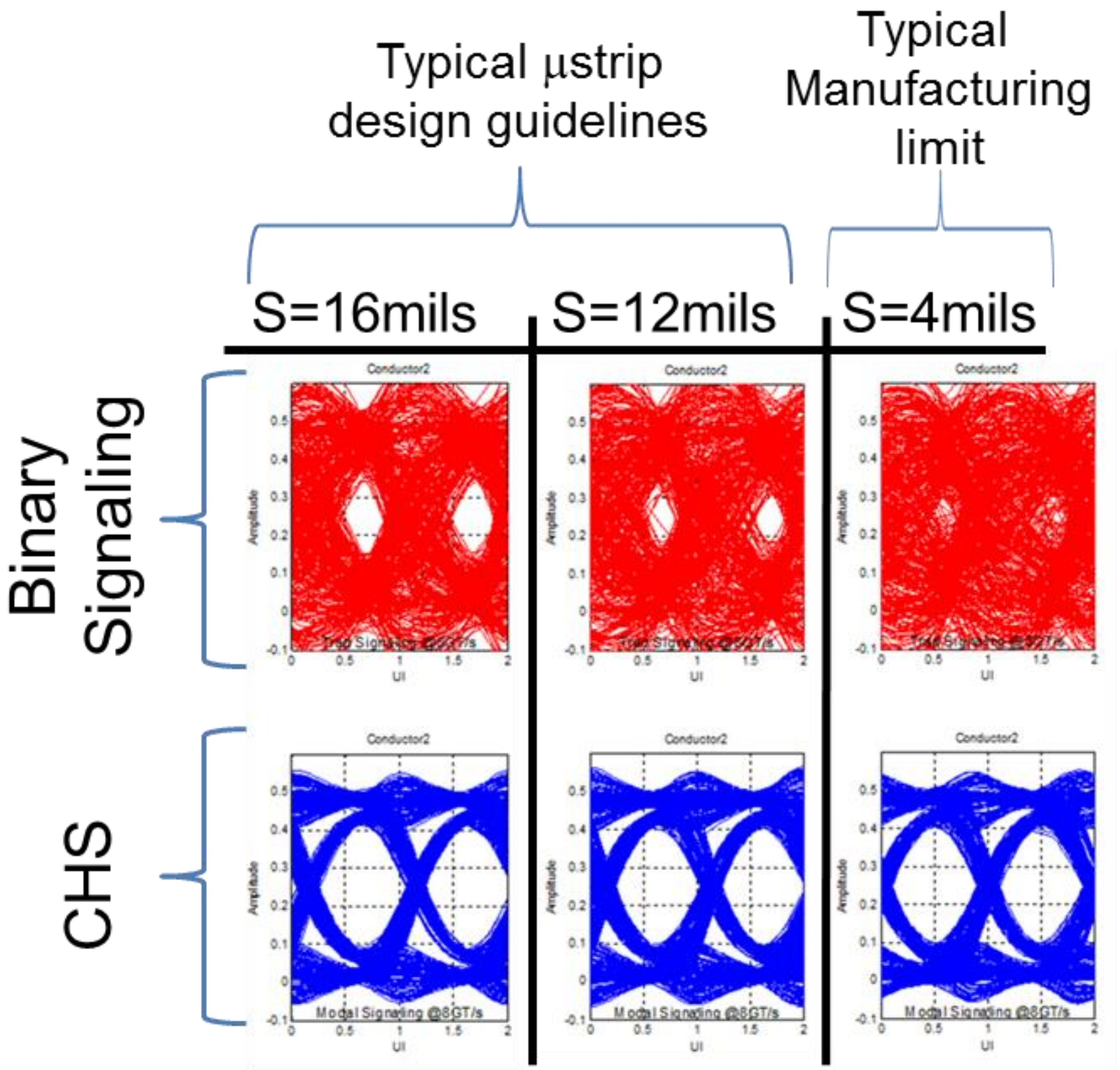
Each bit is sent so energy is spread out across all lines in the bus instead if in discrete voltage pulses

- **Helps minimize harmful crosstalk effects**



Data can be sent in a way that is less sensitive to crosstalk noise

CHS can help remove the crosstalk barrier

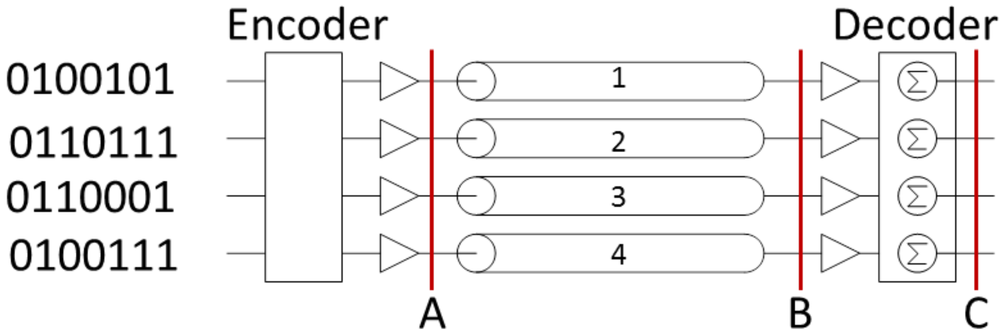


Eyes due to CHS are almost independent of trace spacing, thus allowing higher routing density.

Eye diagrams of traditional binary signaling compared to CHS for 5” long channel with varying trace spacing on conductor 3, running at 8 GT/s.

How does CHS compare?

CHS: encodes the data so that each bit is spread across multiple conductors, where crosstalk becomes part of the signal & is removed during decode



- ✓ Quaternary signaling
- ✓ Encode 4 bits at a time

Pros: Retains many benefits of modal signaling without the overhead

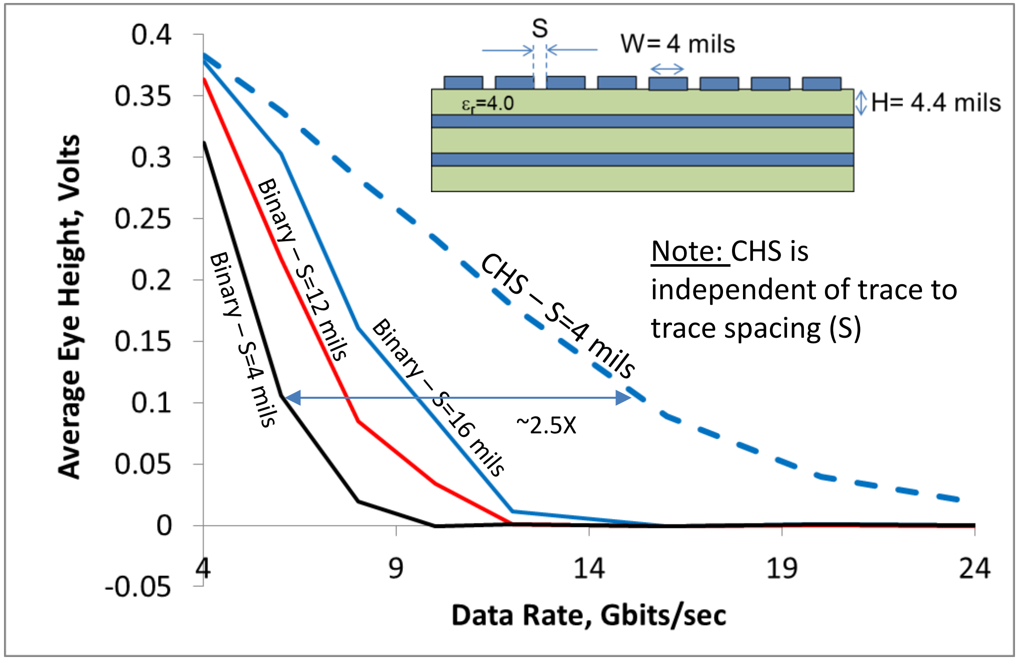
- Agnostic to interconnect behavior … only the number of lines matter
- No training required, one matrix works for N lines
- No complex termination needed … maybe none in some cases
- Removes fundamental BW limitation & allows maximum density routing

Cons:

- May be sensitive to phase, ISI and power noise
- Noise will prevent total cancellation of crosstalk terms during decode
  - Long microstrip lines may need static delay compensation

Theoretical Performance Gains over Binary

4 coupled PCB lines (1 nibble)



Note: CHS is independent of trace to trace spacing (S)

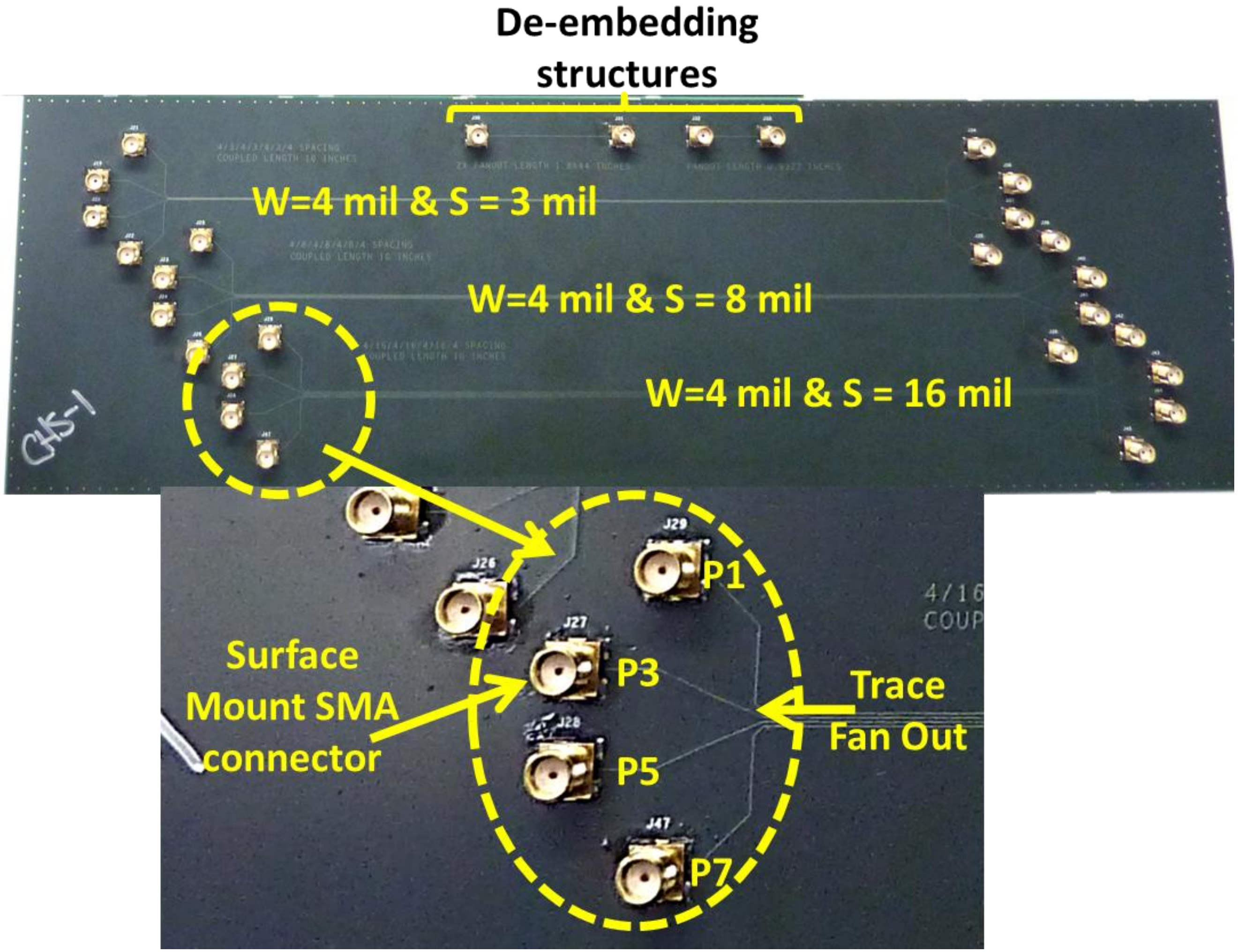
When is CHS the most beneficial?

- **Data rates > 4 Gbits/s**
- **Maximum routing density manufacturer can achieve**
- **Crosstalk dominated buses**
- **Microstrip layers**

CHS shows significant gains for both bus speed & routing density

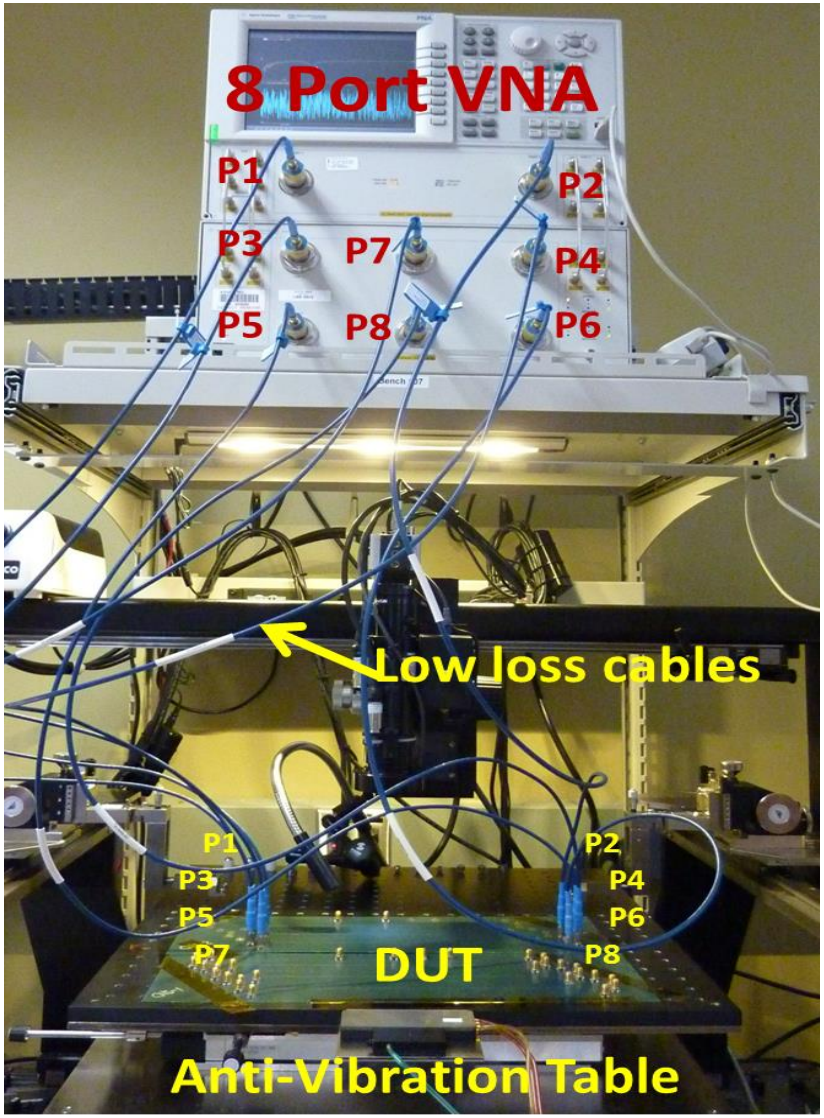
- **~2.5X increase in bus speed**
- **… <u>and</u> ~2.3X increase in routing density**
- **Loss equalization would increase the benefit**

CHS Measurement Validation

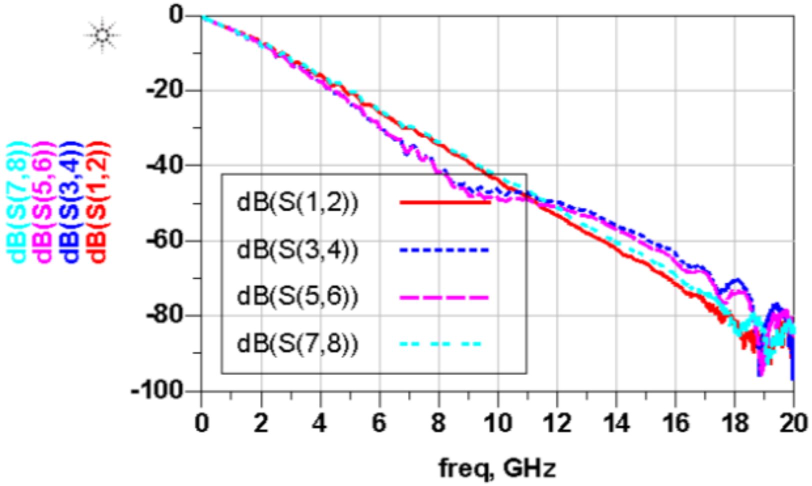


Passive PCB fabricated for measurement

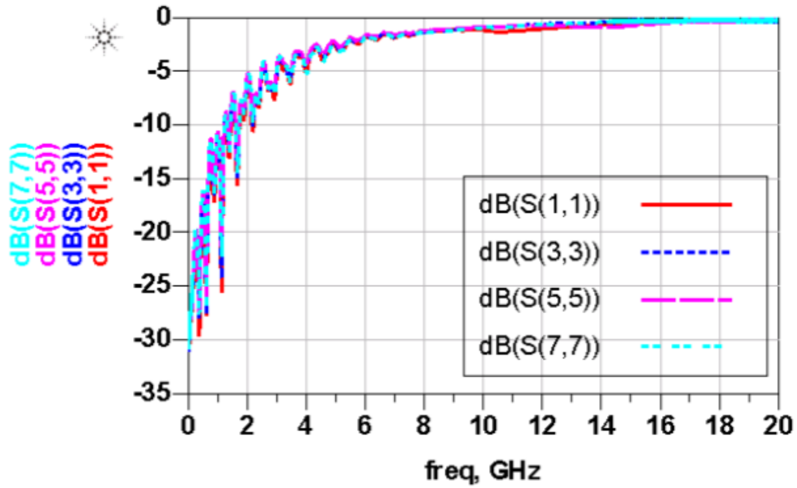
8 Port VNA Measurements:

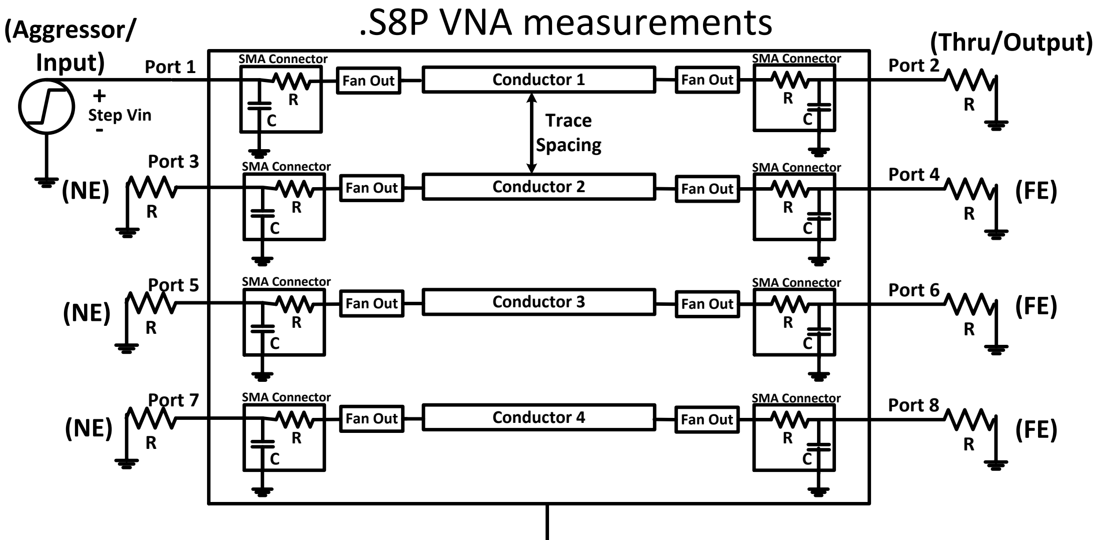


$$\text{Insertion Loss} = -20Log_{10}\left|S_{21}\right| dB$$

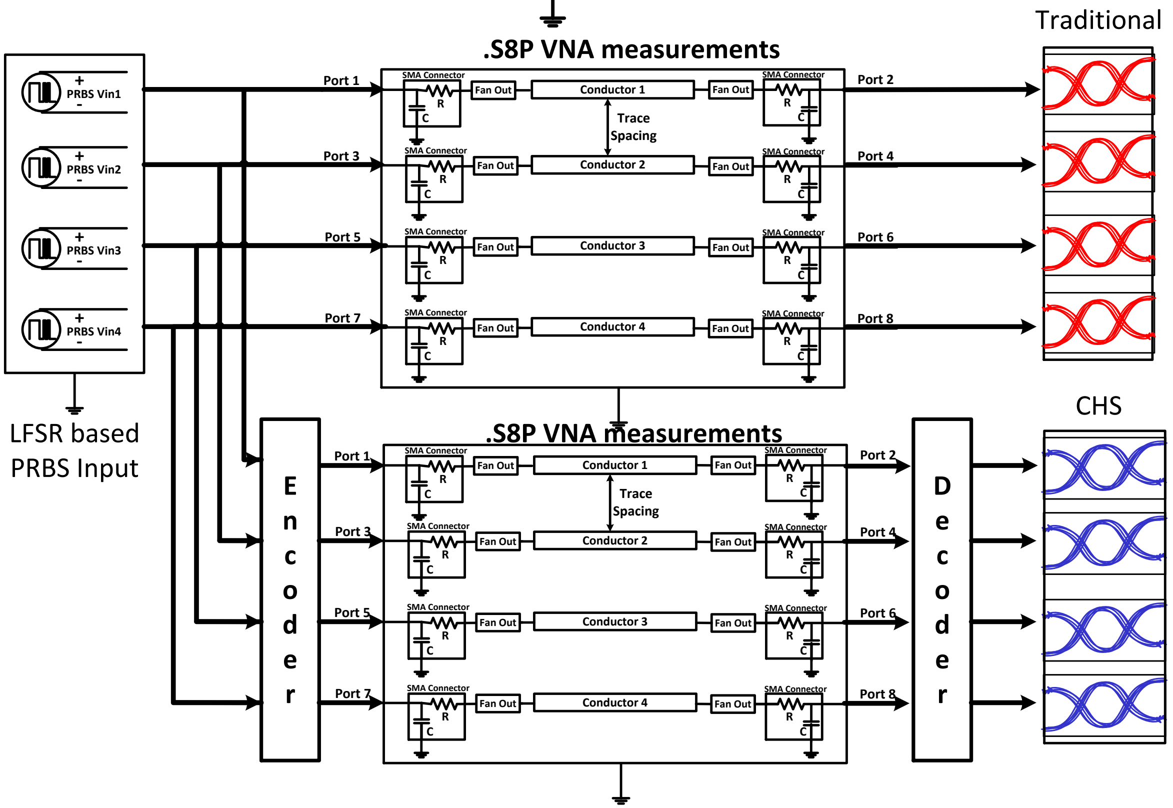


$$\text{Return Loss} = -20Log_{10}\left|S_{11}\right| dB$$



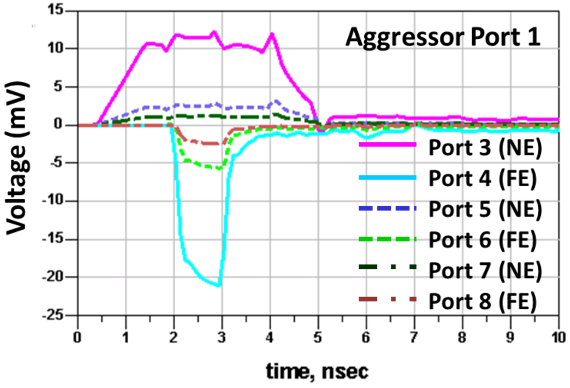


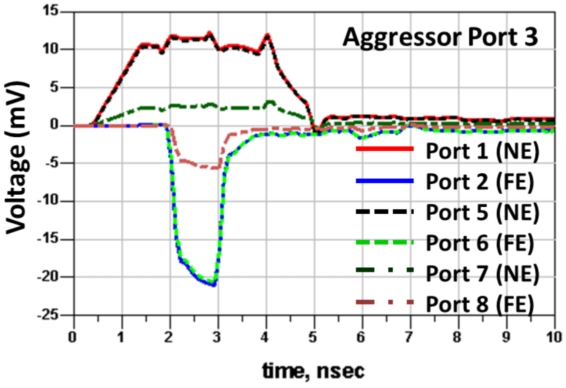
8 Port TDR ADS setup



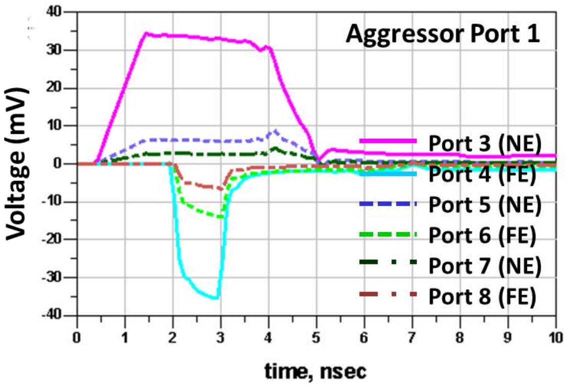
Traditional vs. CHS eye diagram analysis ADS setup

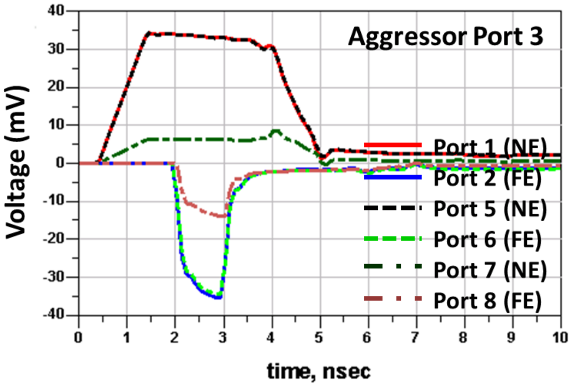
8 Port TDR results





16 mil Trace Spacing





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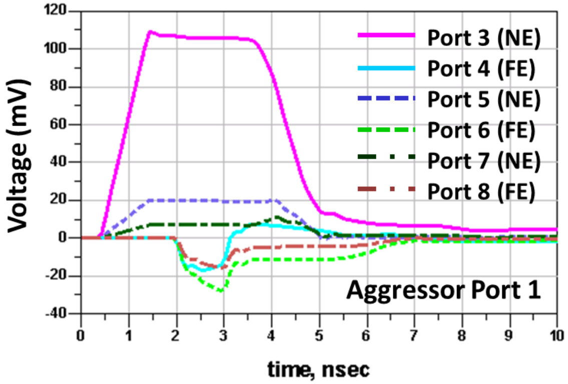
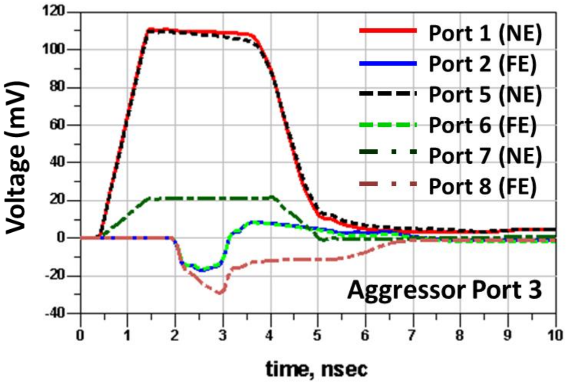
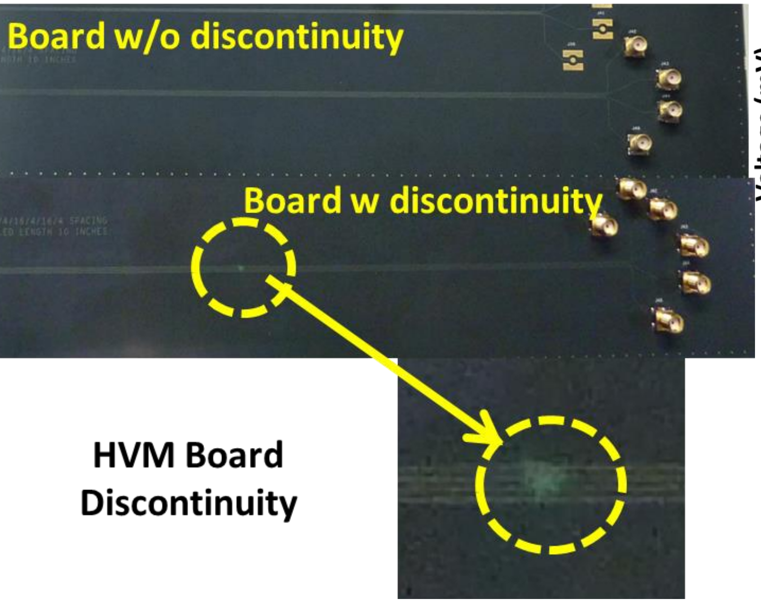
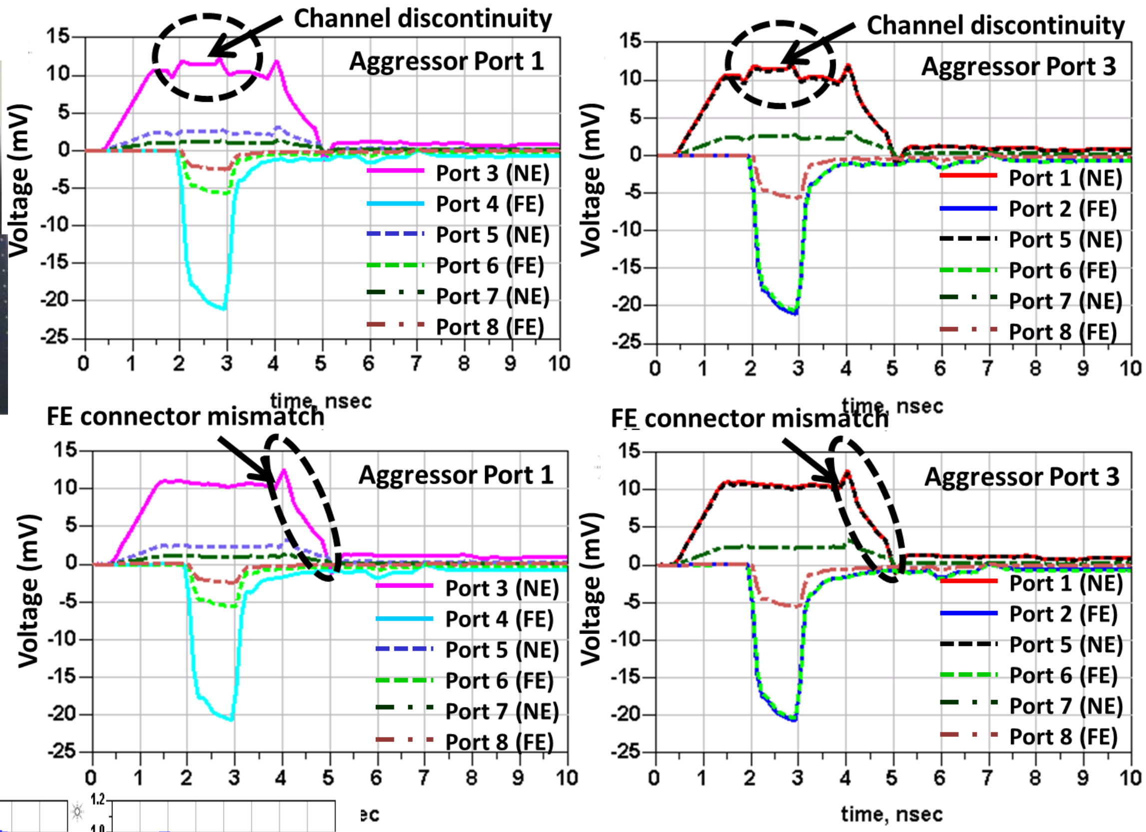


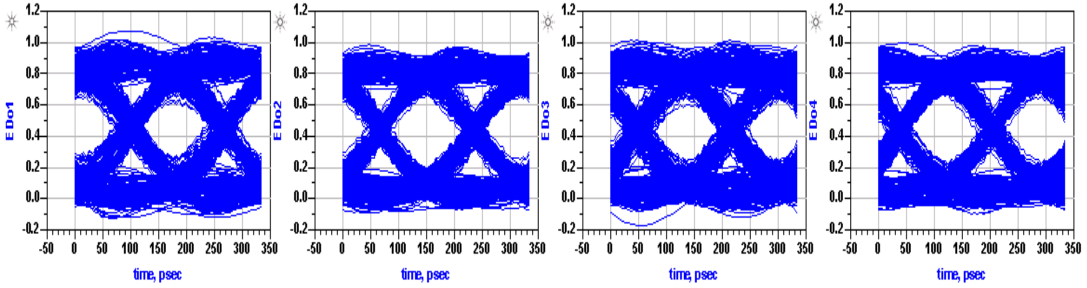


3 mil Trace Spacing

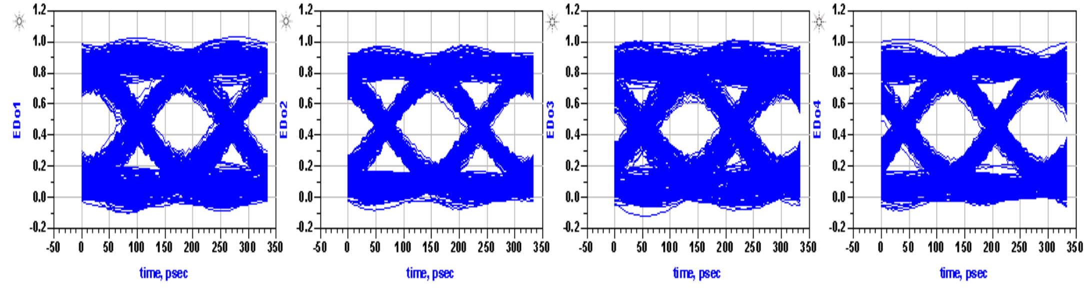


HVM Board Discontinuity



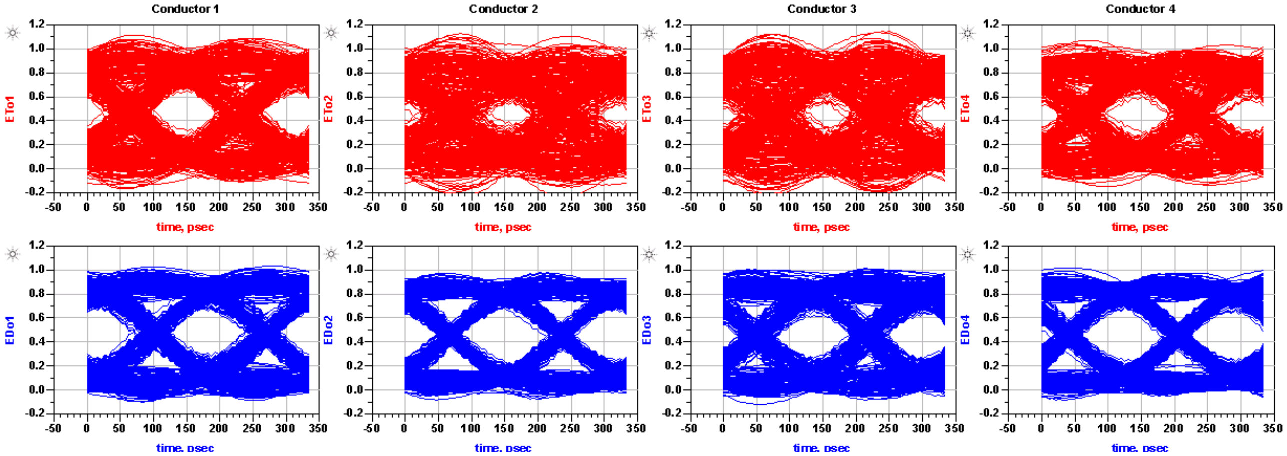


w discontinuity @ 6GT/s

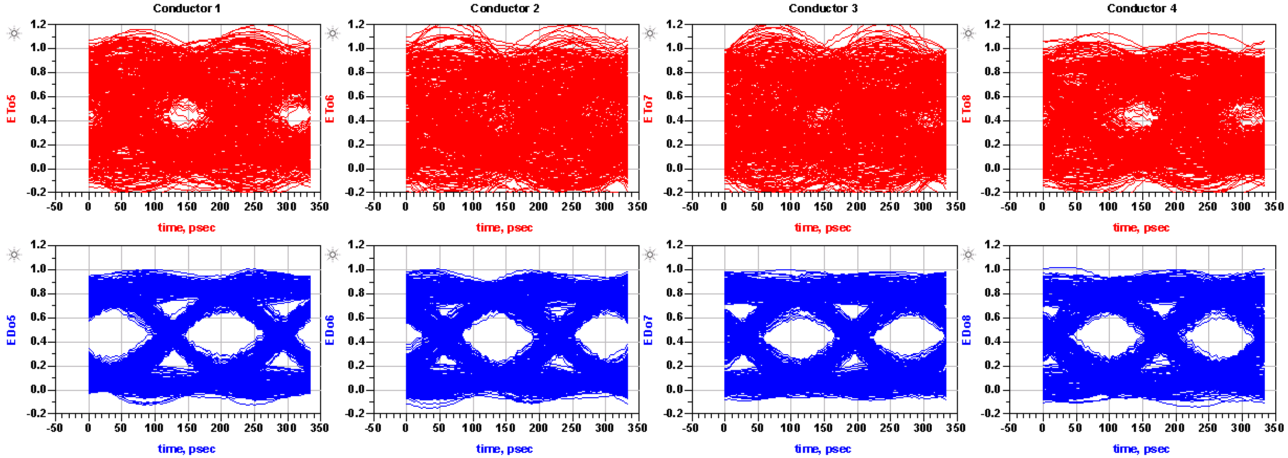


w/o discontinuity @ 6GT/s

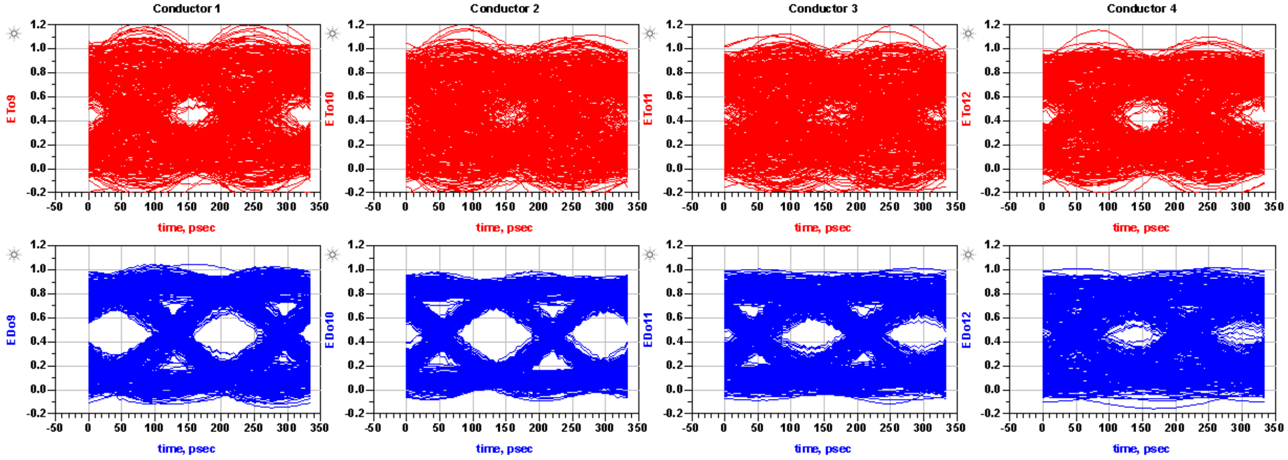
Eye Diagrams @ 6GT/s



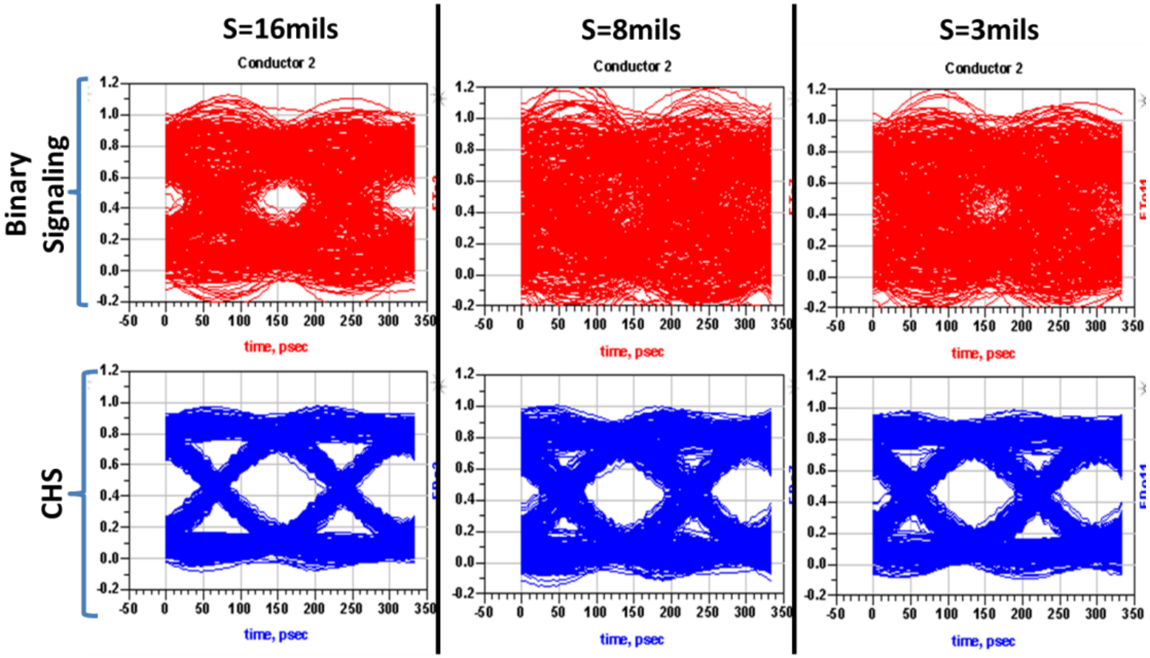
16 mil Trace Spacing



8 mil Trace Spacing

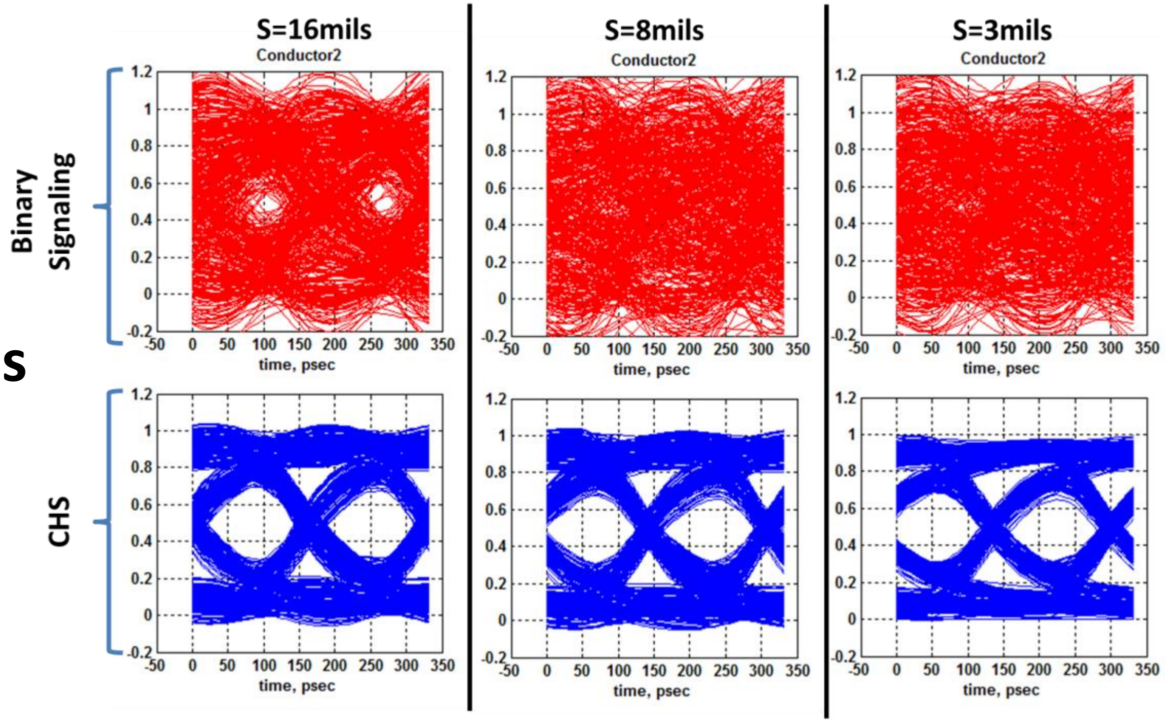


3 mil Trace Spacing



Measured Eye Diagrams

Simulated Eye Diagrams



Summary

Goal: Remove the crosstalk roadblock, allowing very dense routing so the maximum computational performance can be designed into the smallest possible volume

- **Effects of cross-talk** in terms of bandwidth and routing density that prevent bus performance from scaling with Moore's Law
- **Modal decomposition:** works well but its cost in terms of power and circuit and implementation complexity was deemed too high for it to be a viable alternative to traditional binary signaling
- **Modal composition:** significantly better than the decomposition technique but its dependence on channel characteristics for transformation matrix computation remains its biggest drawback
- **Crosstalk harnessed signaling (CHS)** is not Eigen mode signaling - the data is not encoded into specific modes defined by the decoupling transformation matrix - but it does retain some of the benefits without the overhead.
- **Measurement results corroborate simulations**
- Feasibility analysis indicates **further research is warranted to investigate its applicability beyond PCB's** to novel layout structures that can maximize the channel bandwidth per unit volume.

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