ECE 546
Lecture - 26
Modal Signaling

Spring 2024

Jose E. Schutt-Aine
Electrical & Computer Engineering
University of Illinois
jesa@illinois.edu

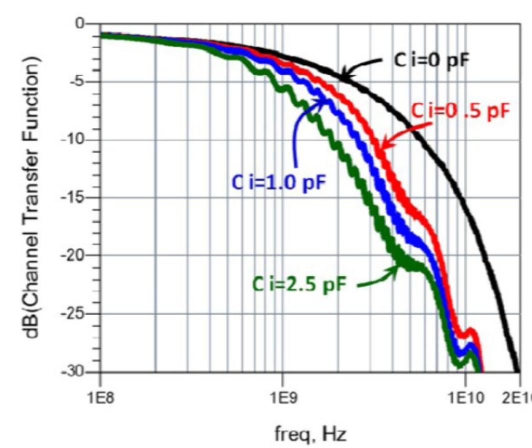
Signal Integrity Impairments In High-Speed Buses

– SI issues limit system performance to well below channel Shannon capacity
– Inter-Symbol Interference (ISI) is an issue for long backplane buses

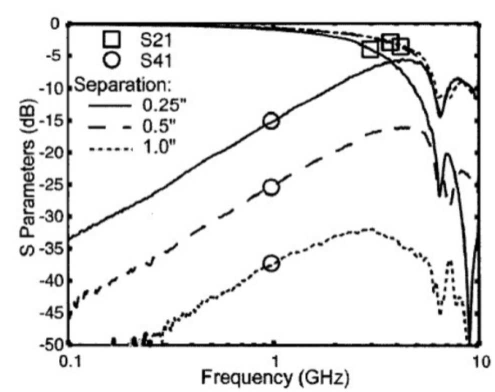
– For short, low-cost parallel links, dominant noise source is crosstalk
  - Far-end crosstalk (FEXT) induces timing jitter (CIJ), impacts timing budget

– Other SI impairments:
  - Simultaneous-switching (SSO) noise
  - Thermal noise
  - Jitter from PLL/DLL

Insertion loss of a single DDR channel



FEXT increases with routing density



Mutual Inductance and Capacitance

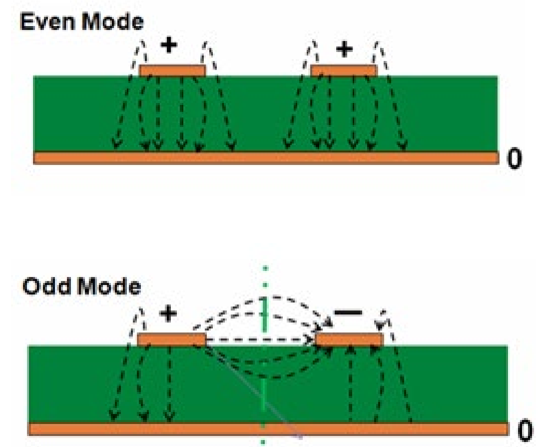
- Crosstalk is the coupling of energy from one line to another via:
  - *Mutual capacitance (electric field)*
  - *Mutual inductance (magnetic field)*
  - – The circuit elements that represents this transfer of energy are the following familiar equations:

$$V_{Lm} = L_m \frac{dI}{dt} \qquad\qquad I_{Cm} = C_m \frac{dV}{dt}$$

- The mutual inductance will induce current on the victim line opposite of the driving current (Lenz's Law)
- The mutual capacitance will pass current through the mutual capacitance that flows in both directions on the victim line
- Near-end crosstalk is always positive
  - Currents from Lm and Cm always add and flow into the node
- For PCBs, far-end crosstalk is *usually* negative
  - Current due to Lm larger than current due to Cm

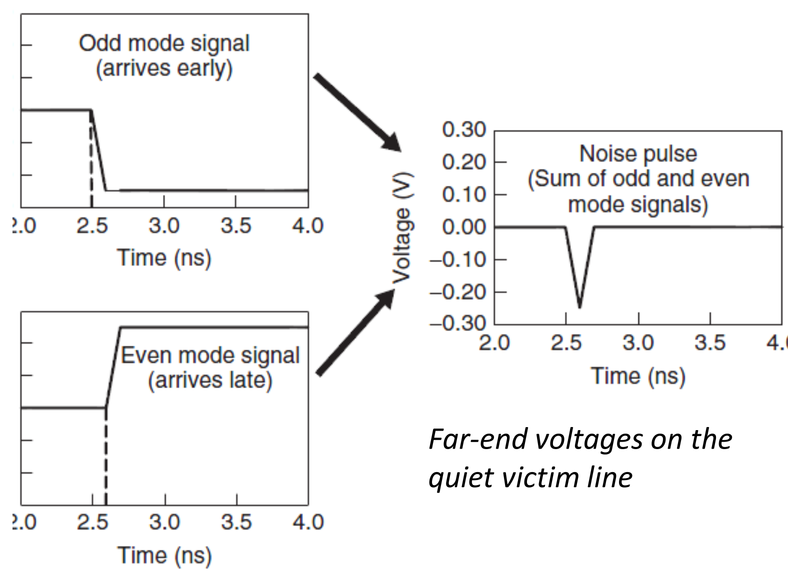
Crosstalk in Non-Homogenous Media

- Propagation modes have different velocities
  - Time of flight depends on parameters per unit length (self- and mutual L and C)
- Example: two-line single-ended signaling



$$T_o = l\sqrt{\left(1-{L_m}/{L_s}\right)\left(1+{C_m}/{C_s}\right)},\quad T_e = l\sqrt{\left(1+{L_m}/{L_s}\right)\left(1-{C_m}/{C_s}\right)}$$

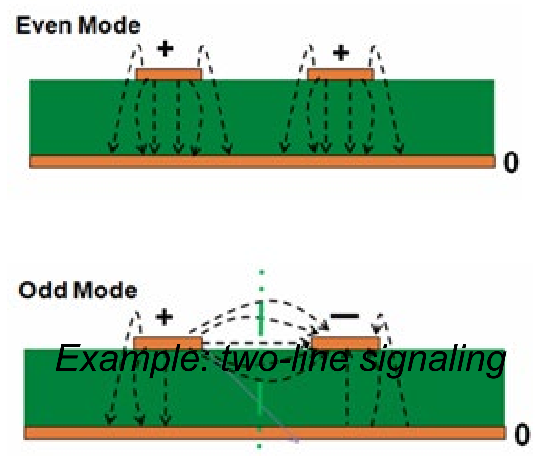
- In microstrip PCB, typically:
  - $L_m/L_s > C_m/C_s$ → Odd mode is faster
- NRZ signal on aggressor line induces both modes
  - → Noise pulse on the victim line
  - FEXT; translates into timing jitter

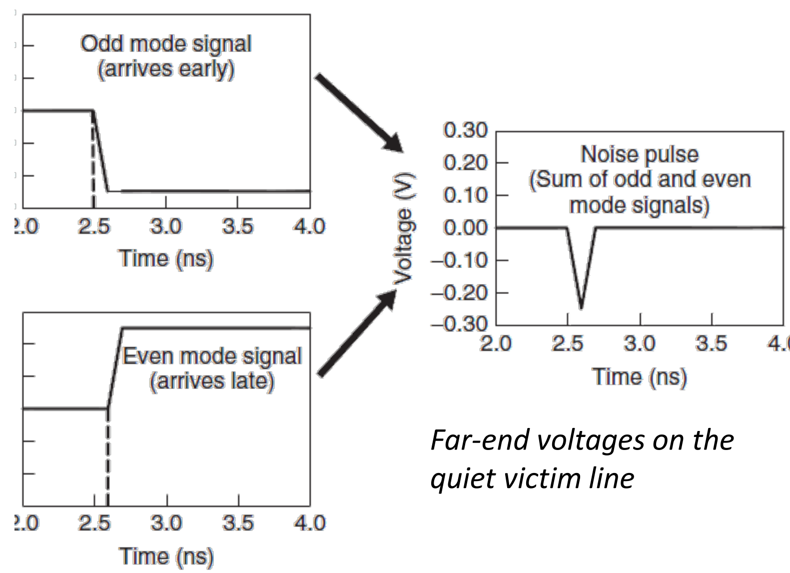


Far-end voltages on the quiet victim line

Crosstalk in Non-Homogenous Media

- Propagation modes have different velocities
  - Time of flight depends on parameters per unit length (self- and mutual L and C)
  - FEXT noise pulses translate into timing jitter
- Previous proposed methods:
  - Treat coupling as undesired, try removing its effects
  - Harder to implement as coupling gets tighter
- Modal signaling takes advantage of coupling
  - Enables increased routing density
  - Special cases explored in previous work
  - Lossless, homogenous media
  - Uniform parallel lines
- This work explores the general case
  - Lossy metal and dielectric (FR-4)
  - Non-homogenous media (microstrip)
  - Cascaded segments, vias/connectors





Far-end voltages on the quiet victim line

Crosstalk-Induced Noise

- Different propagation modes have different propagation delays and impedances:

$$TD_{even} = \sqrt{L_{even} C_{even}} = \sqrt{(L_{11} + L_{12})(C_{11} - C_{12})}$$

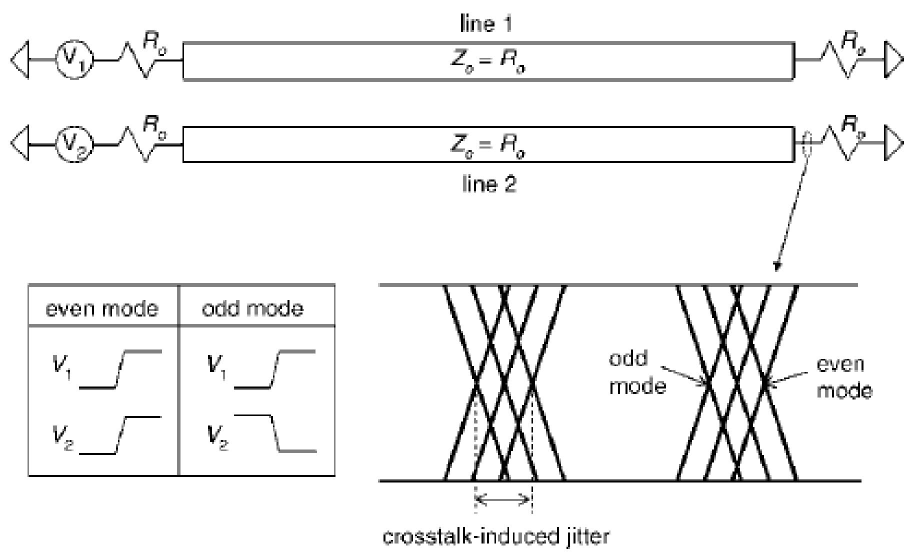
$$TD_{odd} = \sqrt{L_{odd} C_{odd}} = \sqrt{(L_{11} - L_{12})(C_{11} + C_{12})}$$

$$Z_{even} = \sqrt{\frac{L_{even}}{C_{even}}} = \sqrt{\frac{L_{11} + L_{12}}{C_{11} - C_{12}}} \qquad Z_{odd} = \sqrt{\frac{L_{odd}}{C_{odd}}} = \sqrt{\frac{L_{11} - L_{12}}{C_{11} + C_{12}}}$$

- Weak coupling approximations:
  - $k_C = C_m / C_s \ll 1$, $k_L = L_m / L_s \ll 1$
- Model of inductive coupling coeff: $k_{ij} = e^{-as^b}$
  - where *s* is the pitch spacing between wire *i* and wire *j*, *a* and *b* are constants depending on the wire width and P/G plane distance

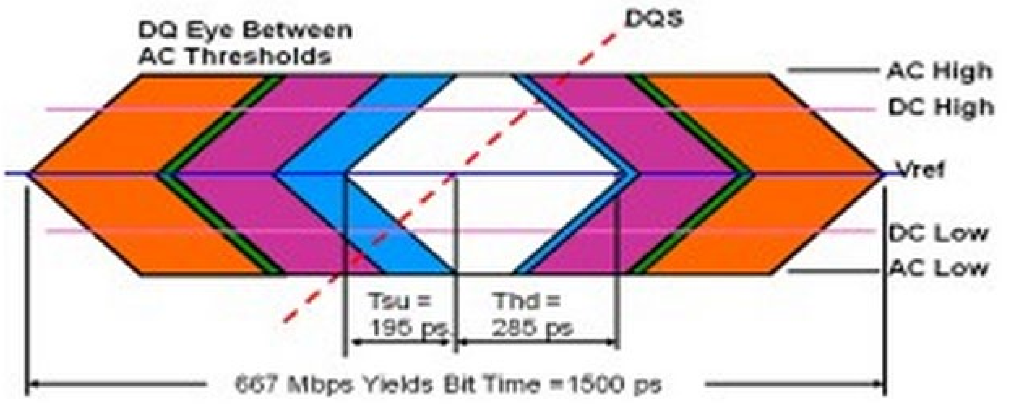
Crosstalk-Induced Jitter (CIJ)

- Timing jitter is more dominant in chip-to-chip links than voltage margin reduction
- Most of FEXT coupled energy introduced at transitions
  - Affects zero crossing, causing jitter
  - CIJ: independent of signal swing, insensitive to transition slope
- N-line bus: N distinct modes with different velocities



Crosstalk Sources, Timing Budget

- Crosstalk impacts both timing and voltage margins
- Limits routing density, especially for single-ended links
- Crosstalk sources:
  - Coupling at vias, connectors, terminations
  - Coupling in package (wirebonds, escape traces)
  - Coupling in PCB traces (bus or adjacent layers for wide bus)
    - Dominant in low-cost microstrip buses (e.g. DDR3)



A typical DDR timing budget: Rx jitter (orange), routing skew (green), Tx jitter (purple); the remaining portion needs to cover all the timing uncertainties due to interconnects (blue) [4]

Crosstalk Mitigation Techniques

- Signal Coding
  - Forbidden transition codes, Incremental, Differential or Pseudo-differential signaling
- CIJ Compensation
  - Detect mode combination, retime the signals
- FEXT Cancelation
  - Estimate FEXT, inject the opposite signal to cancel
- Passive Equalization
  - Reduce mode velocity mismatch

- None of the above are in practical use for off-chip links
  - Hard to generalize to buses, power-hungry, too costly or complex to implement for realistic channels

Crosstalk Mitigation Approach

- Extend the applicability of crosstalk mitigation using modal signaling to realistic tightly coupled low-cost interconnects.

- Examine the properties of building blocks of a modal signaling system; propose practically realizable low-complexity models.

- Introduce a noise-aware system perspective of modal signaling; provide design tradeoffs for a given level of performance.

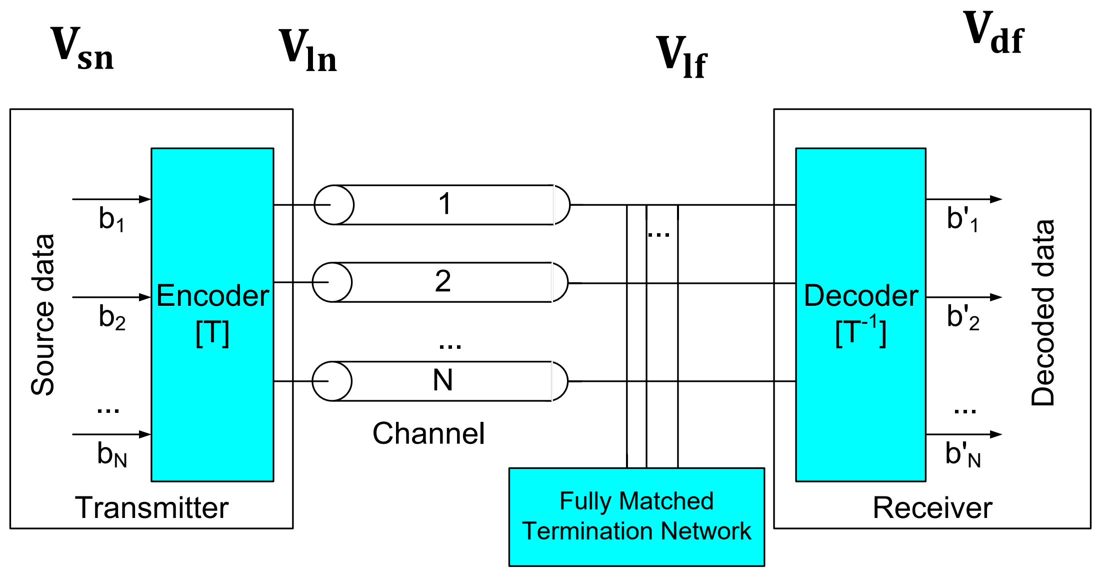
- Establish a practical design flow of the modal transceiver system.

- The overall goal: enable crosstalk-free high-speed signaling on dense, low-cost chip-to-chip interconnects

Mode-Aware Signaling for Optimal FEXT Mitigation

- Common for all previous proposed methods:
  - Treat coupling as undesired, try to remove its effects
  - Harder to implement as coupling gets tighter (more crosstalk to cancel)
- An alternative approach: Modal signaling
  - Takes advantage of tight coupling using channel diagonalization
  - ✓ Enables increased routing density
  - Special cases have been explored
  - Attempt to solve the general case

Modal Signaling System – Ideal Lines



$$\mathbf{V_{mn} = EV_{ln}}$$

$$\mathbf{V_{mf} = X_m V_{mn}}$$

$$\mathbf{V_{mf} = X_m E V_{ln}}$$

$$\mathbf{V_{lf} = E^{-1} V_{mf} = E^{-1} X_m E V_{ln}}$$

E: Eigenvector matrix

$$\mathbf{V_{df} = T E^{-1} X_m E T^{-1} V_{sn}}$$

X_m: Propagation matrix (diagonal)

If we choose $T=E^{-1}$ all signals are perfectly reconstructed

Multiconductor Theory

- Line bundle can be described by matrices per unit length
- $$\mathbf{Z}=\mathbf{R}+j\omega\mathbf{L},\ \mathbf{Y}=\mathbf{G}+j\omega\mathbf{C}$$
- Telegrapher's equations in frequency domain reveal coupling

$$\frac{d^2\mathbf{V}}{dz^2}=(\mathbf{ZY})\mathbf{V} \qquad \frac{d^2\mathbf{I}}{dz^2}=(\mathbf{YZ})\mathbf{I}$$

- Goal: introduce modal variables, diagonalizing the line equations
- Issue: For lines with discontinuities, Z and Y change over length

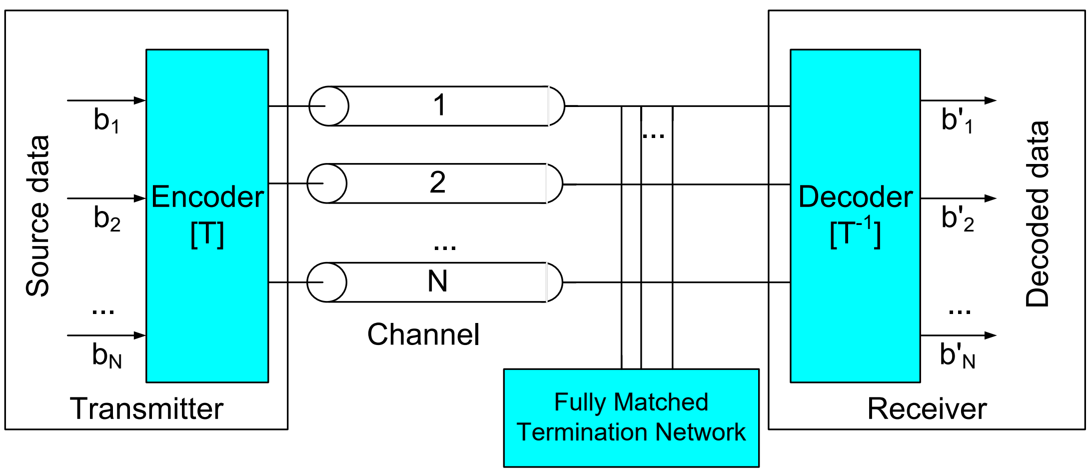
- Only interested in voltages/currents at ends of the channel
- Start by describing the channel by its ABCD-parameters (one choice):

$$\begin{bmatrix} v_S \\ i_S \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} v_R \\ i_R \end{bmatrix}$$

Modal Signaling System

- For unidirectional signaling in forward direction:
  - Map signals onto propagation modes at Tx; retrieve at Rx
  - We can use $T=W_{Fv}$ or $T=W_{Fi}$ waveshapes for signaling
  - Terminate the lines with $Y_{term}=Y_{C,F}$ to eliminate reflections and mode conversion
  - Optimal signaling from crosstalk mitigation standpoint

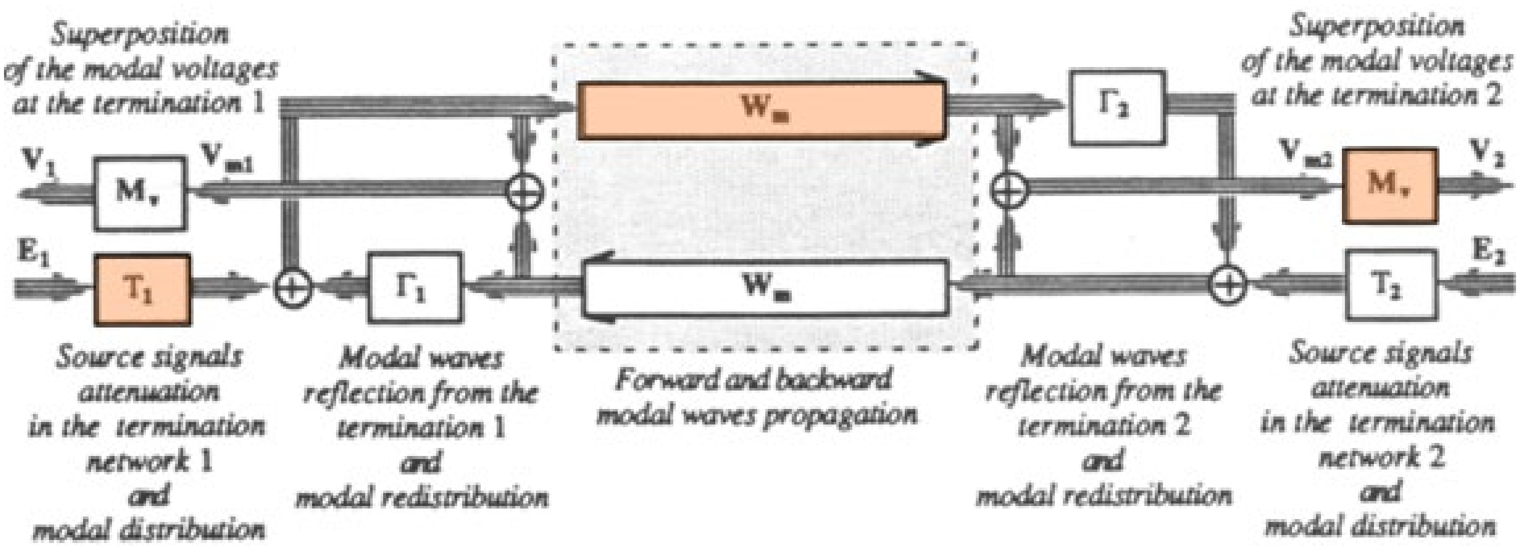
- Block diagram of the proposed direct implementation:



- **Encoder, decoder – linear combinations of signals (channel eigenvectors)**
- **Matching network – needed to avoid reflections and mode conversion**

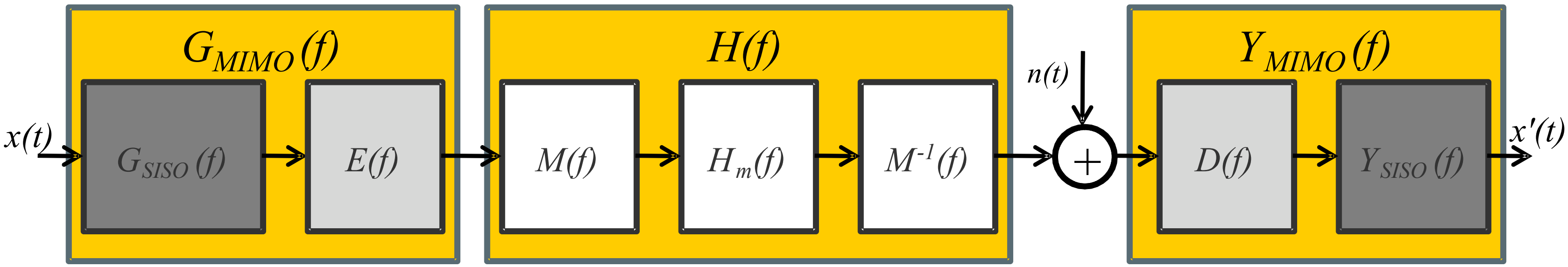
Need for Termination Network

- In case of reflections at the far-end, signals would represent the superposition of the incoming waves and the reflected ones;
- Modal redistribution - translates into crosstalk between modal channels;
- Therefore into crosstalk between decodes signal as well.



Frequency domain modal propagation model in matrix form (after Kuznetsov/Schutt-Aine 1992).

Modal Signaling Concept: Decoupling of Modal Channels



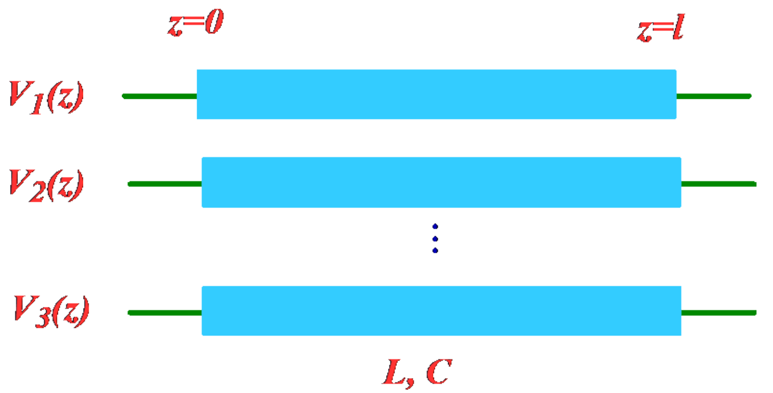
- Block diagram of Tx – channel – Rx
- $H_m(f)$ – diagonal modal propagation matrix: $H_m(f)=diag(e^{-\alpha(f)l-j\beta(f)l})$

• In frequency domain: $X' = D\,(M^{-1}\,H_m\,M)\,E\,X$

• If we choose Tx encoder $E=M^{-1}$, Rx decoder $D=M$:
  - After decoding: $X' = M\,(M^{-1}\,H_m\,M)\,M^{-1}\,X = H_m\,X$

• H_m diagonal: crosstalk is completely eliminated
  - Need to implement a termination network for channel $H(f)$
  - Need to take into account noise present in the system

TELGRAPHER'S EQUATION FOR N COUPLED TRANSMISSION LINES



$$-\frac{\partial V}{\partial z} = L\frac{\partial I}{\partial t}$$

$$-\frac{\partial I}{\partial z} = C\frac{\partial V}{\partial t}$$

V and *I* are the line voltage and line current VECTORS respectively (dimension n).

Eigenvalues and Eigenvectors

$$ELCE^{-1} = \Lambda_m^2$$

gives

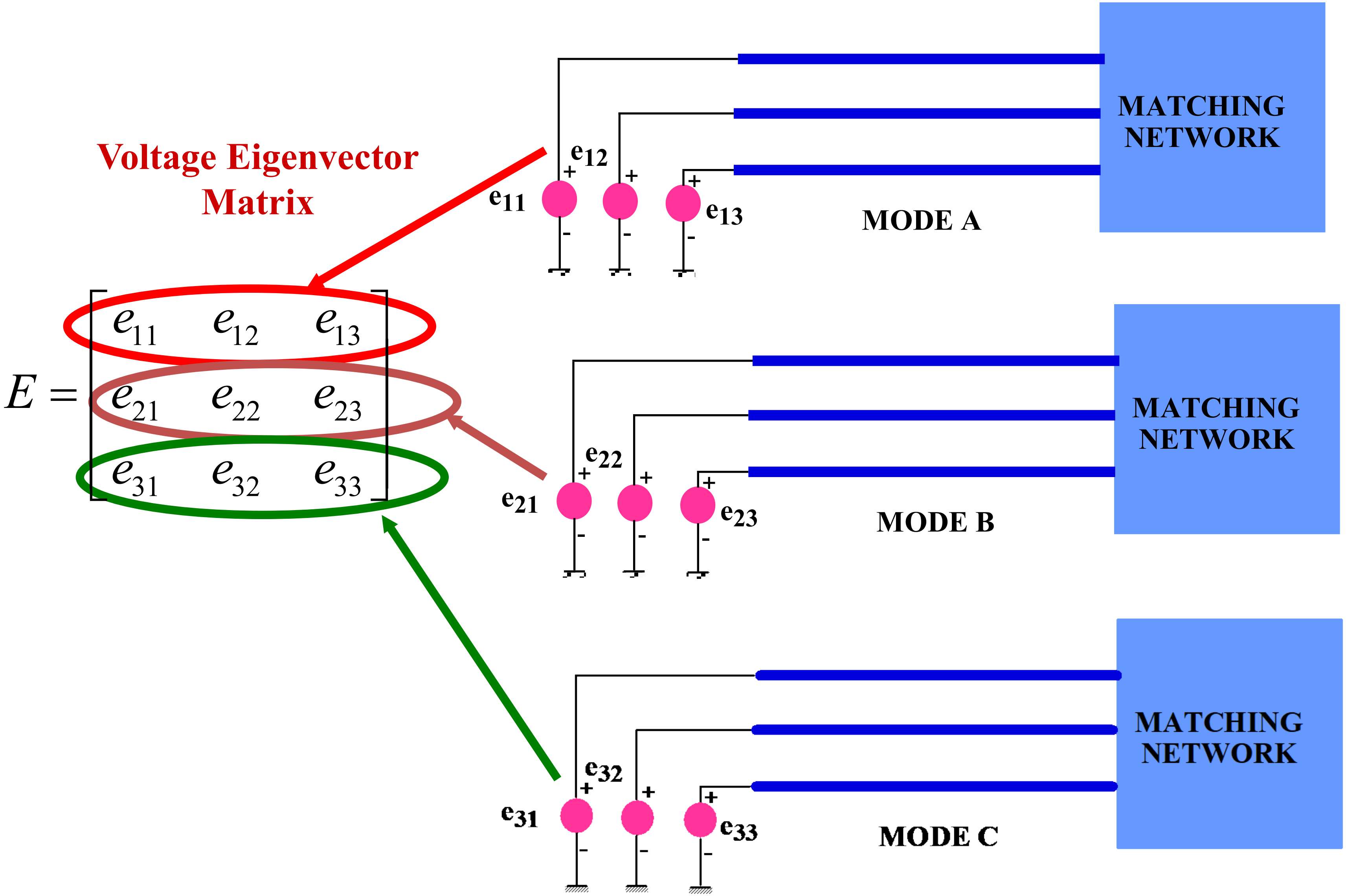
$$E = \begin{bmatrix} e_{11} & e_{12} & e_{13} \\ e_{21} & e_{22} & e_{23} \\ e_{31} & e_{32} & e_{33} \end{bmatrix} \qquad \Lambda_m = \begin{bmatrix} \frac{1}{v_{m1}} & 0 & 0 \\ 0 & \frac{1}{v_{m2}} & 0 \\ 0 & 0 & \frac{1}{v_{m3}} \end{bmatrix}$$

$$HCLH^{-1} = \Lambda_m^2$$

gives

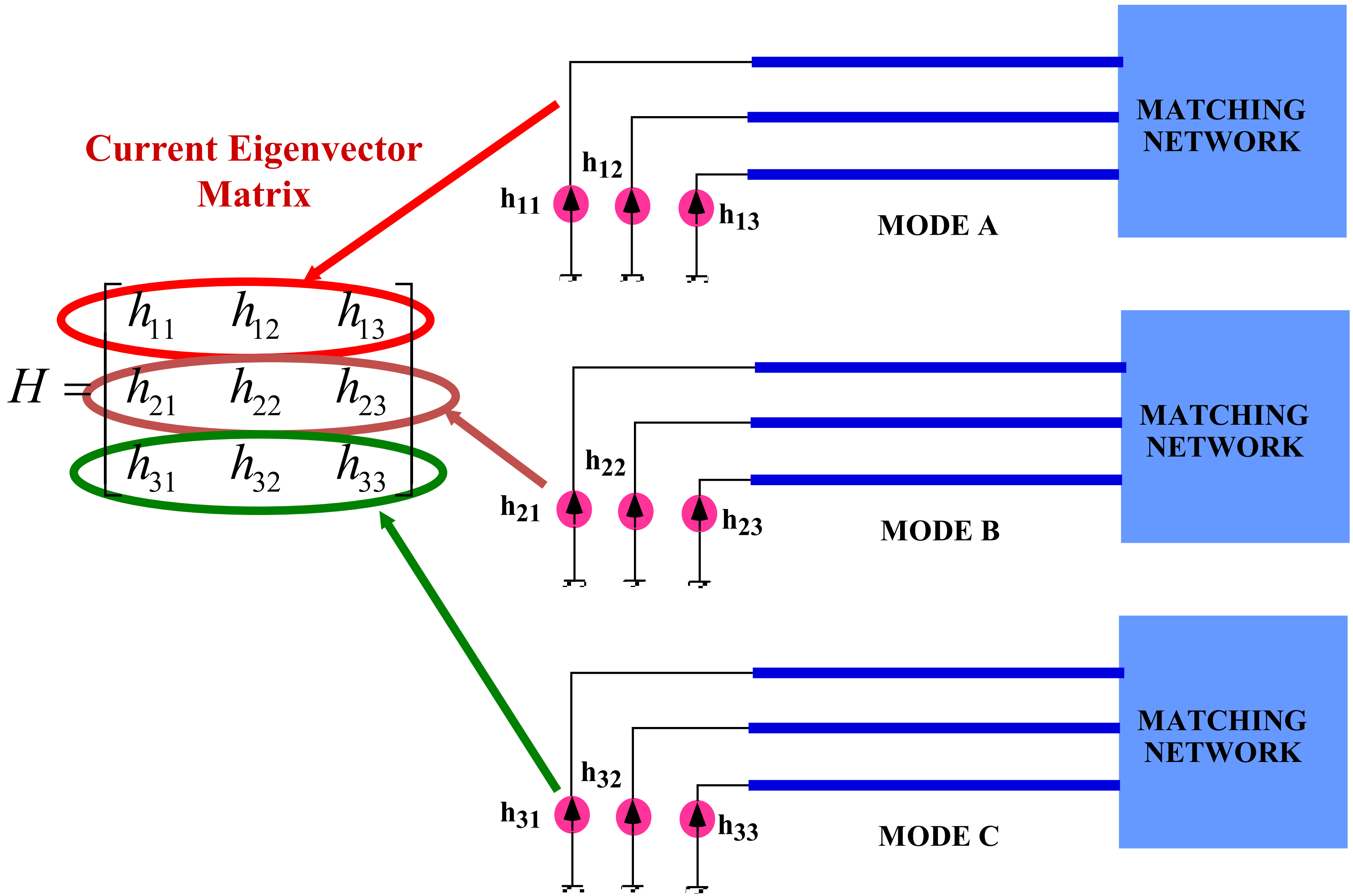
$$H = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix} \qquad \Lambda_m = \begin{bmatrix} \frac{1}{v_{m1}} & 0 & 0 \\ 0 & \frac{1}{v_{m2}} & 0 \\ 0 & 0 & \frac{1}{v_{m3}} \end{bmatrix}$$

Modal Voltage Excitation



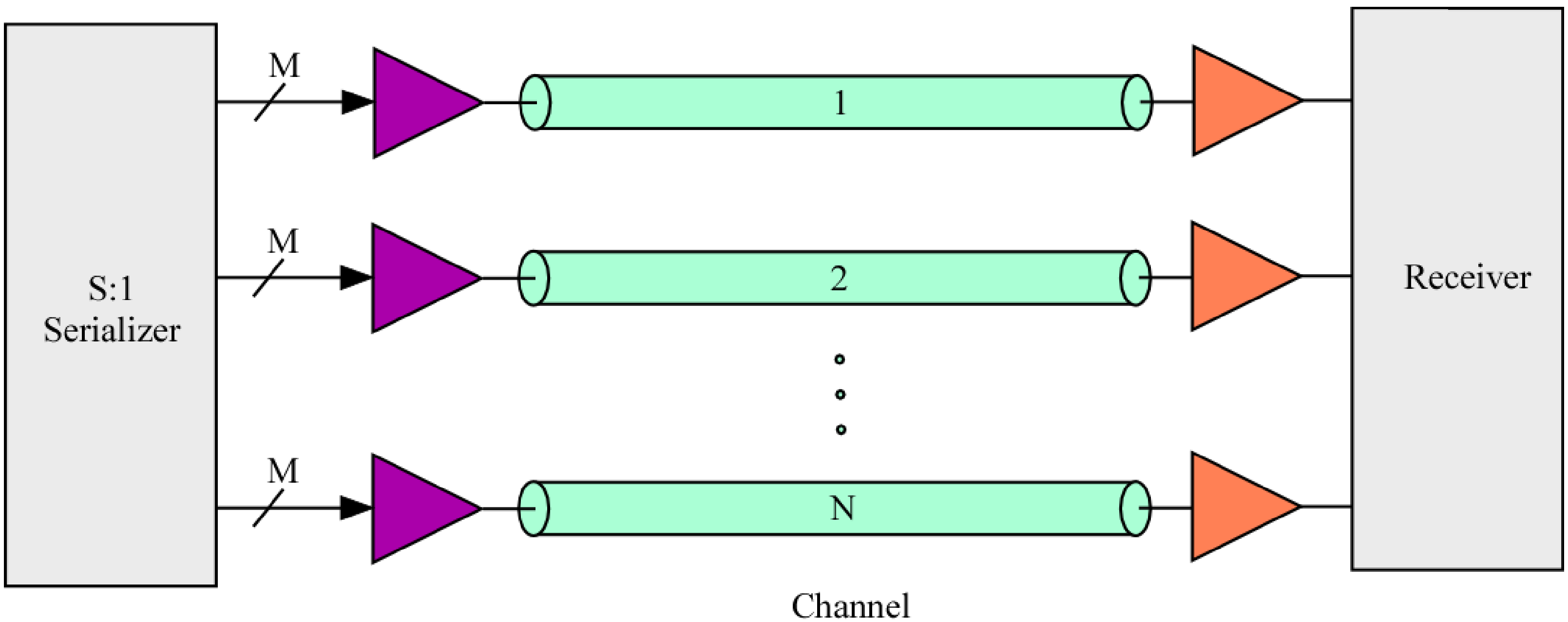
$$E = \begin{bmatrix} e_{11} & e_{12} & e_{13} \\ e_{21} & e_{22} & e_{23} \\ e_{31} & e_{32} & e_{33} \end{bmatrix}$$

Modal Current Excitation



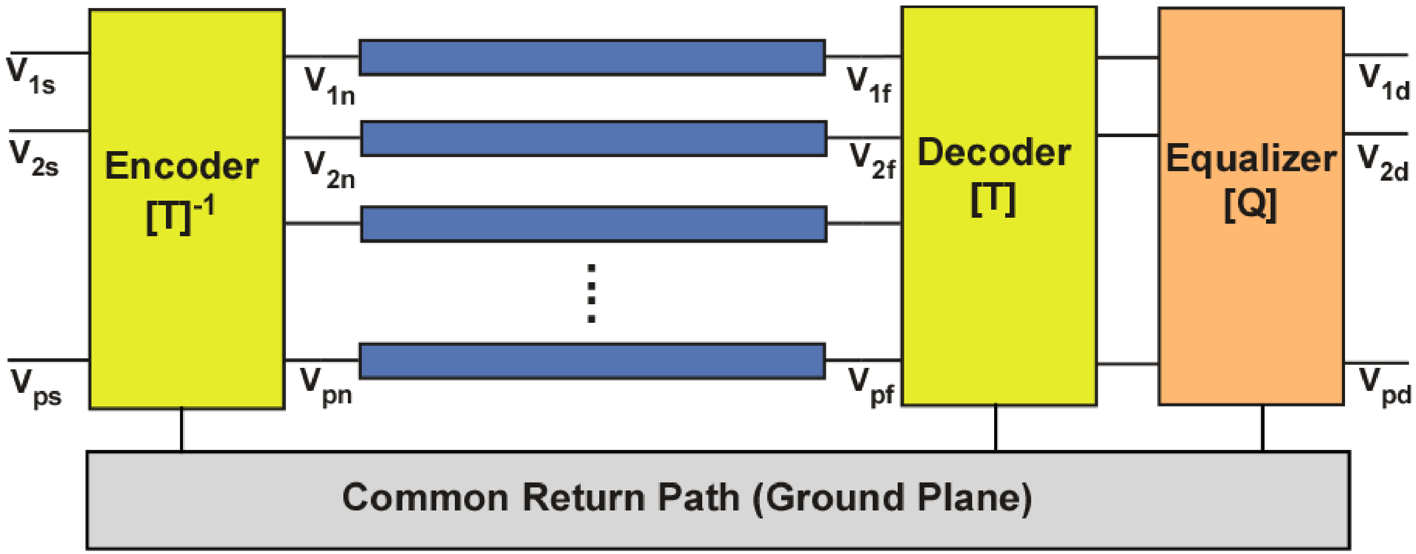
Crosstalk – Uniform Channel

Channel consists of uniform transmission lines



Crosstalk can be described by multi-conductor TL theory

Crosstalk Mitigation in Parallel Buses



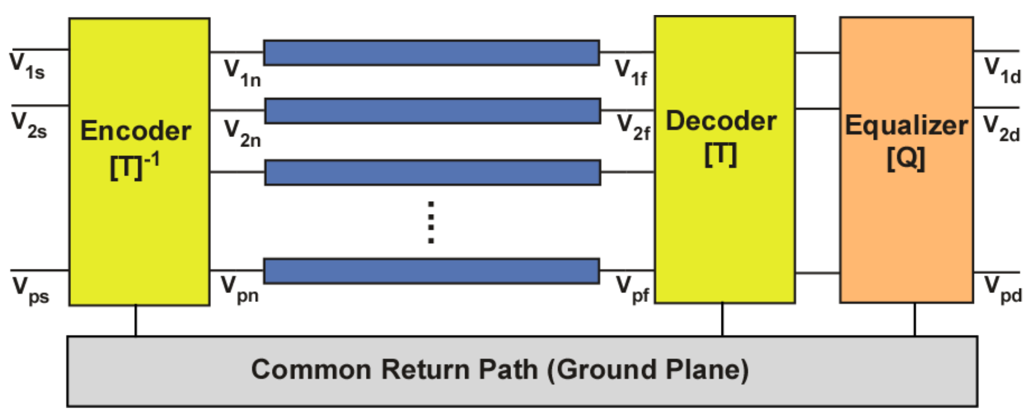
$$\mathbf{V_{sn}} = \begin{bmatrix} V_{1s} \\ V_{2s} \\ \cdot \\ V_{ps} \end{bmatrix} \qquad \mathbf{V_{ln}} = \begin{bmatrix} V_{1n} \\ V_{2n} \\ \cdot \\ V_{pn} \end{bmatrix} \qquad \mathbf{V_{lf}} = \begin{bmatrix} V_{1f} \\ V_{2f} \\ \cdot \\ V_{pf} \end{bmatrix} \qquad \mathbf{V_{df}} = \begin{bmatrix} V_{1d} \\ V_{2d} \\ \cdot \\ V_{pd} \end{bmatrix}$$

Crosstalk Mitigation in Parallel Buses

$$\mathbf{V}_{mn} = \mathbf{E}\mathbf{V}_{ln}$$

where $\mathbf{V}_{ln}$ is the *line* voltage vector and $\mathbf{V}_{mn}$ is the *modal* voltage vector at the near end. **E** is the voltage eigenvector matrix associated with the multi-conductor system. In general, **E** will be complex and a function of frequency. The modal voltage vector at the far end, $\mathbf{V}_{mf}$ will be given by:

$$\mathbf{V}_{mf} = \mathbf{X}_m \mathbf{V}_{mn}$$



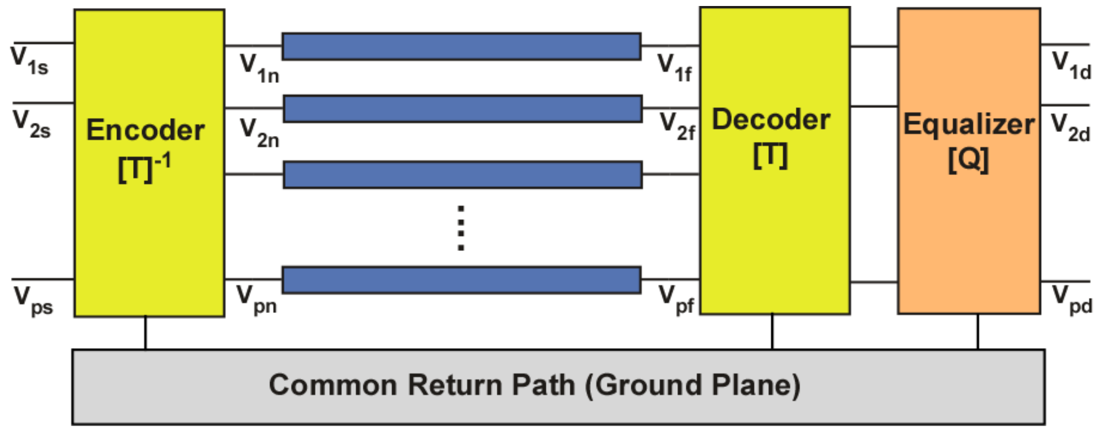
Crosstalk Mitigation in Parallel Buses

$\mathbf{X_m}$ is the complex propagation matrix function given by

$$\mathbf{X_m} = \begin{bmatrix} e^{-\alpha_1 l - j\beta_1 l} & & & \\ & e^{-\alpha_2 l - j\beta_2 l} & & \\ & & \cdot & \\ & & & e^{-\alpha_p l - j\beta_p l} \end{bmatrix}$$

in which $\alpha_i + j\beta_i$ is the complex propagation constant, associated with the ith mode and l is the length of the lines. In terms of near-end signals this reads

Crosstalk Mitigation in Parallel Buses



$$\mathbf{V}_{mf} = \mathbf{X}_m \mathbf{E} \mathbf{V}_{ln}$$

The far-end line voltage vector, $\mathbf{V}_{lf}$ can be recovered using:

$$\mathbf{V}_{lf} = \mathbf{E}^{-1}\mathbf{V}_{mf} = \mathbf{E}^{-1}\mathbf{X}_m \mathbf{E} \mathbf{V}_{ln}$$

Crosstalk Mitigation in Parallel Buses

Now, assume that the information signals are encoded with the encoder **T** such that the signals are mapped to the orthogonal modes, as follows:

$$\mathbf{V_{ln}} = \mathbf{T^{-1}V_{sn}}$$

At the far end the decoded voltage vector would be given by:

$$\mathbf{V_{df}} = \mathbf{QTV_{lf}}$$

where **Q** is an equalization matrix representing any equalizer box that might be implemented at the output of the channel, we get

Crosstalk Mitigation in Parallel Buses

$$\mathbf{V_{df}} = \mathbf{QTE^{-1}X_m ET^{-1}V_{sn}}$$

If we choose **T=E** we obtain

$$\mathbf{V_{df}} = \mathbf{QX_m V_{sn}}$$

$$\begin{bmatrix} V_{1d} \\ V_{2d} \\ \cdot \\ V_{pd} \end{bmatrix} = \mathbf{Q} \begin{bmatrix} e^{-\alpha_1 l - j\beta_1 l} & & & \\ & e^{-\alpha_2 l - j\beta_2 l} & & \\ & & \cdot & \\ & & & e^{-\alpha_p l - j\beta_p l} \end{bmatrix} \begin{bmatrix} V_{1s} \\ V_{2s} \\ \cdot \\ V_{ps} \end{bmatrix}$$

Crosstalk Mitigation in Parallel Buses

If in addition, we implement an equalizer with property

$$\mathbf{Q} = \begin{bmatrix} e^{+\alpha_1 l} & & & \\ & e^{+\alpha_2 l} & & \\ & & \cdot & \\ & & & e^{+\alpha_p l} \end{bmatrix}$$

this gives

$$\begin{bmatrix} V_{1d} \\ V_{2d} \\ \cdot \\ V_{pd} \end{bmatrix} = \begin{bmatrix} e^{-j\beta_1 l} & & & \\ & e^{-j\beta_2 l} & & \\ & & \cdot & \\ & & & e^{-j\beta_p l} \end{bmatrix} \begin{bmatrix} V_{1s} \\ V_{2s} \\ \cdot \\ V_{ps} \end{bmatrix} = \begin{bmatrix} e^{-j\frac{\omega l}{v_{m1}}} & & & \\ & e^{-j\frac{\omega l}{v_{m2}}} & & \\ & & \cdot & \\ & & & e^{-j\frac{\omega l}{v_{mp}}} \end{bmatrix} \begin{bmatrix} V_{1s} \\ V_{2s} \\ \cdot \\ V_{ps} \end{bmatrix}$$

Crosstalk Mitigation in Parallel Buses

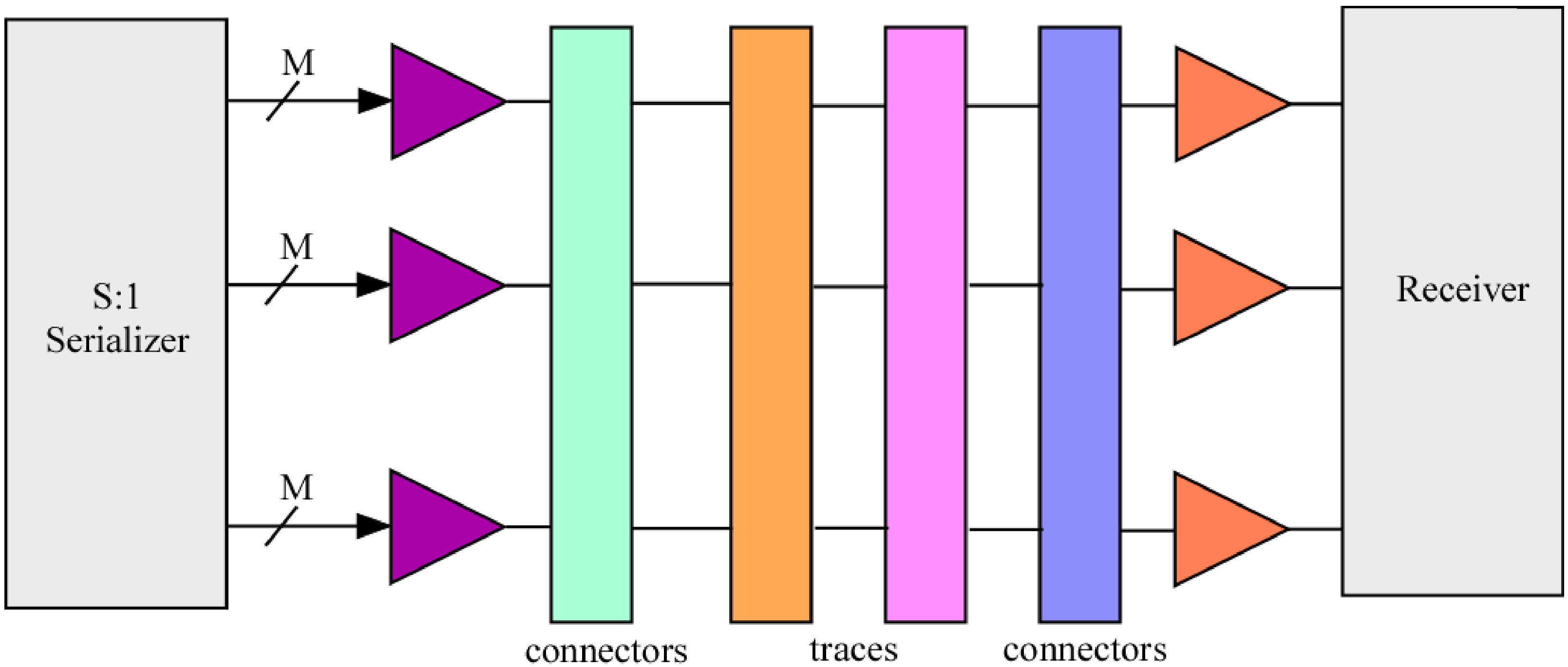
$$\begin{bmatrix} V_{1d} \\ V_{2d} \\ \cdot \\ V_{pd} \end{bmatrix} = \begin{bmatrix} e^{-j\beta_1 l} & & & \\ & e^{-j\beta_2 l} & & \\ & & \cdot & \\ & & & e^{-j\beta_p l} \end{bmatrix} \begin{bmatrix} V_{1s} \\ V_{2s} \\ \cdot \\ V_{ps} \end{bmatrix} = \begin{bmatrix} e^{-j\frac{\omega l}{v_{m1}}} & & & \\ & e^{-j\frac{\omega l}{v_{m2}}} & & \\ & & \cdot & \\ & & & e^{-j\frac{\omega l}{v_{mp}}} \end{bmatrix} \begin{bmatrix} V_{1s} \\ V_{2s} \\ \cdot \\ V_{ps} \end{bmatrix}$$

in which we used the relation $\beta_i = \omega/v_{mi}$. This shows that if the proper encoder, decoder and equalizer can be implemented, ***all signals can be perfectly reconstructed, with no crosstalk, no attenuation and no dispersion.***

In the special case where the lines are lossless, $\alpha_i = 0$, Q= I (the identity matrix) and no equalization is needed. Also E is real and does not depend on frequency.

Crosstalk – Non-uniform Channel

Channel consists of connectors and traces



Cascade of S parameters

Generalized Modal Decomposition

- Traditional modal decomposition diagonalizes $ZY=(R+j\omega L)(G+j\omega C)$ matrix
  - Issues: For lines with multiple segments, Z and Y change over length; Discontinuites

- For signaling, only interested in Tx/Rx voltages/currents: v_S, i_S, v_R, i_R
  - Use eigenvalue decomposition to diagonalize overall channel (S- or ABCD-parameters):

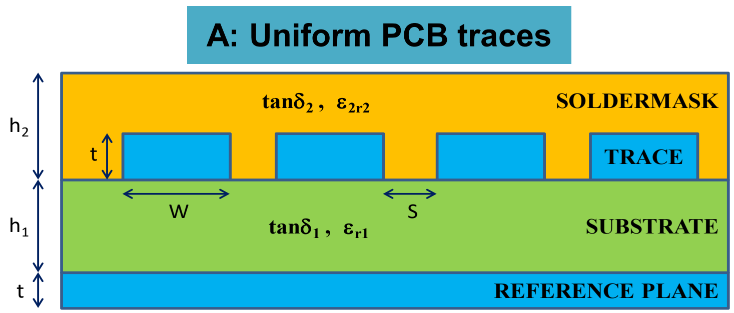
$$\begin{bmatrix} v_S \\ i_S \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} v_R \\ i_R \end{bmatrix} = \begin{bmatrix} W_{Fv} & W_{Bv} \\ W_{Fi} & W_{Bi} \end{bmatrix} \begin{bmatrix} \lambda_F & \\ & \lambda_B \end{bmatrix} \begin{bmatrix} W_{Fv} & W_{Bv} \\ W_{Fi} & W_{Bi} \end{bmatrix}^{-1} \begin{bmatrix} v_R \\ i_R \end{bmatrix}$$

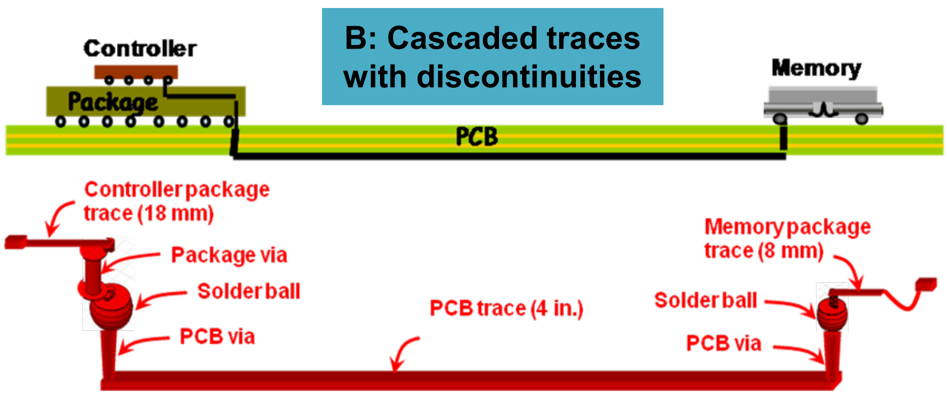
- Submatrices describe forward- and backward-propagating mode waves
  - Fundamental modes are linearly independent in all cases of interest
- Characteristic admittances: $Y_{C,F} = W_{Fi} W_{Fv}^{-1}$ and $Y_{C,B} = W_{Bi} W_{Bv}^{-1}$

- All the submatrices complex, frequency dependent (for a lossy channel)

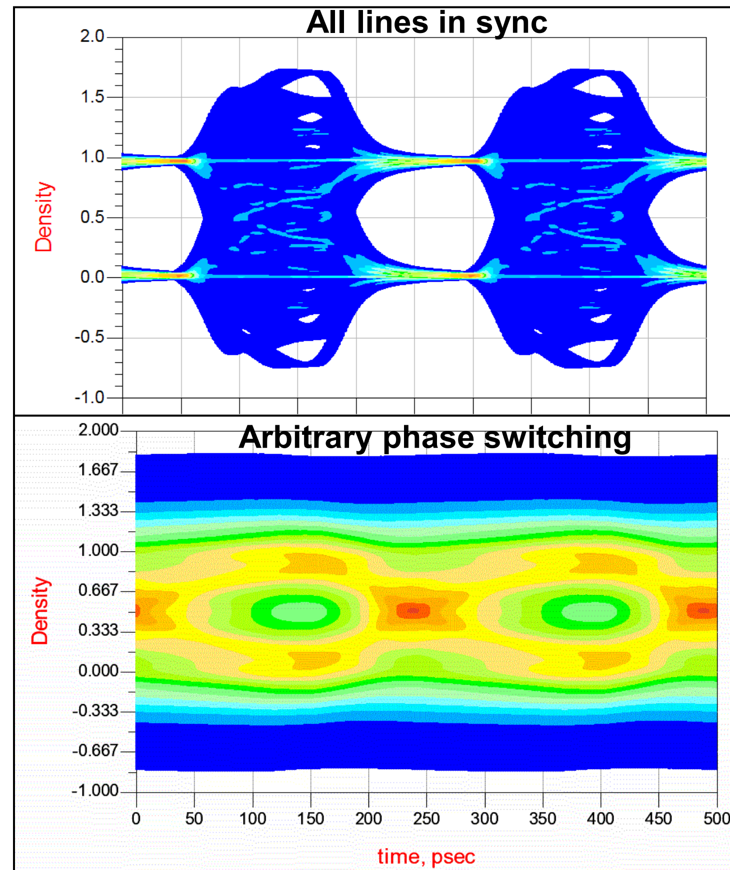
Four Tightly Coupled Lines

- Analyze waveshape properties of modal decomposition of channel parameter matrix (S, ABCD, …)
- Extract encoder/decoder/termination values at each frequency



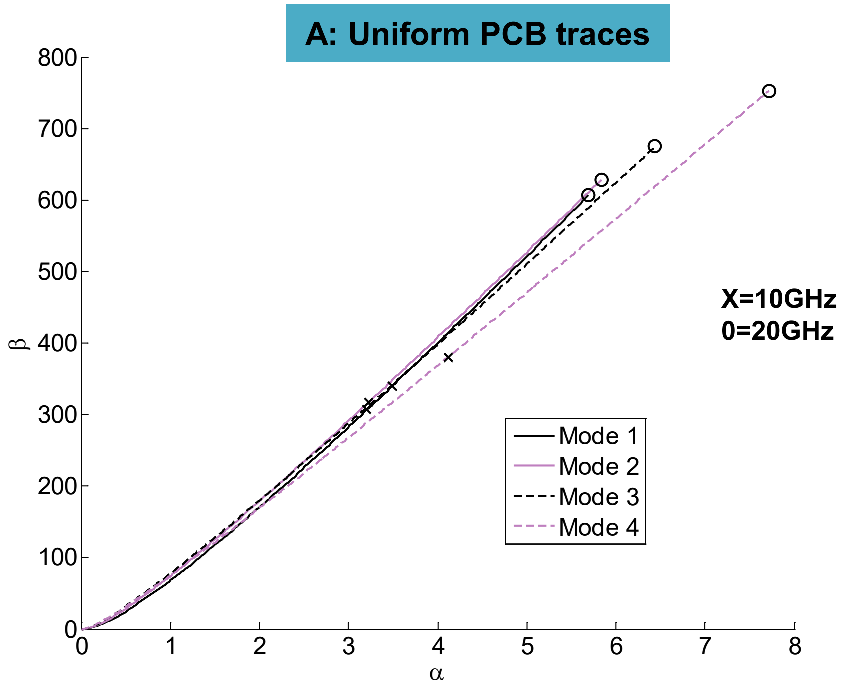


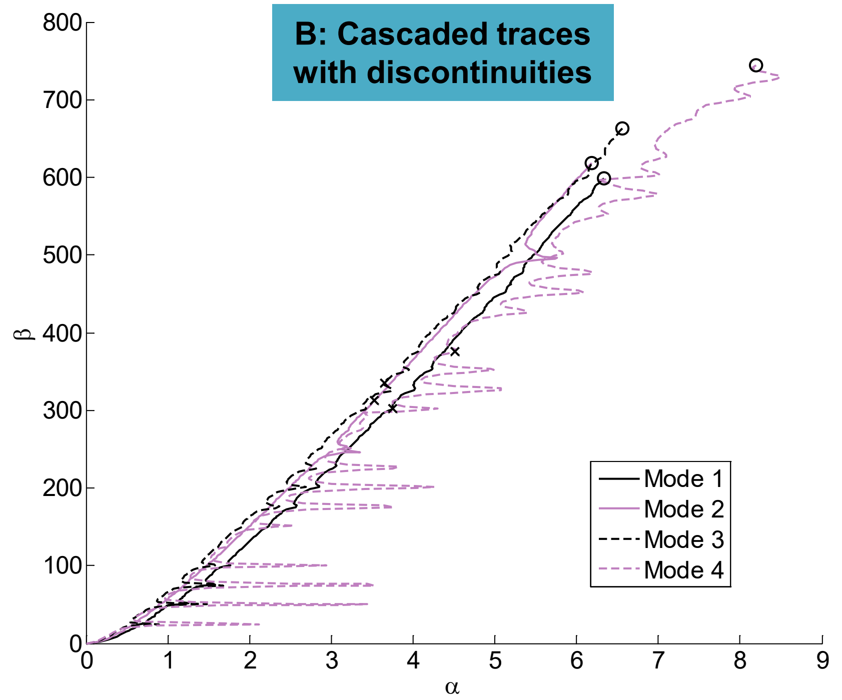
Parameter	εr1	εr2	tanδ1, tanδ2	h1 [µm]	h2 [µm]	W [µm]	S [µm]	t [µm]
PCB	4.1	3.5	0.02	118	60	173	132	50
package	3.35	3.5	0.02	35	37	35	35	17



Case B, 4 Gb/s NRZ t_r=67ps, uncoded

Propagation Constants of Modes



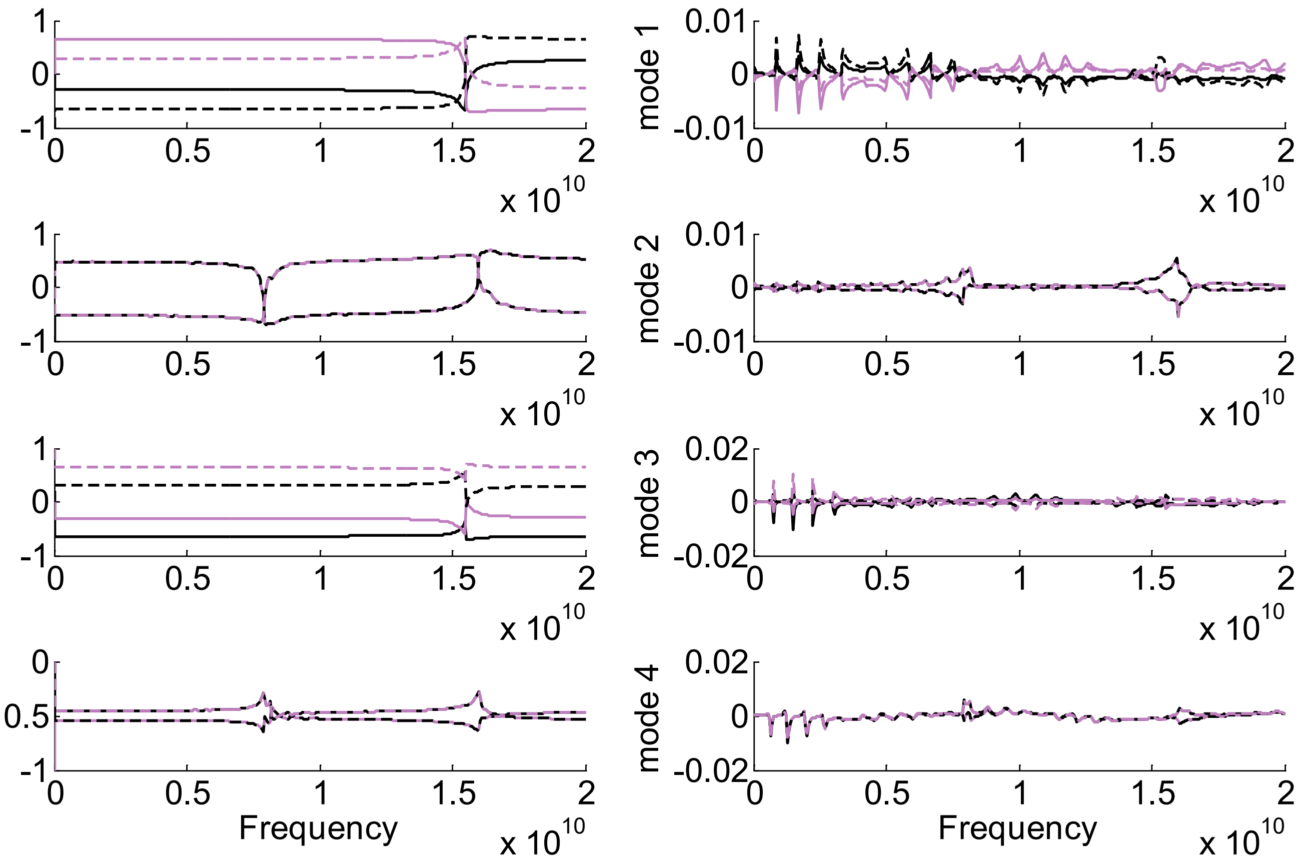


Encoder/decoder/terminations can be approximated by constant, real values

P. Milošević, J. Schutt-Ainé, and W. Beyene, "Crosstalk mitigation of high-speed interconnects with discontinuities using modal signaling," *Conf. on Electrical Performance of Electronic Packaging and Systems, 2010*

- Propagation constants exhibit resonances - resonant eigenvectors
- Interaction of modes between cascaded segments
- Some modes more resonant than others due to coupling mechanisms

Modeshapes (Eigenvectors)



Voltage **Current**

Eigenvectors (modeshapes) for the cascaded channel

- Voltage vectors stable over a wide freq. range
- Predominantly real

- Encoder/decoder still a linear combination matrix of constant coeff.

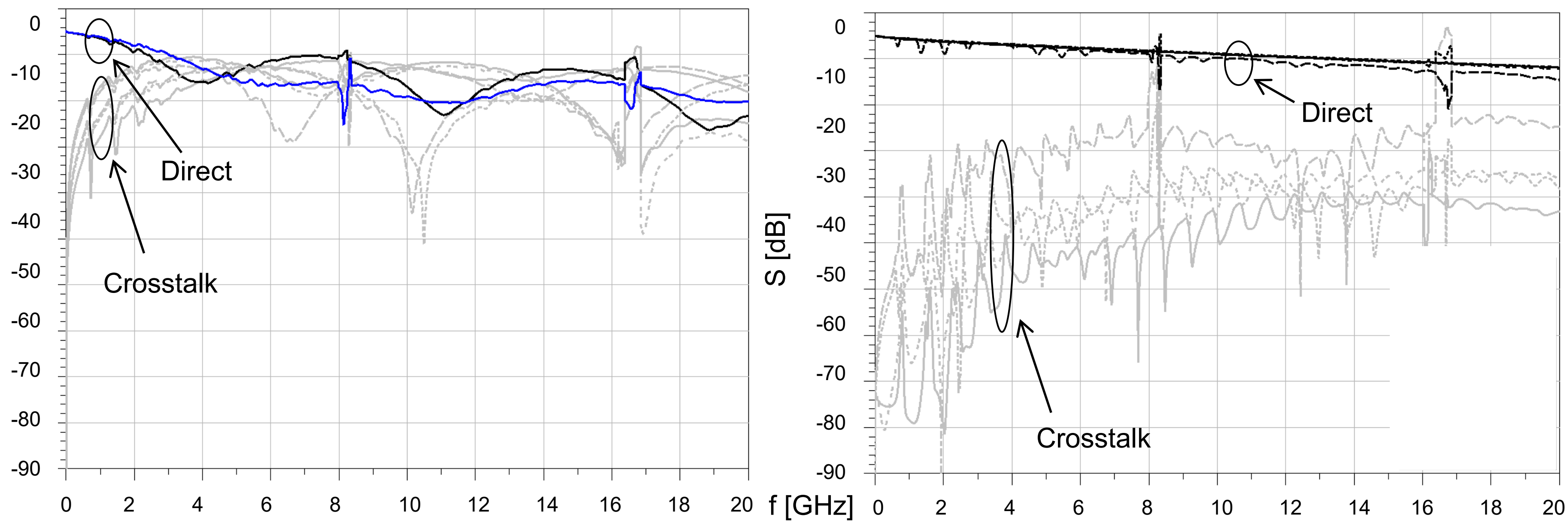
B. Cascaded Channel			
Mode 1	Mode 2	Mode 3	Mode 4
-0.6394	-0.5243	-0.2862	-0.4533
-0.3017	0.4743	0.6464	-0.5426
0.3017	0.4743	-0.6464	-0.5426
0.6394	-0.5243	0.2862	-0.4533

- Current vectors more resonant due to inductive coupling
- Will result in resonances in char. admittance matrix

Uncoded vs Optimal Modal Signaling

Uncoded channels
with no reflections

Modal coded channels
with optimal terminations

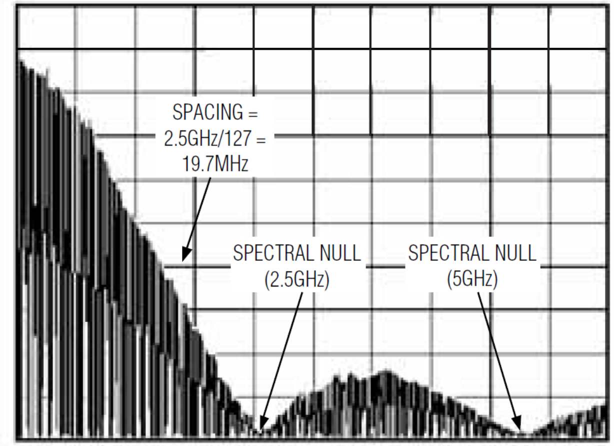


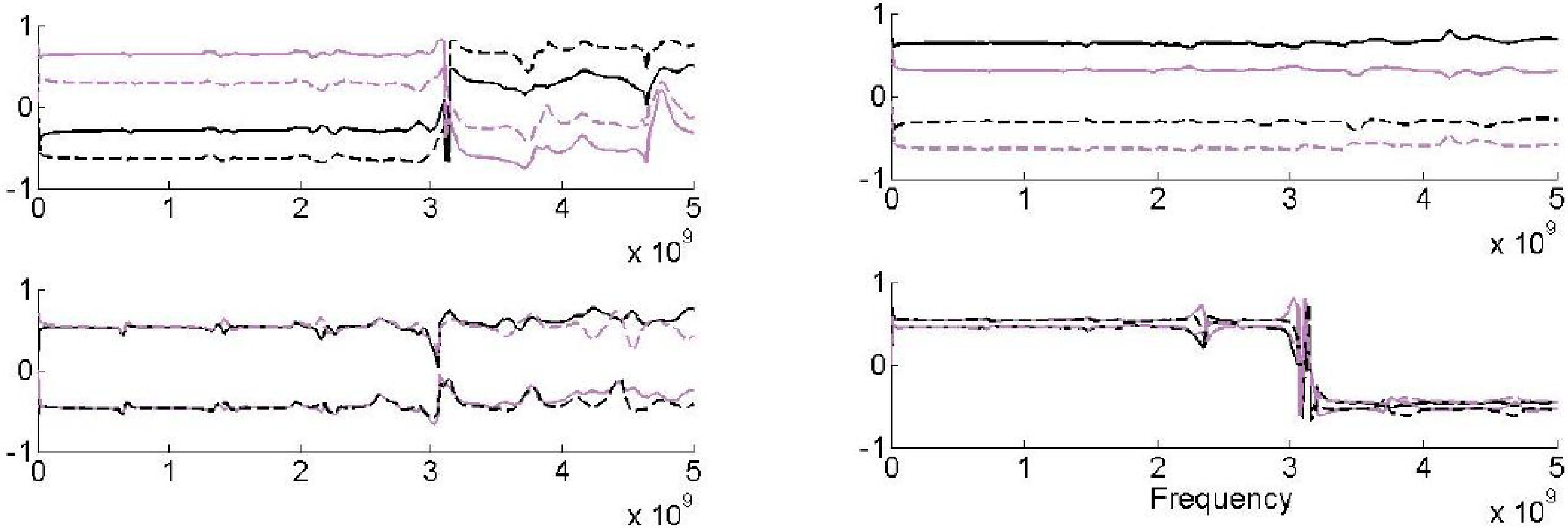
- Excellent crosstalk cancelation predicted (25 dB guardband up to 6GHz)
  - Shows the limits of modal signaling performance with optimal elements
- Flexible simulation framework set up (Agilent ADS/MATLAB)
  - Allows to study properties and tradeoffs of different block realizations

Impact of Discontinuities

- Non-TL artifacts (vias, solderballs, connectors) limit max. data rate
  - Eigenvectors start to exhibit freq. dependence at high frequencies
  - Most of NRZ signal energy is contained below 1st spectral null

2^7-1 PRBS PATTERN, 2.5Gbps



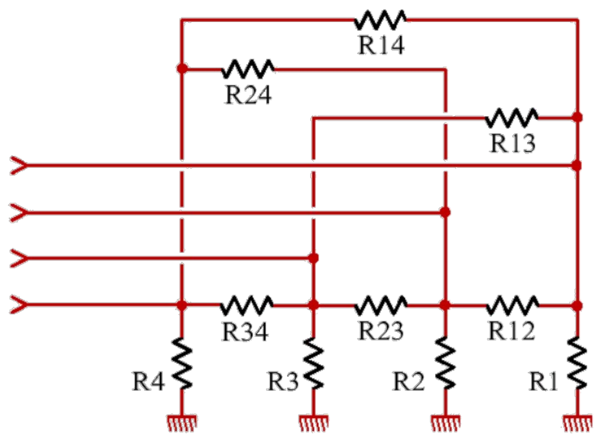


Voltage eigenvectors (modeshapes) for the cascaded channel with vias and solderballs

Optimal Termination Network

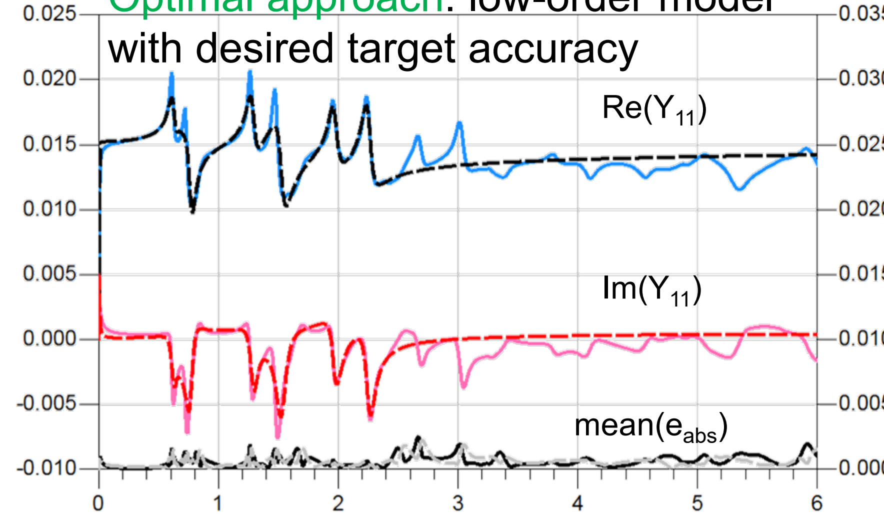
- Resistive approaches: use low-freq values or optimize for minimized total reflection

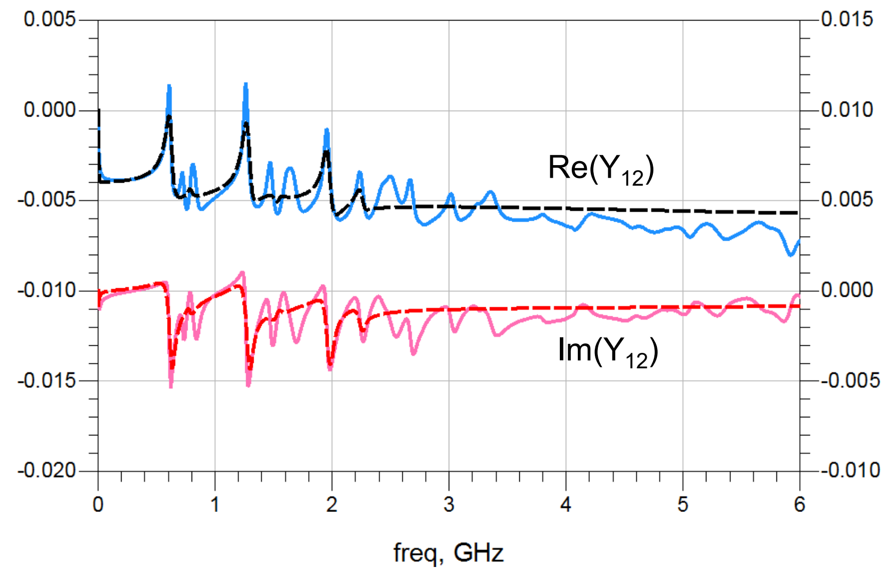
Termination Resistors [Ω]	Uniform (PCB)	Uniform (package)	Cascaded (100MHz)	Cascaded (optimized)
R11, R44	87.3	125.8	97.5	101
R22, R33	108.6	187.1	123.9	131
R12, R34	273.6	181.2	267.1	280
R23	280.6	187.9	277.2	312
R13, R24	2955.4	2133.7	2318.2	1450
R14	5904.6	4451.4	4901.2	2453



P. Milošević, W. Beyene, and J. Schutt-Ainé, "Optimal Terminations for Crosstalk Mitigation of High-Speed Interconnects with Discontinuities Using Modal Signaling", *submitted for publication*

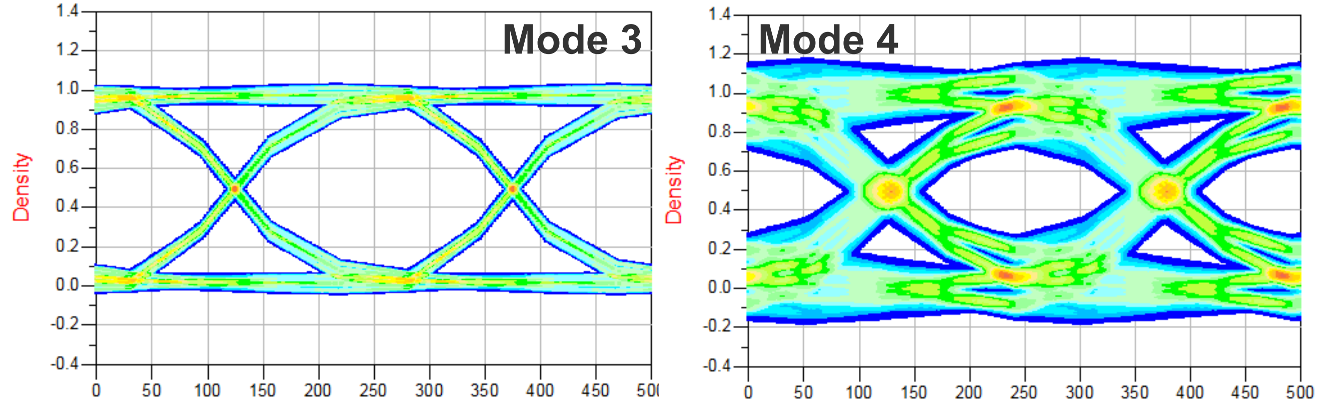
Optimal approach: low-order model with desired target accuracy





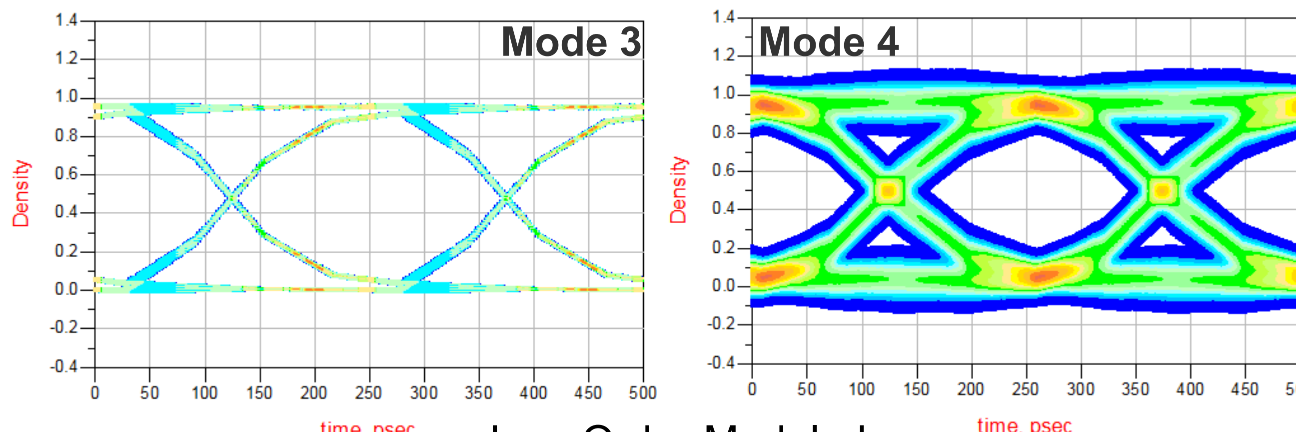
Performance Comparison of the Termination Networks

- Statistical eye diagrams of 4 Gb/s NRZ, t_r=67ps, all modes switching
  - Only 2 out of 4 channels shown
- *Note: channel for which uncoded eye was closed*



Resistive Terminations

- Vertical eye opening increase of 39%
- Reduction in peak-to-peak jitter of 27%
- “Ground mode” #4 suffers from ISI of internal reflections



Low-Order Modeled

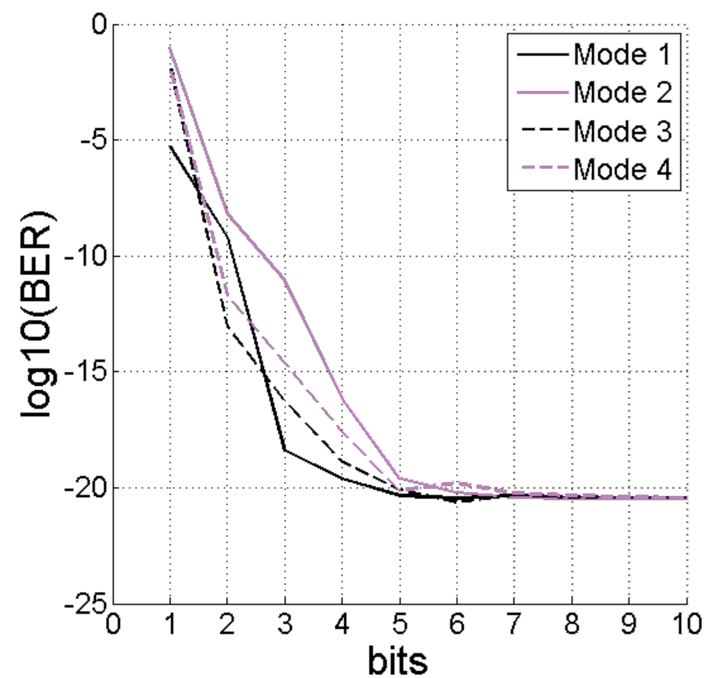
Noise in Modal Signaling Systems

- Encoder and decoder tunable → quantization noise
- Random (thermal, input-referred) noise
  - Not dominant today, but low-power trends can make it an issue
- MIMO communication theory approach
  - Methods of determining Tx/Rx design tradeoffs in presence of noise
  - Several key issues explored

Mode	1	2	3	4
SNRcom [dB]	∞	58.5	∞	37.5
SNRuncor [dB]	38.2	37.6	38.1	37.5

1. Theoretical impact of common and uncorrelated far-end noise – modal signaling robustness

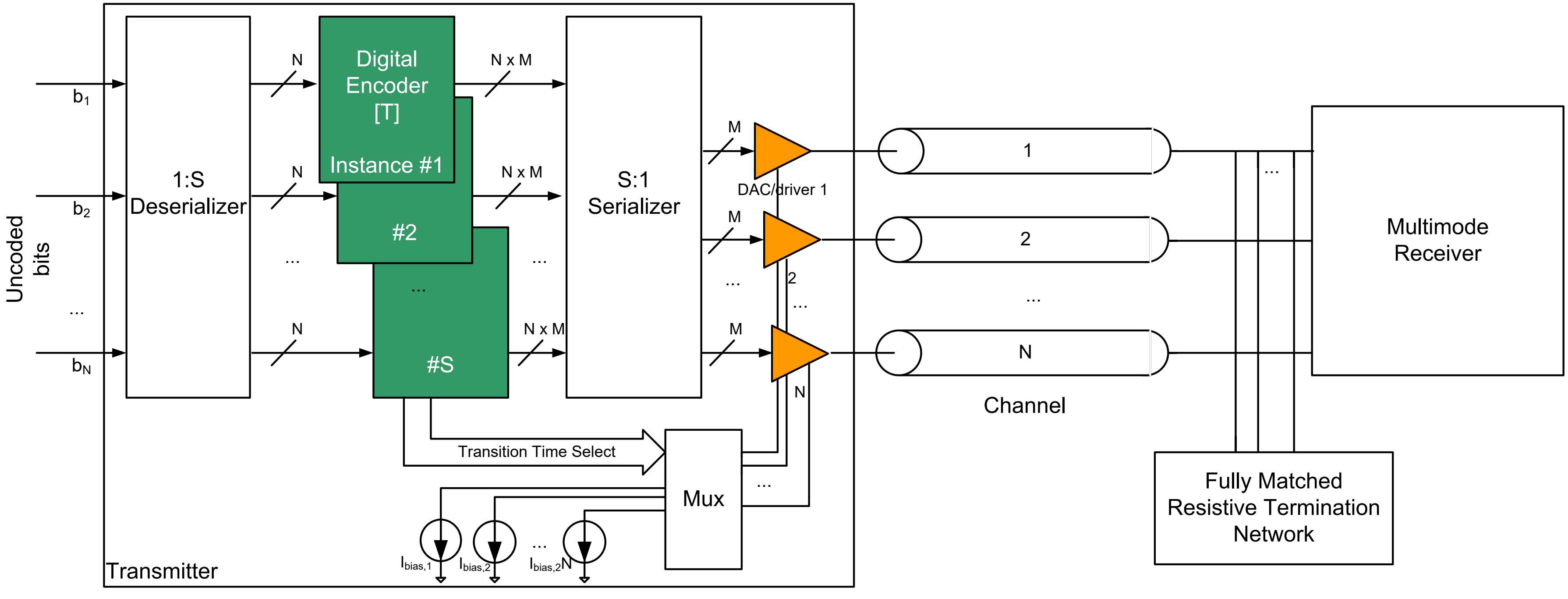
P. Milošević and J. Schutt-Ainé, "System-Level Characterization of Modal Signaling for High-Density Off-Chip Interconnects," Symp. On Electrical Design of Adv. Packaging & Systems, 2011



2. Impact of resolution of eigenvector coefficient quantization on BER

Physical Realization (1)
DSP-based Encoding

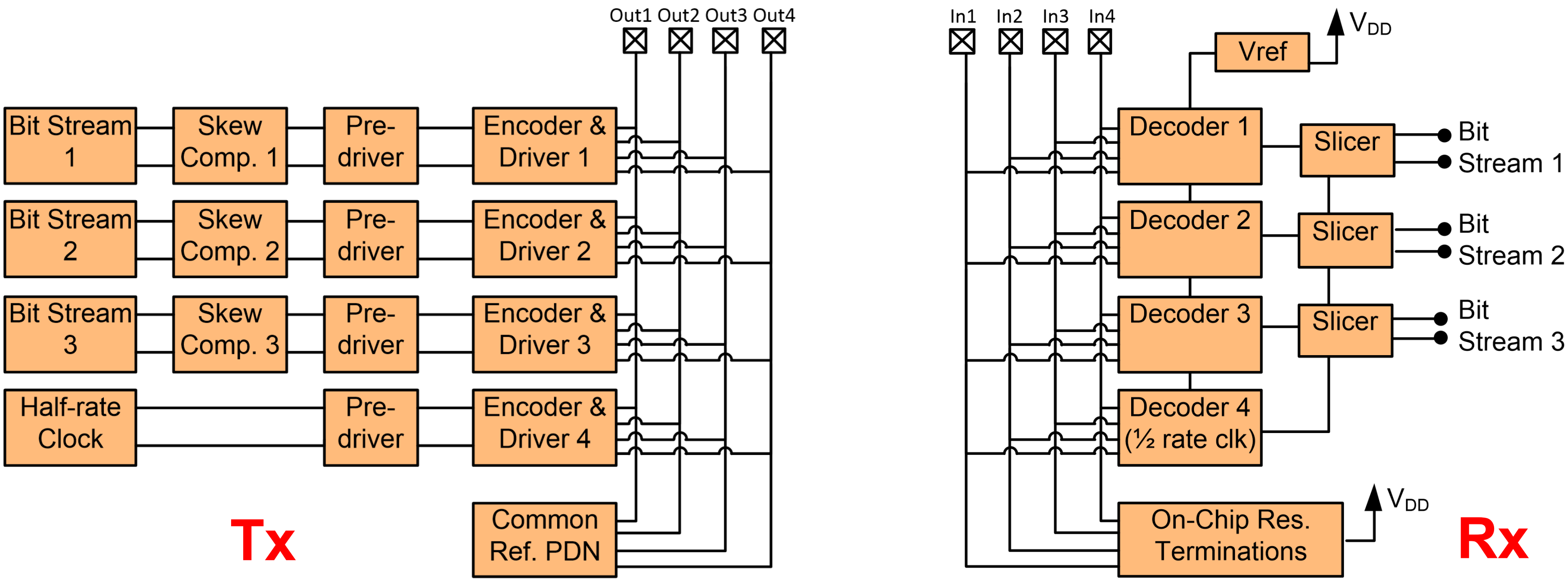
– DSP encoder directly calculates final transition values
– DAC/line drivers need to generate proper transition waveforms
– Most suited to Tx with DSP core (and SerDes) already in place



Physical Realization (2) Analog Frontend

- Channel: 4-line 4-inch pkg-PCB-pkg bus
- 3 bitstreams x 4 Gb/s = 12 Gb/s
- Forwarded clock uses ground mode
  - Half rate (2Gb/s) to alleviate limited bandwidth
  - This allows simple resistive terminations

P. Milošević and J. Schutt-Ainé, "Design of a 12Gb/s Transceiver for High-Density Links with Discontinuities using Modal Signaling" *Conf. on Electrical Performance of Electronic Packaging and Systems, 2011*

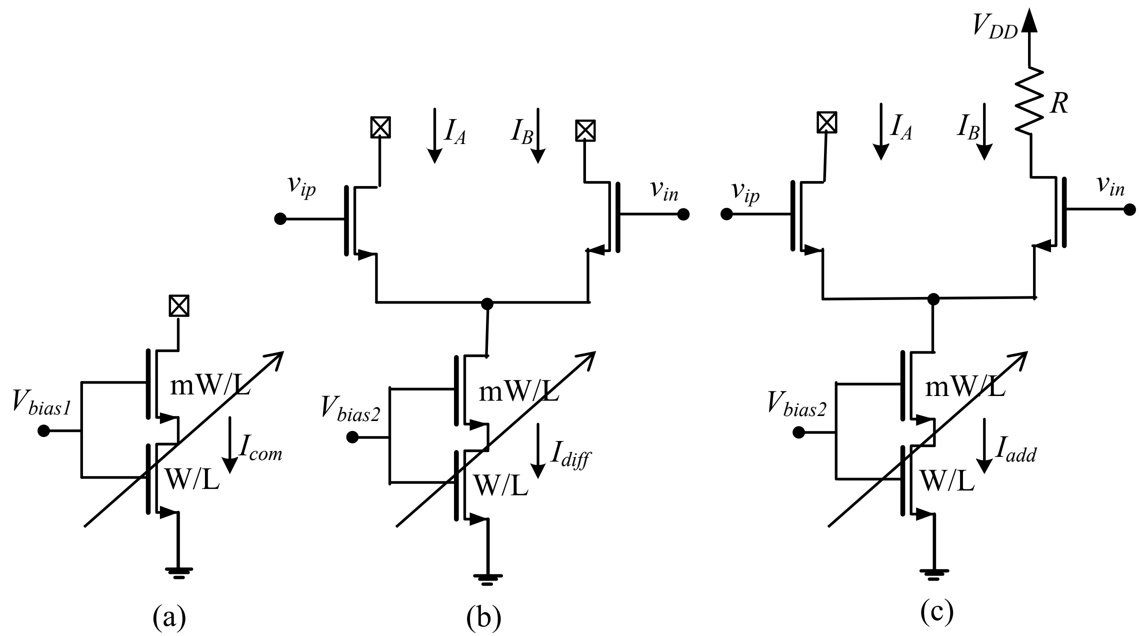


Analog Implementation: Encoder/Driver Block

- Currents needed to generate modes (250 m$V_{p\text{-}p}$ each):

	ΔI [mA]				
Line	Mode 1	Mode 2	Mode 3	Mode 4	Common
1	1.0650	1.1950	-0.7970	0.5270	0.6740
2	0.4670	-1.0000	1.6773	0.6060	0.0252
3	-0.4670	-1.0000	-1.6773	0.6060	0.0252
4	-1.0650	1.1950	0.7970	0.5270	0.6740

- Pseudo-open-drain driver style
  - Self-cascode used to increase output res. (strong coupling)
- Modes 1 and 3 can share current
- Modes 2 and 4 need additional current



(a) Open-drain drivers producing the common-voltage levels;
(b) Current-steering for shared currents, and (c) for non-shared currents

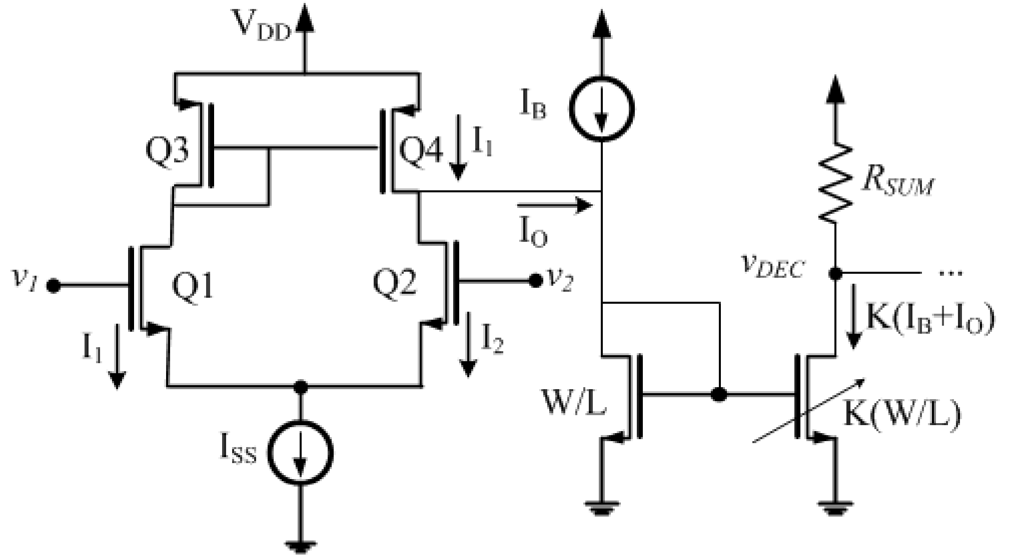
Analog Implementation: Decoder Block

- Each linear combination is a weighed sum/difference of 4 received voltages

- Convert received voltages to currents

- Coefficients using current mirror sizing

- Sum all currents onto a resistor to generate decoded voltage



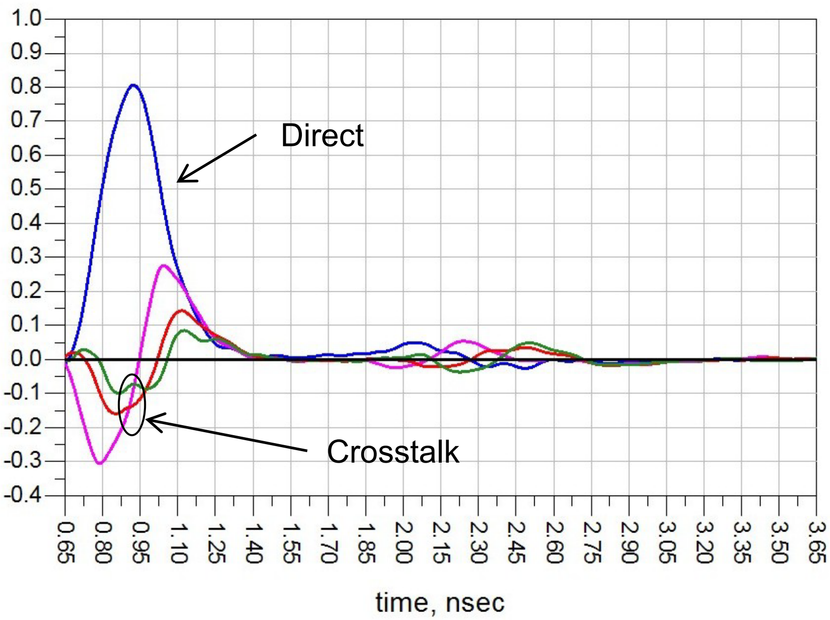
$$I_O = I_1 - I_2 = \frac{1}{2} k_n' \frac{W}{L} (V_1 - V_2) \sqrt{\frac{4 I_{SS}}{k_n' \frac{W}{L}} - (V_1 - V_2)^2}$$

$$\approx \sqrt{k_n' \frac{W}{L} I_{SS}} (V_1 - V_2)$$

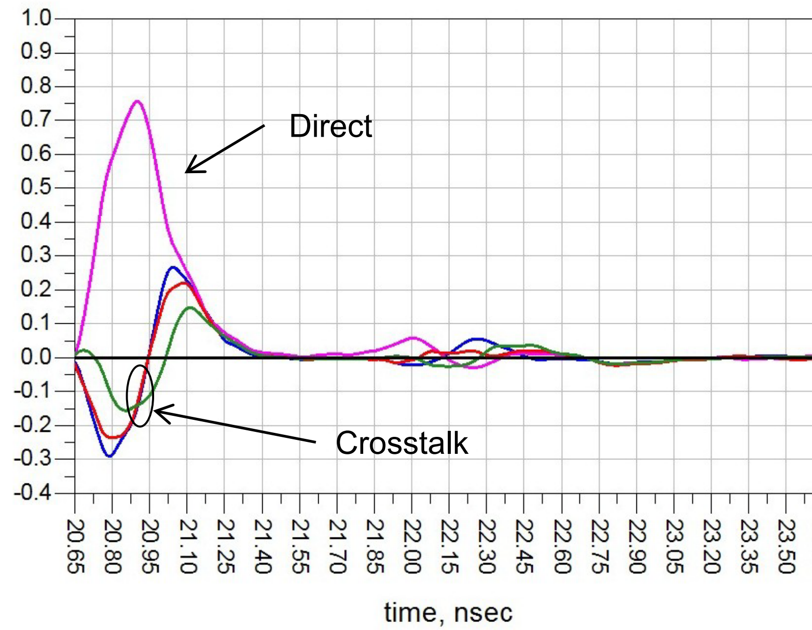
For appropriately chosen W/L and I_{SS} (incomplete switching)

NRZ on Uncoded Channel with C_i

- Pulse on an outer line



- Pulse on an inner line

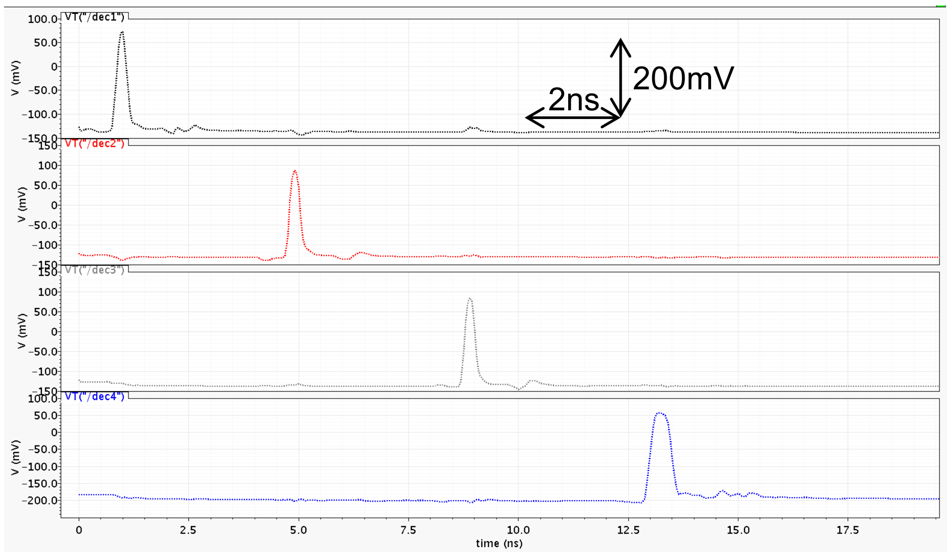


Even at ½ rate, jitter value is still half of the unit interval, which greatly exceeds the allocated jitter budget.

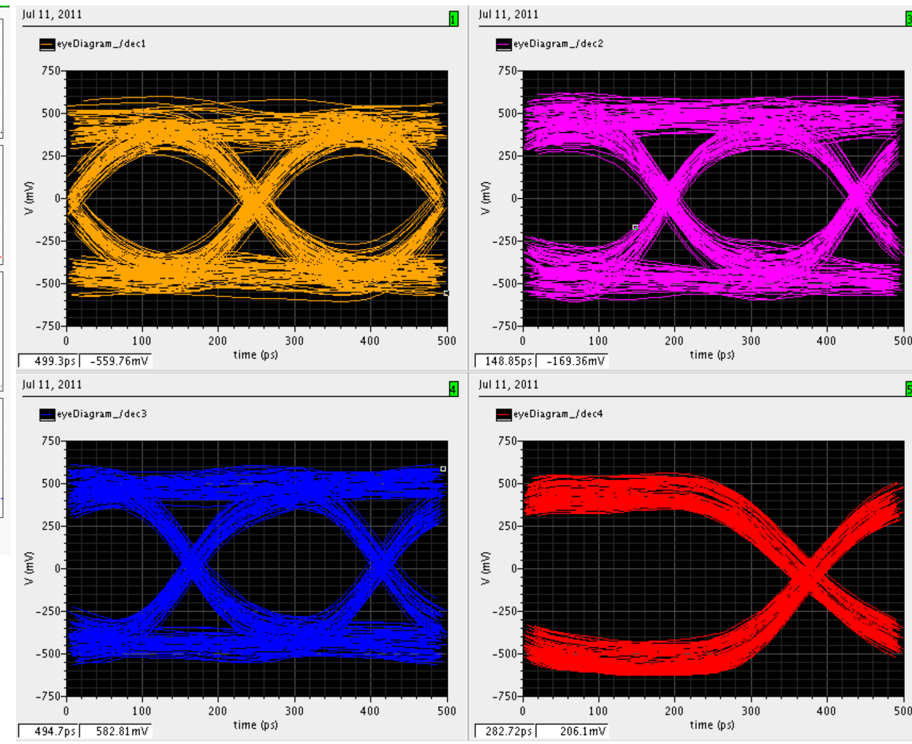
Bit Rate	Line	J_{pp}_$prbs$ [ps]	J_{pp}_$stat$ [ps]
4Gb/s	2,3	246.3	(eye closed)
	1,4	149.0	(eye closed)
2Gb/s	2,3	185.0	296.6
	1,4	100.1	241.1

Modal Signaling – Circuit-level Results

- Process used: IBM 90 nm low-power digital RF, 1.2 V supply
- Encoder/Driver (w/o pre-drivers): 11.0 mW (0.92 mW/Gb/s), 6500μm^2
- Decoder overhead (w/o slicers): 14.5 mW (1.20 mW/Gb/s), 4300μm^2



Unit pulse responses of signals over equivalent modal channels



Normalized eye diagrams of decoded modal signals

Performance Improvements and Comparison

- Max $J_{p\text{-}p}$ reduced to 15.6% of UI
- 2.5x increase in aggregate bandwidth
  - Compared to the conventional NRZ signaling on similar channel

Bit Rate	Mode	J_{pp}_prbs [ps]	J_{pp}_stat [ps]	$J_{pp}\_circuit$ [ps]	Min. Improvement [%]
4Gb/s	1	37.2	40.1	39.0	73.8
	2	31.0	41.8	34.7	76.7
	3	29.5	37.0	32.1	78.4
2Gb/s	4	56.4	76.9	58.0	42.1

- Other mitigation techniques fail due to tight coupling
  - Tx FEXT cancelation: peak-power limit closes vertical eye
  - Rx FEXT cancelation: FEXT pulses hard to mimic, subtract
  - Passive velocity matching: issues with cascaded segments
  - CIJ retiming implementation: too complicated for N>2

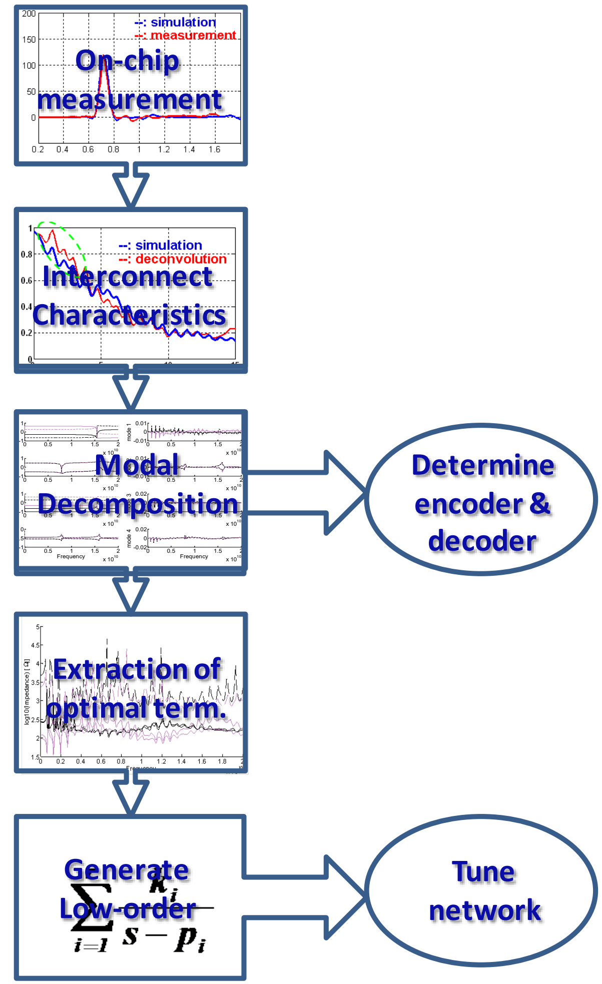
Synthesis Flow

- Procedure for the adaptive optimal crosstalk cancellation method

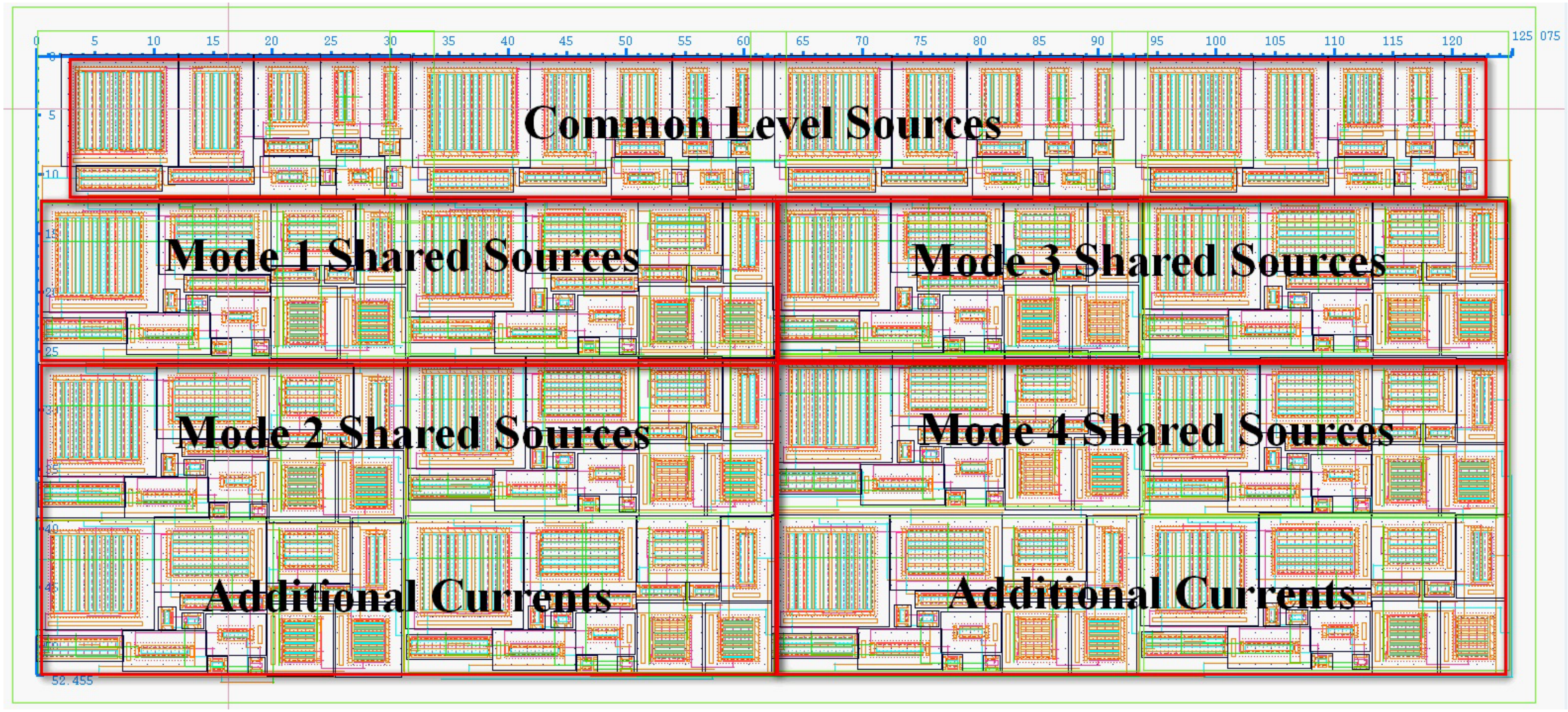
- Starts from realistic system measurements (or models)

- Decomposition – performed by the system or offline

- End result – tuned encoder, decoder and termination network for optimal signaling performance

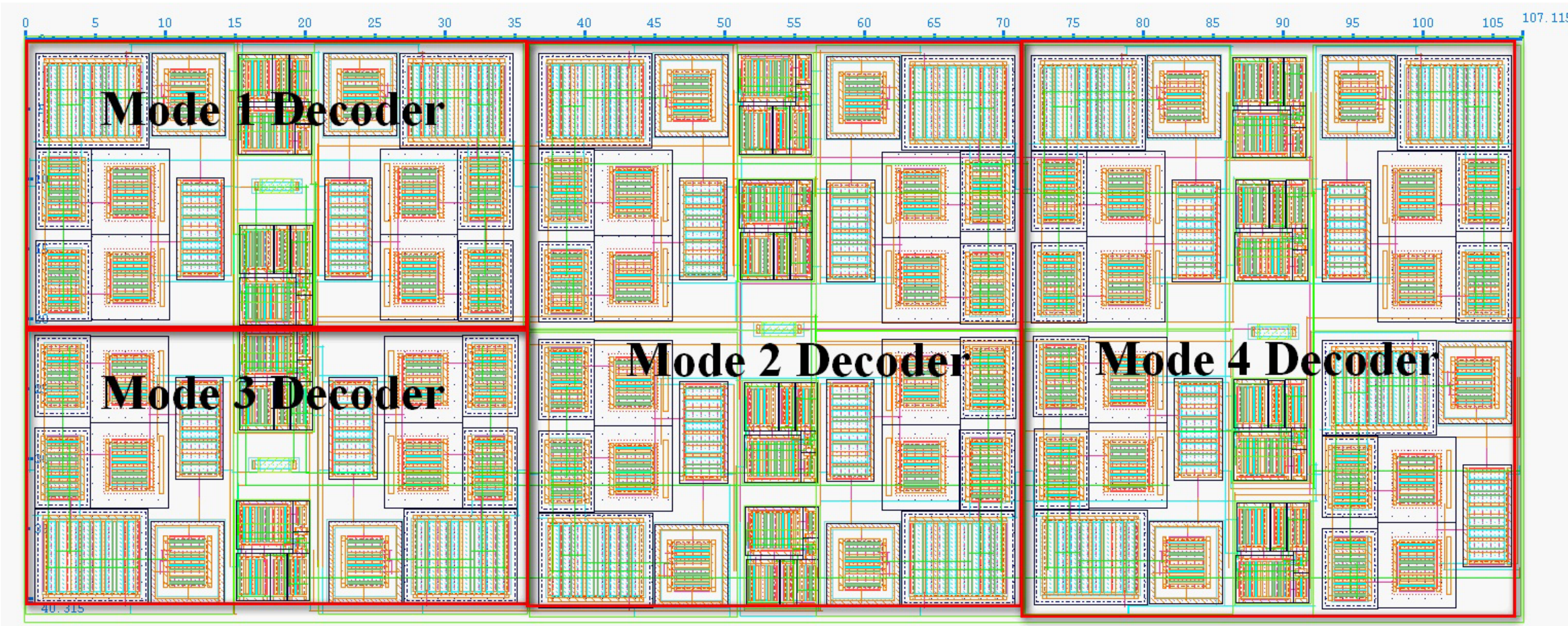


Encoder Layout



Milosevic, P., Schutt-Ainé, J.E., "Transceiver Design for High-Density Links With Discontinuities Using Modal Signaling", *IEEE Trans. Comp. Packaging. Manuf. Tech., vol. 3*, pp. 10-20, January 2013.

Decoder Layout



Milosevic, P., Schutt-Ainé, J.E., "Transceiver Design for High-Density Links With Discontinuities Using Modal Signaling", *IEEE Trans. Comp. Packaging. Manuf. Tech., vol. 3*, pp. 10-20, January 2013.