PCB Design Optimization: What it Means and New Methods

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NWES
NORTHWEST ENGINEERING SOLUTIONS LLC

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Conference & Exhibition

30 YEARS

INTRODUCTION

- What is PCB design optimization?
  - **Marketing speak!**

Our product optimizes performance enhancement while mitigating degradation to optimized improvements…

INTRODUCTION

- **Optimization:** An important area of engineering and design
- All design engineers do optimization subconsciously:
  - **Finding tradeoffs in a design**
  - **Balancing tradeoffs**
- Mathematically: Maximize/minimize something subject to some constraints

What is PCB Design Optimization?

- Mathematical definition:

Max. or min. $f(x_1, x_2, \ldots, x_N)$

My design goal
- Impedance
- S-parameters
- Routing density
- Dispersion

Subject to:

$$g_1(x_1, x_2, \ldots, x_N) \leq A$$
$$g_2(x_1, x_2, \ldots, x_N) \leq A$$
$$\vdots$$

My constraints
- Any design goal could be a constraint

$$|x_1, x_2, \ldots, x_N| \leq C$$

My design variables
- Usually geometric

- How to choose $x_1, x_2, \ldots, x_N$ so that I meet my objective function $f(x_1, x_2, \ldots, x_N)$ while satisfying $g_1, g_2, \ldots$

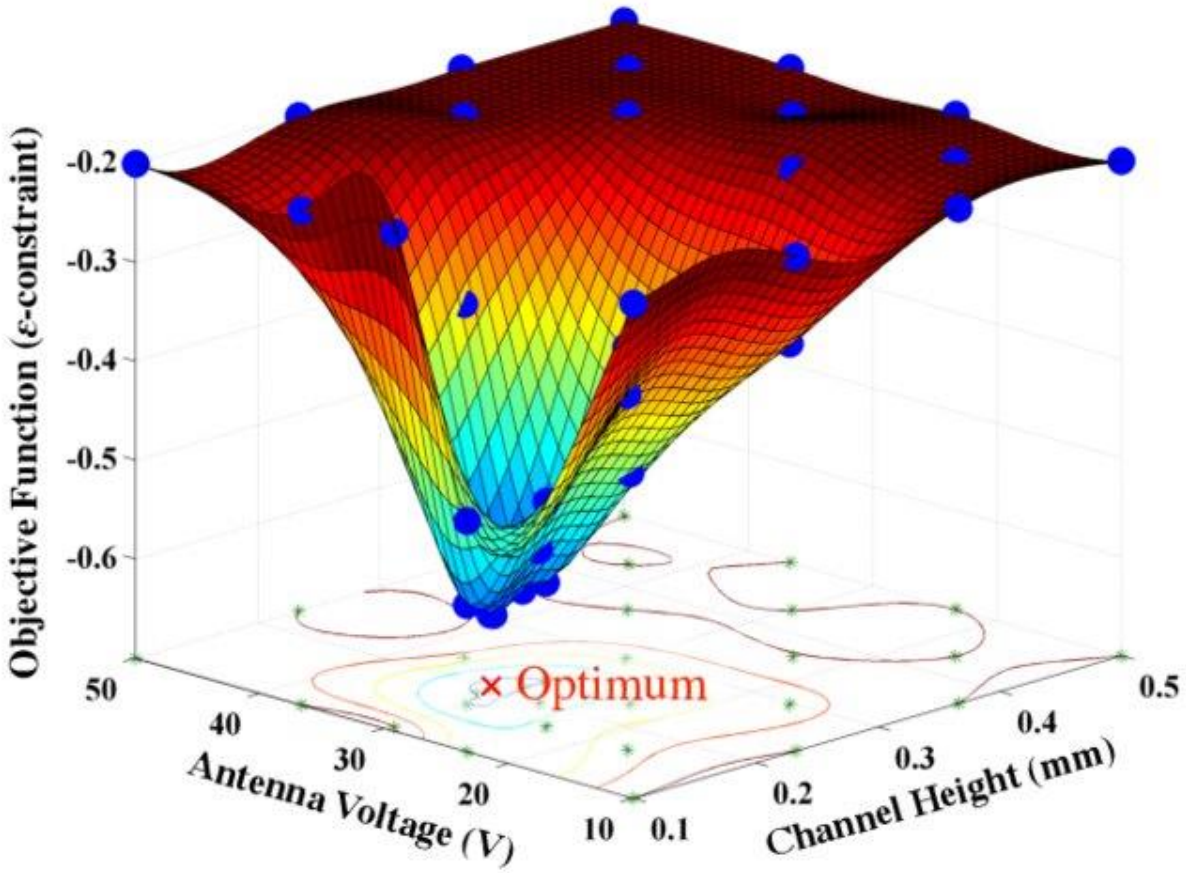
Optimization = Analyzing Tradeoffs

- All engineering problems are optimization problems

- Single objective =

usually* easy to get

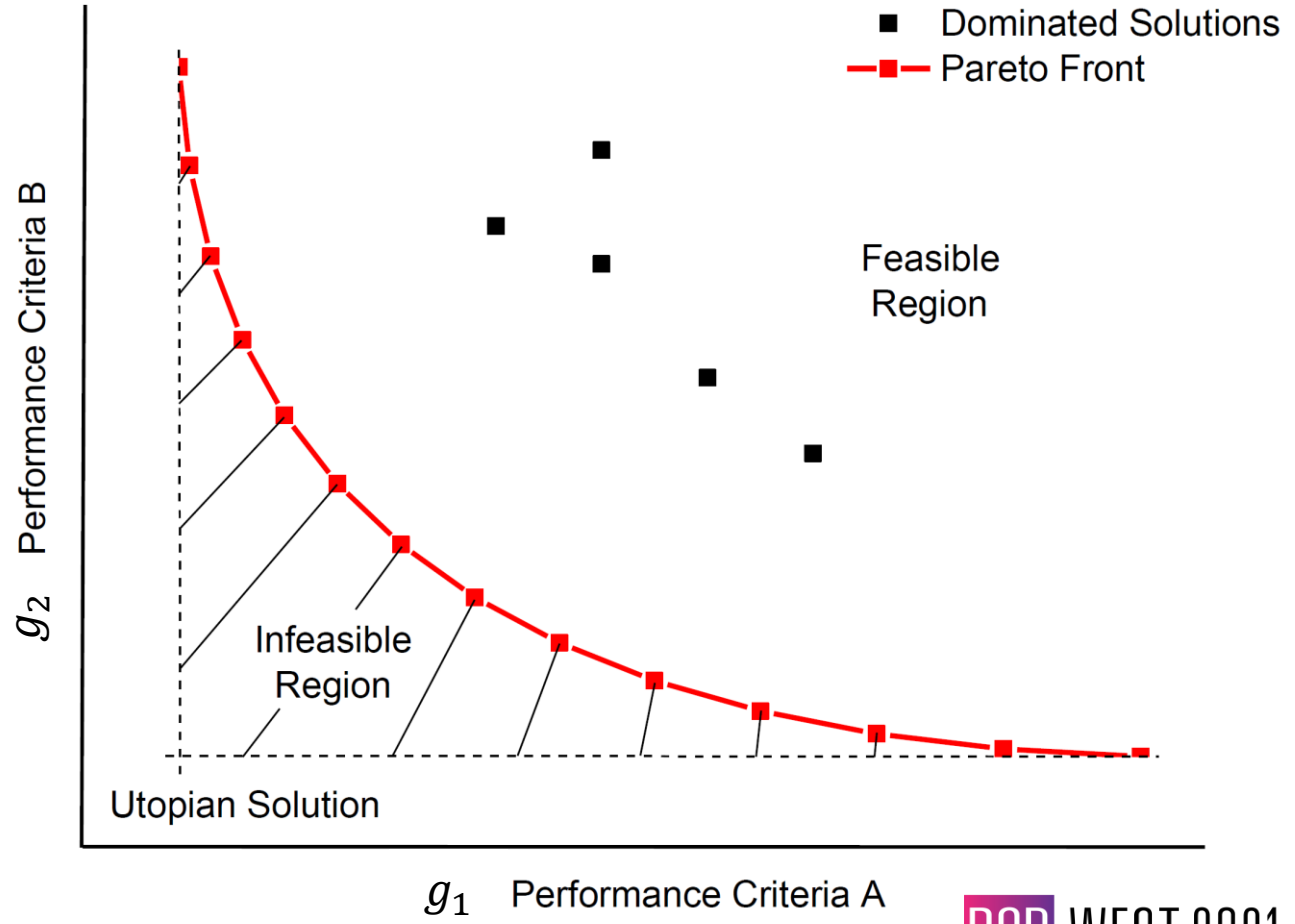
an optimum design



Hartl, D. J., et al. "A liquid metal-based structurally embedded vascular antenna: II. Multiobjective and parameterized design exploration," *Smart Materials and Structures* 26(2) (2016).

Optimization = Analyzing Tradeoffs

- Real problems = multiple objectives = complex tradeoffs
- Impossible to get a "perfect" design
- More objectives = longer computation time, more difficult to visualize



Why Worry About Design Optimization?

- **Motivation:** Newer signaling standards demand design techniques that are optimization problems

- **Motivation (II):** Designs are more complex → Way to balance great complexity

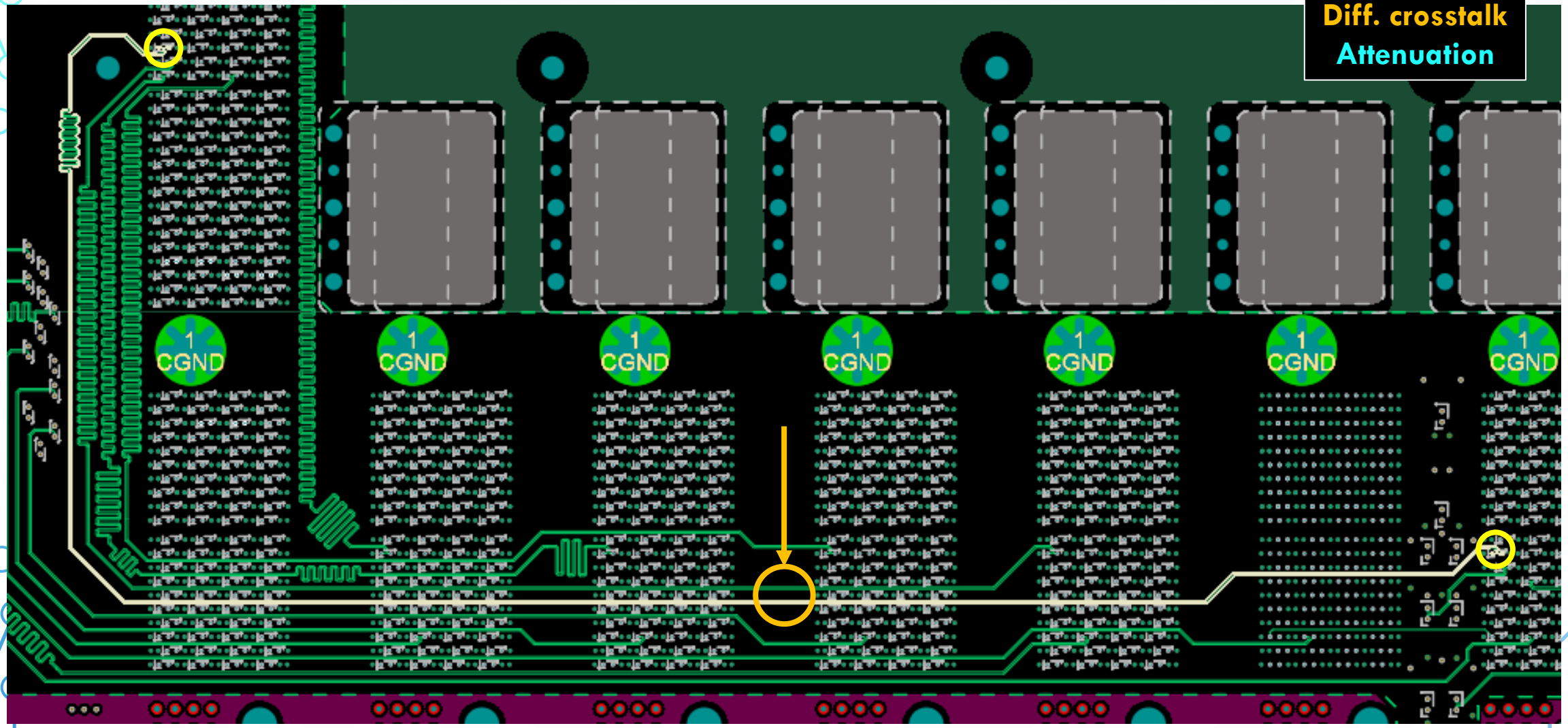
Methods

- **Empirical**
  - Use models extracted from experimental data
- **Numerical**
  - Use simulation tools (field solvers)
- **Analytical**
  - Use equations derived from first principles → direct calculations
- Build a “catalog” of possible designs, pick the best for your system

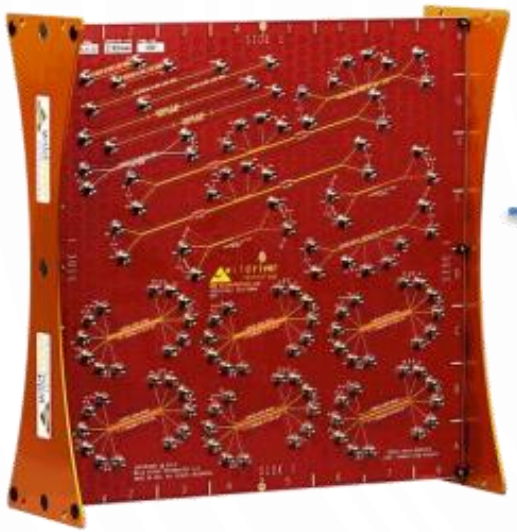
Empirical Methods

- **Involves measurements**
  - Objective function: Signal integrity (S-parameters), impulse response
  - Design variables: Channel geometry
  - Parameters: Roughness, Dk/Df, stackup, via count, …
- **Procedure:** Vary design variables, measure objectives, compare with reference model
- **Drawbacks:** Considers entire interconnect (good and bad!)

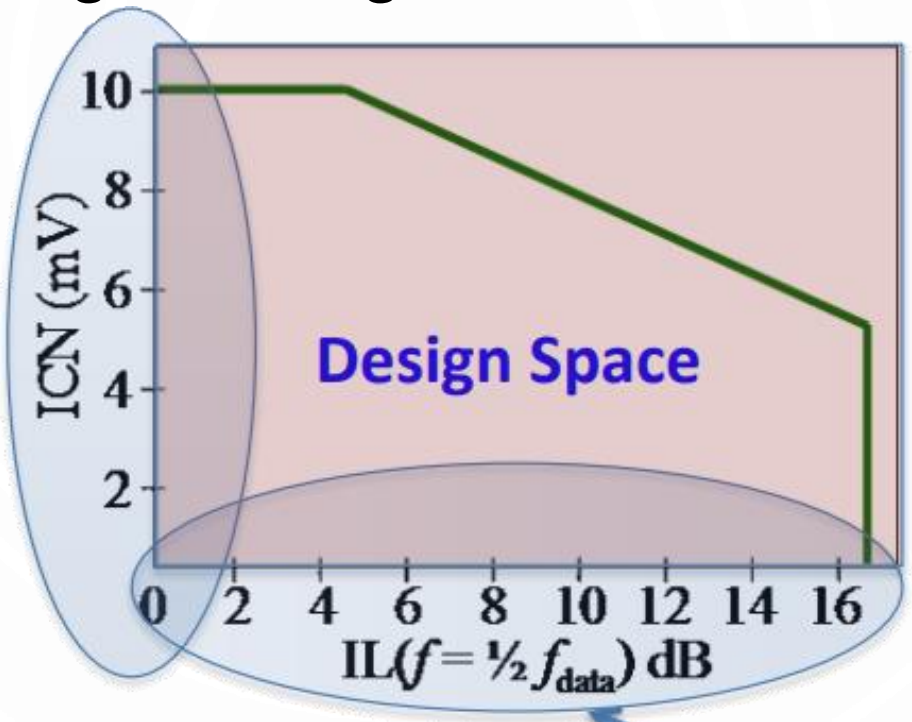
- Example with 56G channels on Eurocard backplane (6U)



- **Neves et al. "Pathological Design", 100GBase-KR**



Crosstalk Noise Test vehicle, calculated RX noise as Integrated Crosstalk Noise (ICN)



Insertion Loss Test Vehicle (IL) at Nyquist Sampling Freq

Neves, A., et al. "32 to 56 Gbps Serial Link Analysis and Optimization Methods for Pathological Channels," *DesignCon 2017*.

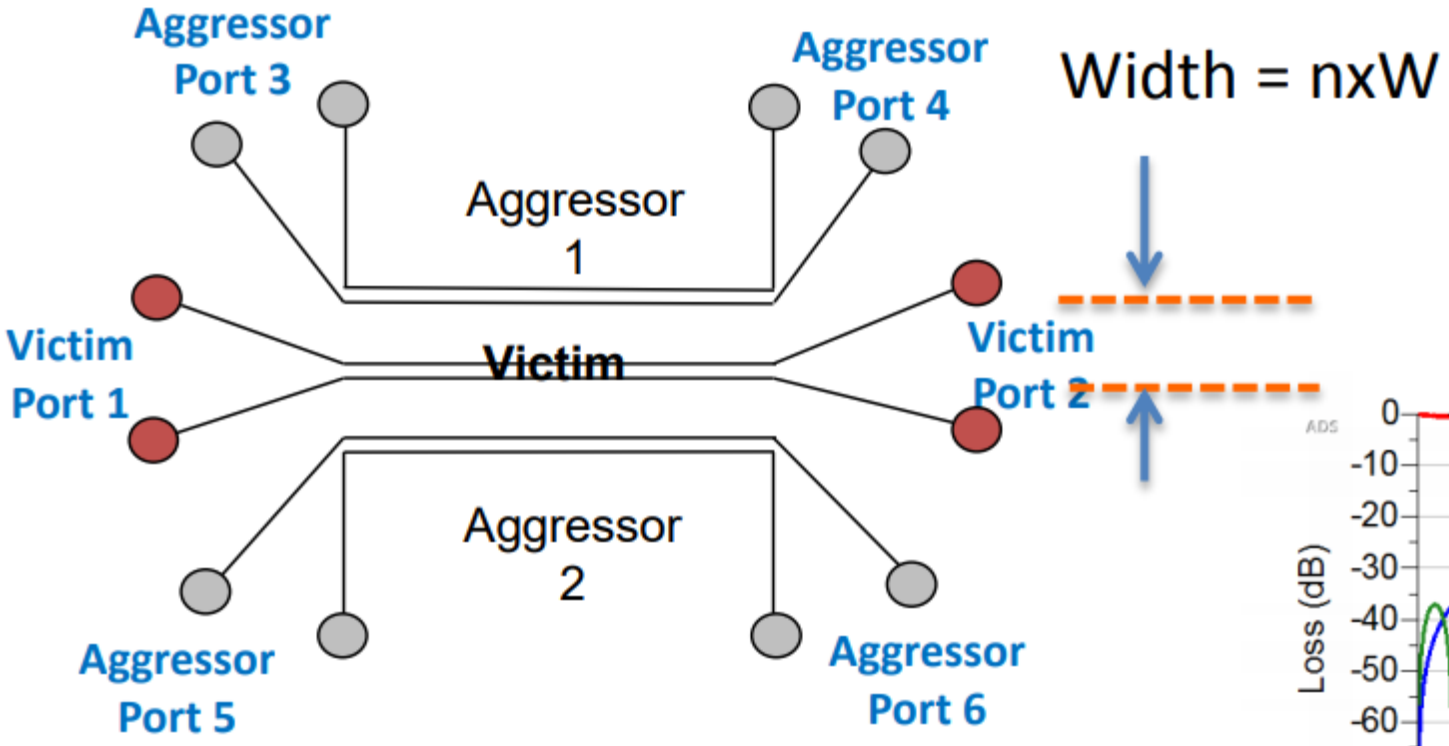
- **Example: Tri-objective problem in 100GBase-KR or USB 4.0**
- Uses Multi-port S-parameters for differential pair design:

Integrated return loss: $$IRL = \sqrt{\frac{\int_0^{fm} |V_{in}(f)|^2 |S_{21}(f)|^2 (|S_{11}(f)|^2 + |S_{22}(f)|^2) df}{\int_0^{fm} |V_{in}(f)|^2 df}}$$

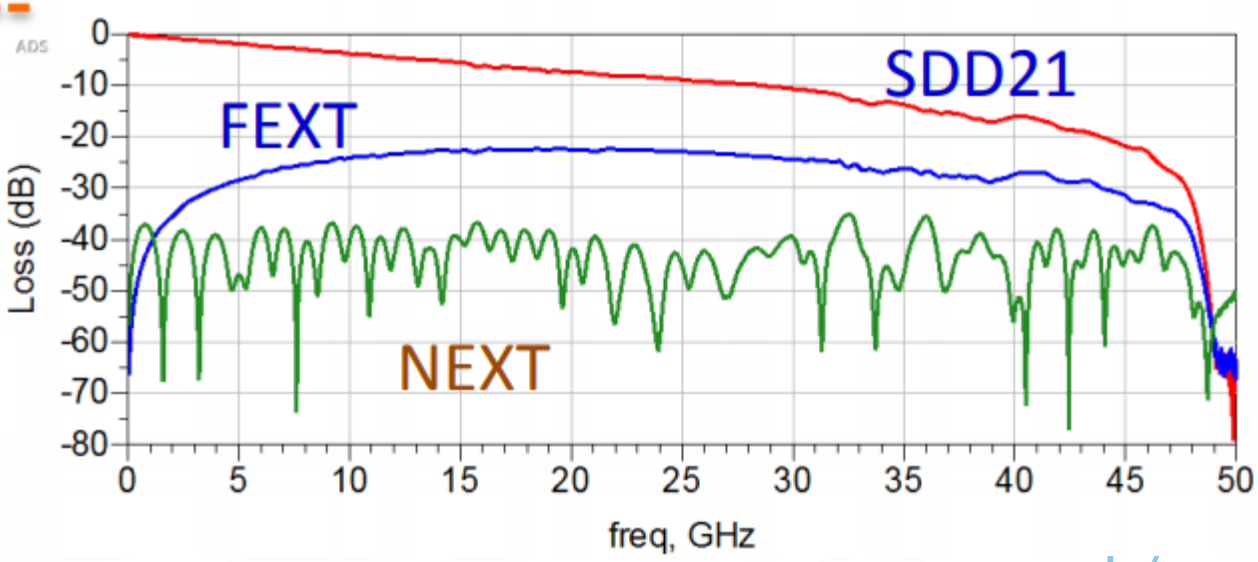
Integrated insertion loss: $$IIL = \sqrt{\frac{\int_0^{fm} |V_{in}(f)|^2 |S_{21}(f)|^2 df}{\int_0^{fm} |V_{in}(f)|^2 df}}$$

Integrated crosstalk: $$ITX = \sqrt{\frac{\int_0^{fm} |V_{in}(f)|^2 \sum_{i \neq j} |S_{ij}(f)|^2 df}{\int_0^{fm} |V_{in}(f)|^2 df}}$$

• Neves et al. "Pathological Design", 100GBase-KR



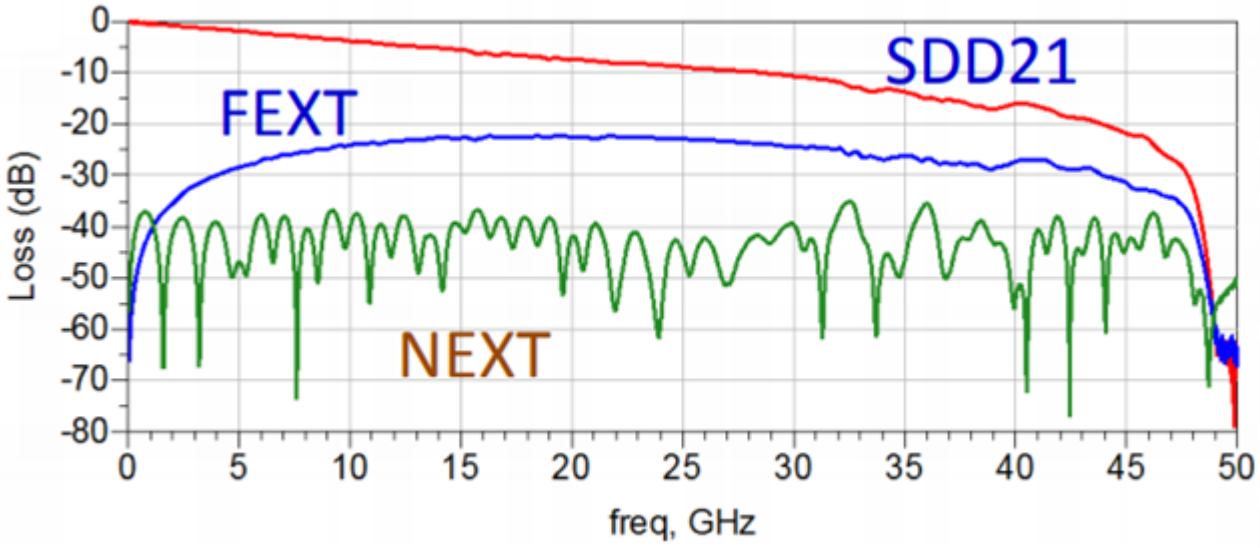
- Decrease width, .5W, 1W, 2W, 4W, and 5W, translates to less crosstalk.
- 4, and 5W would be used with other high loss structures
- Each structure is optimized for same SDD11.

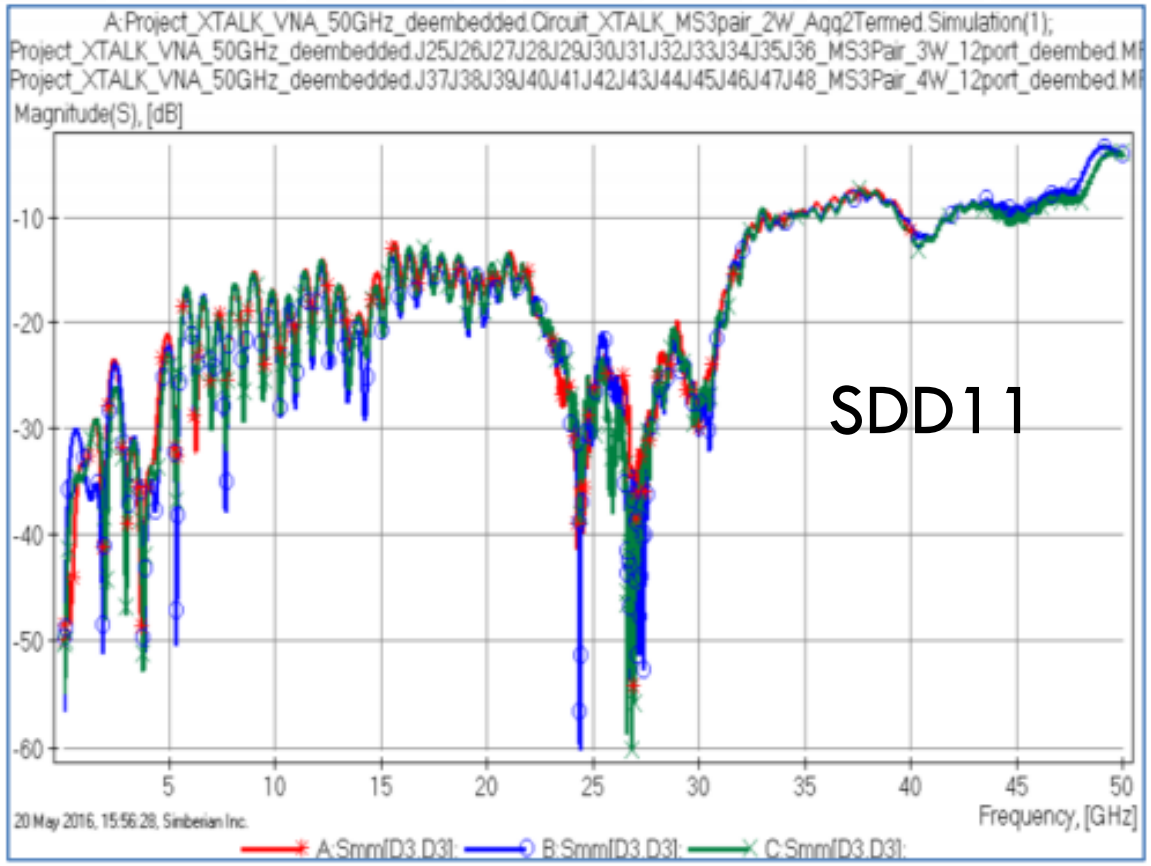


Neves, A., et al. "32 to 56 Gbps Serial Link Analysis and Optimization Methods for Pathological Channels," *DesignCon 2017*.

- **Neves et al. "Pathological Design", 100GBase-KR**

- Measure SDDx1 (FEXT/NEXT) for given SDD11
- Iterate through geometry

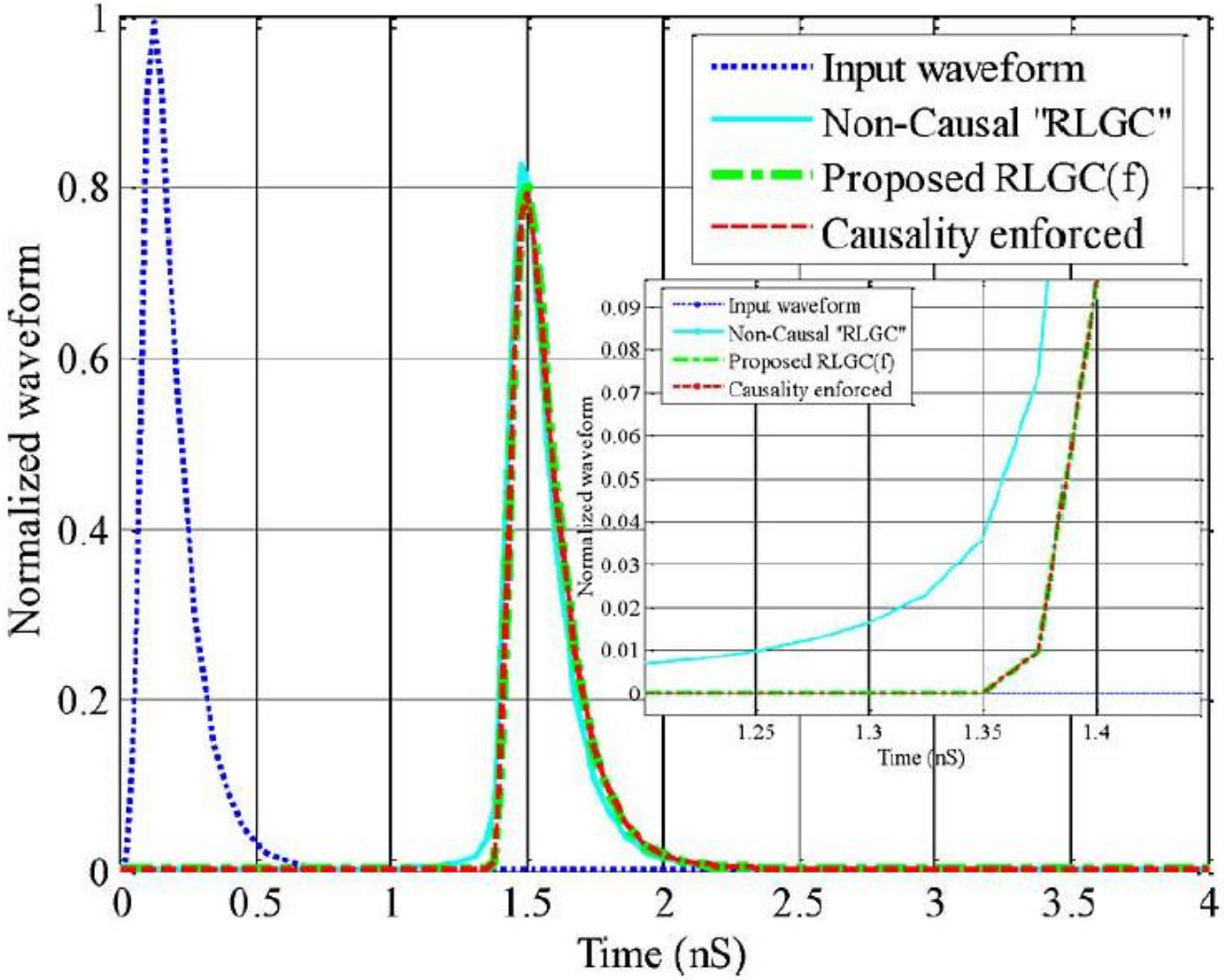




Neves, A., et al. "32 to 56 Gbps Serial Link Analysis and Optimization Methods for Pathological Channels," *DesignCon 2017*.

Zhang et al.: Model extraction

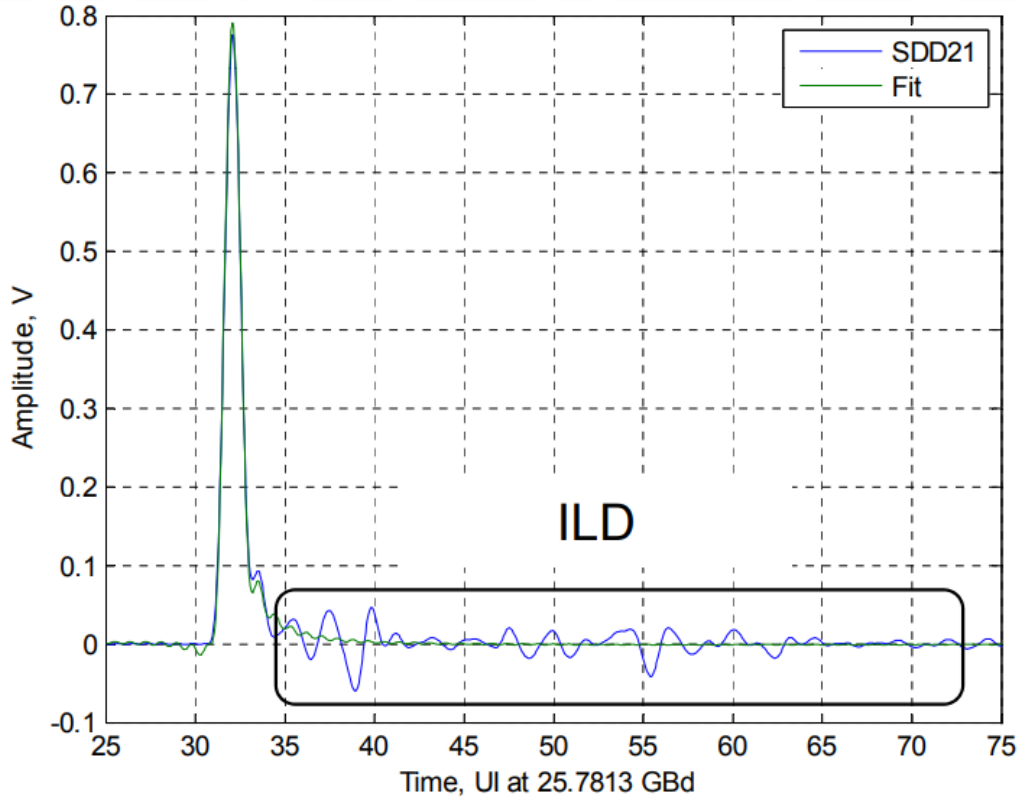
- Input S-parameter and impulse response measurement, extract geometric trends
- Extract transmission line values $(L_\infty, R_s, R_{DC}, K_g, \varepsilon_R, \varepsilon_I)$
- Problems:
  - Copper roughness included in R_s
  - Overly complicated algorithm



Zhang, J., et al. "Causal RLGC(*f*) Models for Transmission Lines From Measured S-Parameters," *IEEE Transactions on Electromagnetic Compatibility*, 52(1), pp.189-198 (2009).

Empirical Design: Evaluation

- Useful to compare with some benchmark → Impulse response
- Example under IEEE P802.3bj and P802.3ba models



$$H = e^{x}$$

$$\log(H_{fit}) = x \cong \gamma_0 + \gamma_1\sqrt{f} + \gamma_2 f + \gamma_4 f^2$$

$$\gamma_i = \alpha_i + j\beta_i$$

$$H_{ild} = H - H_{fit}$$

Minimization objective

Moore, C., and Healey, A. "A method for evaluating channels." *100 Gb/s Backplane and Copper Study Group*, IEEE, 2011.

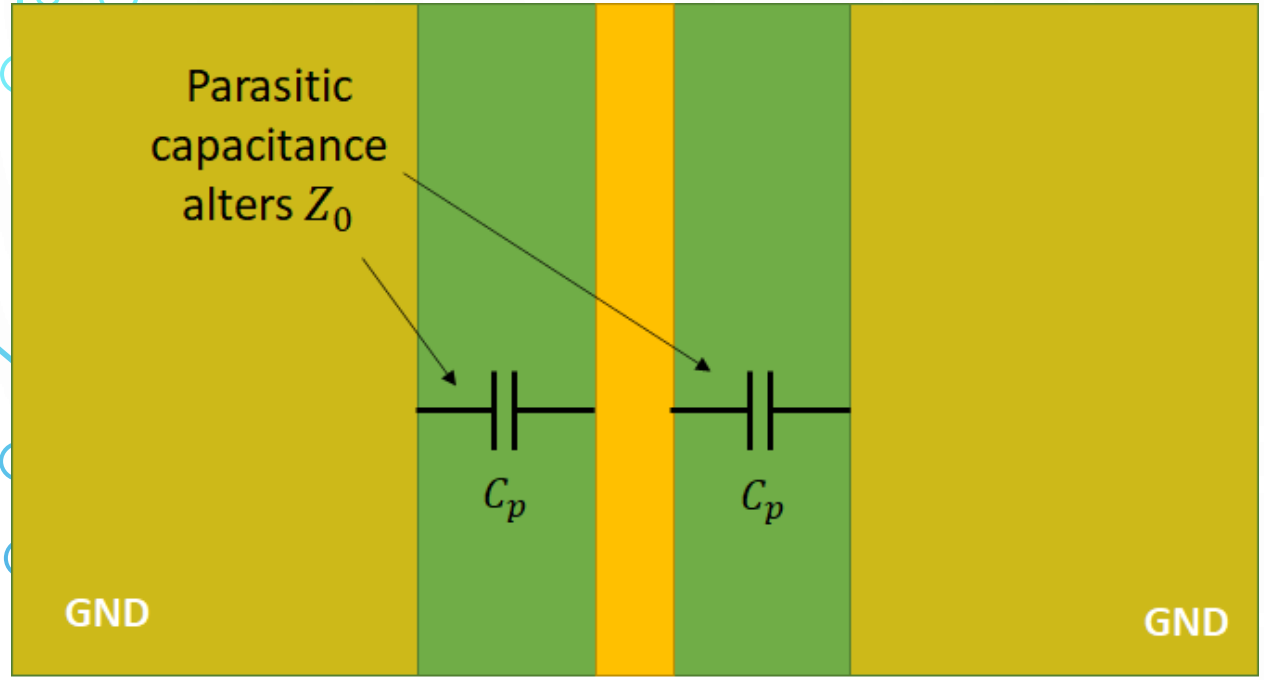
Numerical Methods

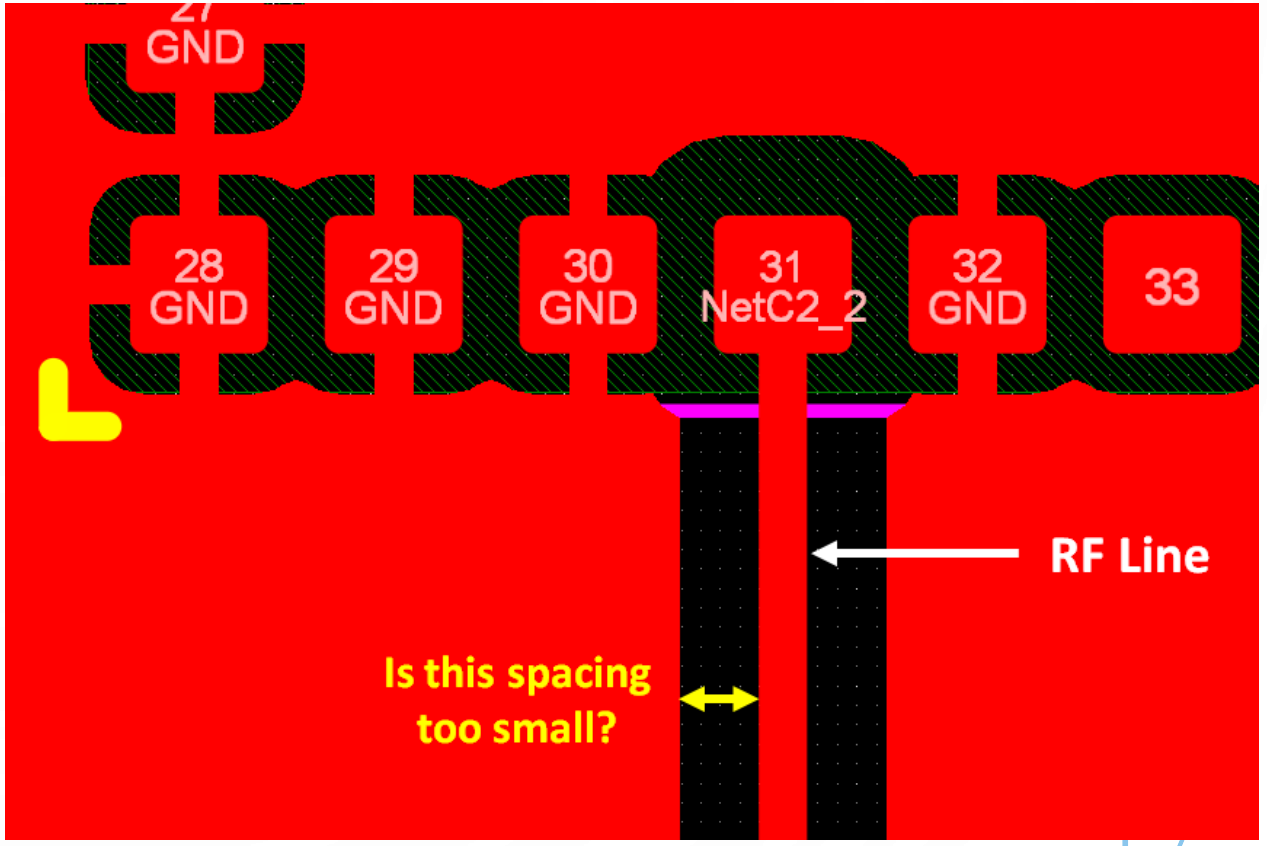
- **A.k.a. Design Exploration**
  - Objective function: Signal integrity (S/Z-parameters), possibly EMI
  - Design variables: Channel geometry
  - Parameters: Roughness, Dk/Df, stack-up, etc.

- **Procedure:** Generate objective, iterate through variable range, build design space
- **Drawbacks:** Requires finished or proposed layout, slow!

Example: Copper Pour Clearance Constraints

- What's the allowed pour clearance near controlled impedance traces?





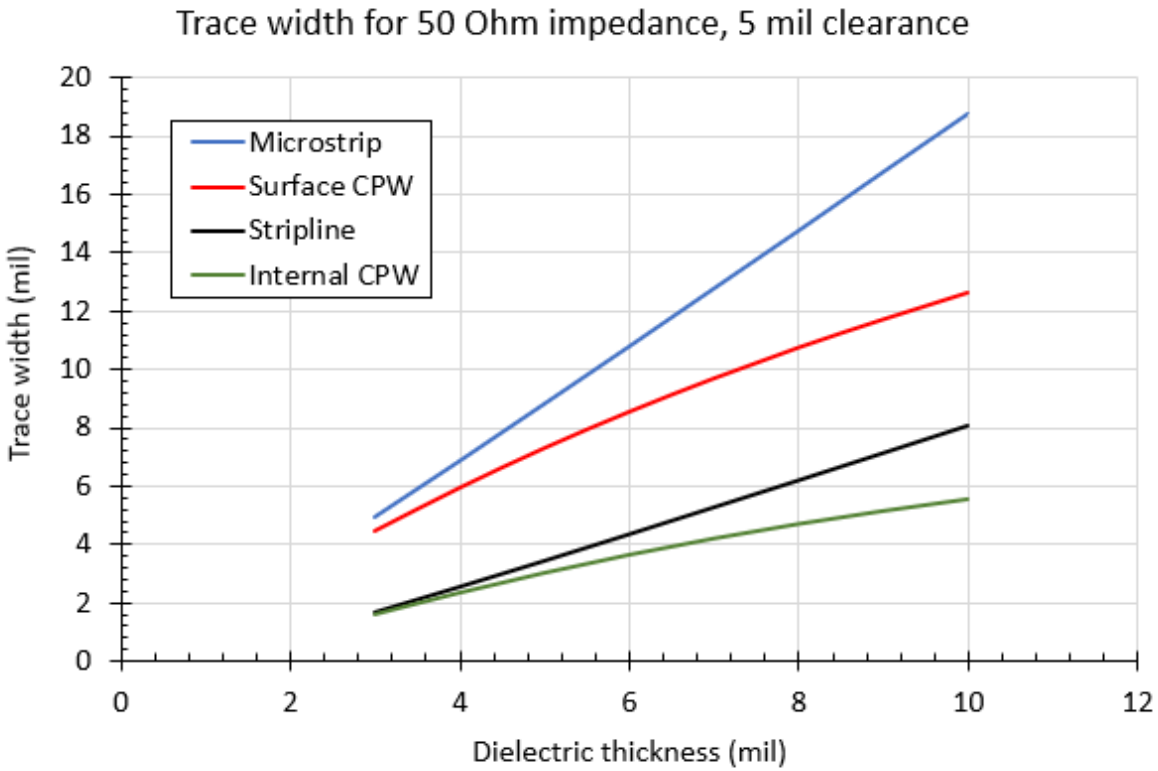
$$Z_0 = \sqrt{\frac{L}{C_{total}}} = \sqrt{\frac{L}{C + 2C_p}}$$

Problem Statement

- What's the smallest allowed clearance?

$$\min\left[\int_{\omega_1}^{\omega_2} \left|Z(\omega) - Z_{target}\right|^p \, d\omega\right]^{1/p}$$

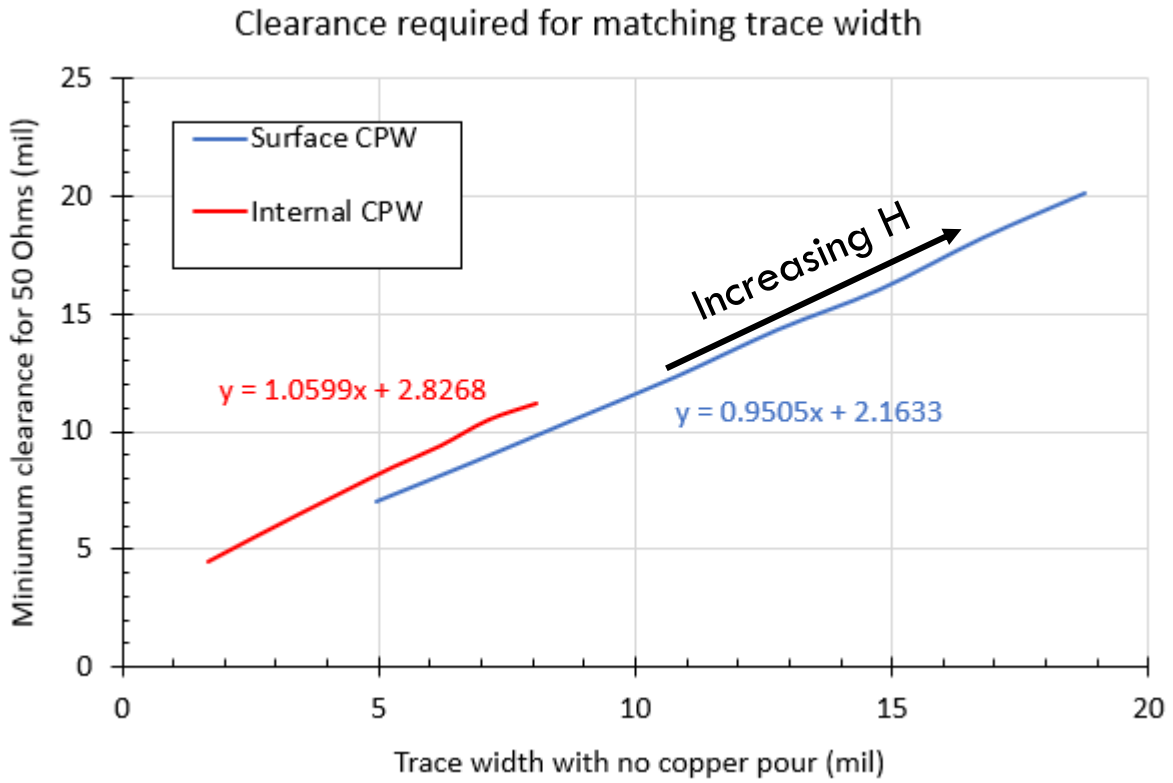
$$\text{s.t.:} \quad \begin{matrix} W > 0 \\ S > 0 \\ T \in \{T_i\} \\ H \in \{H_i\} \end{matrix}$$

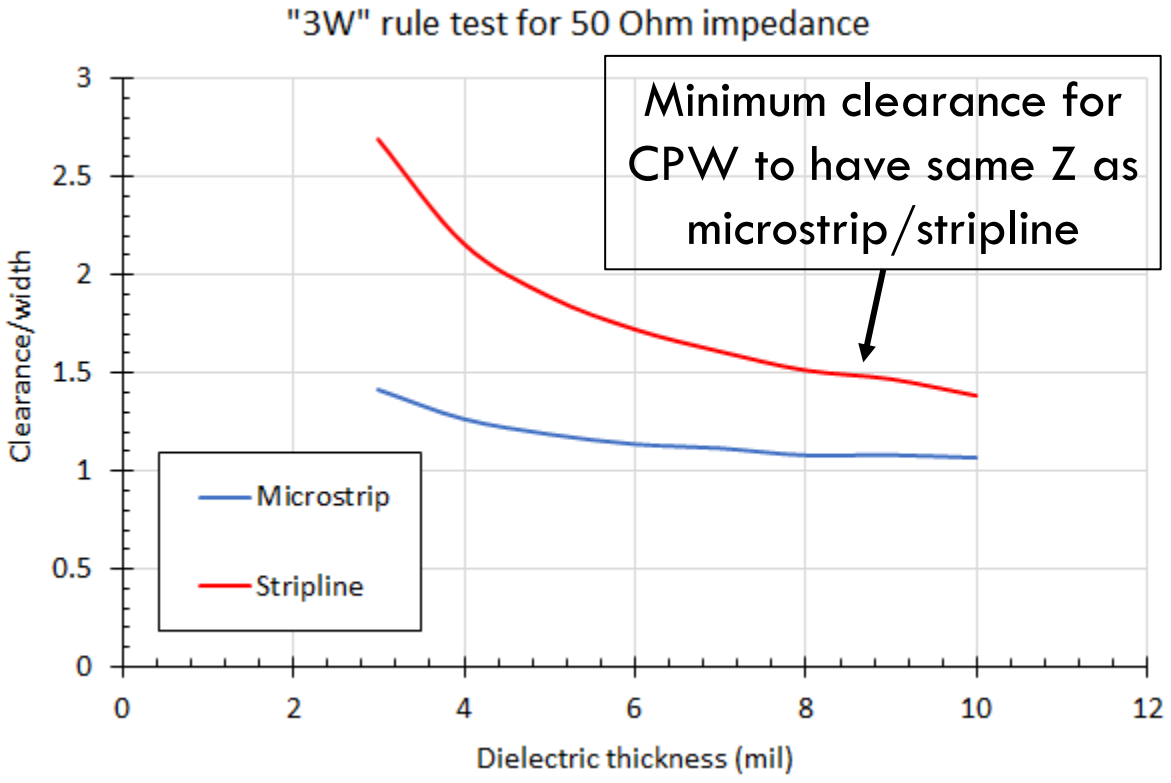


- Determine curve relating CPW with non-CPW

Accidentally Testing "Rules of Thumb"

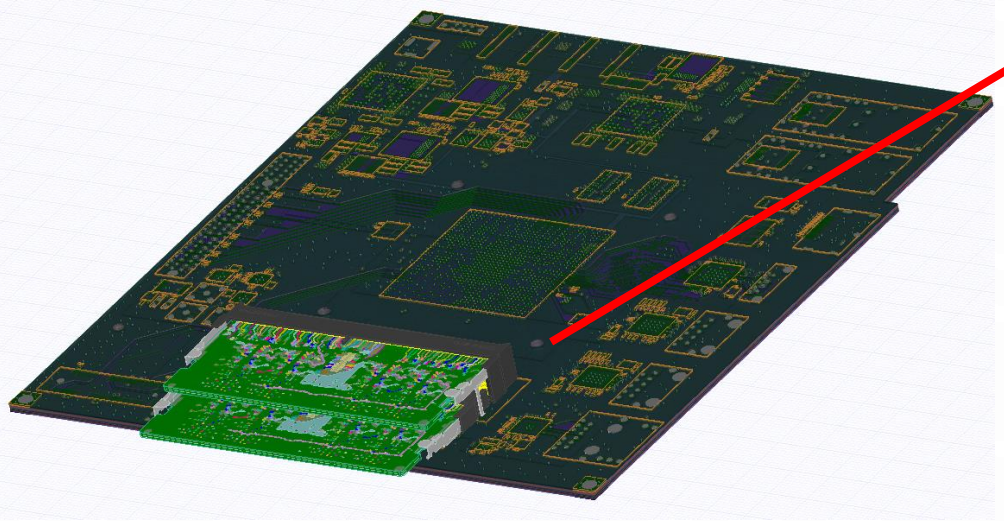
- We can easily violate the "3W" clearance rule without affecting impedance



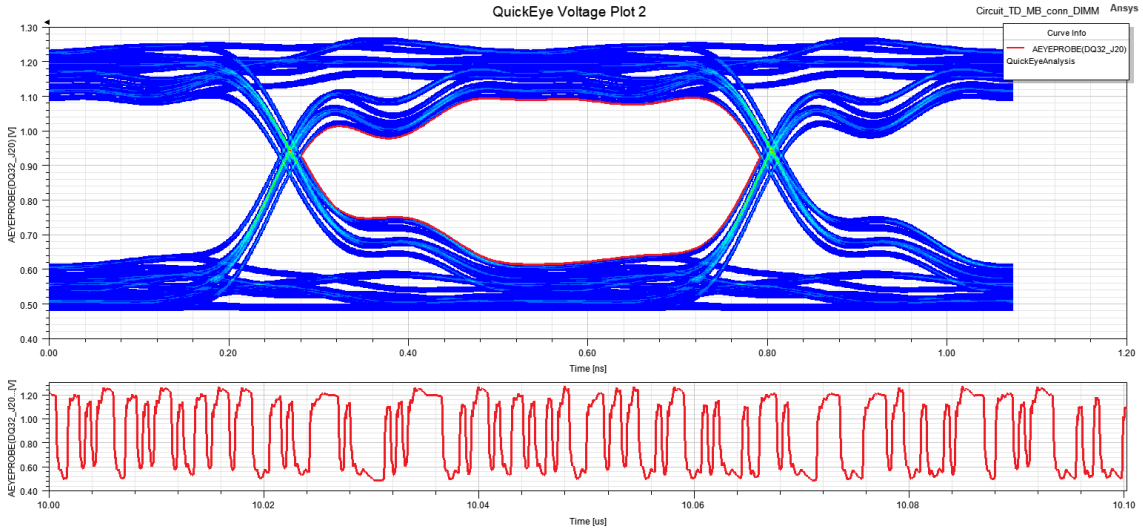


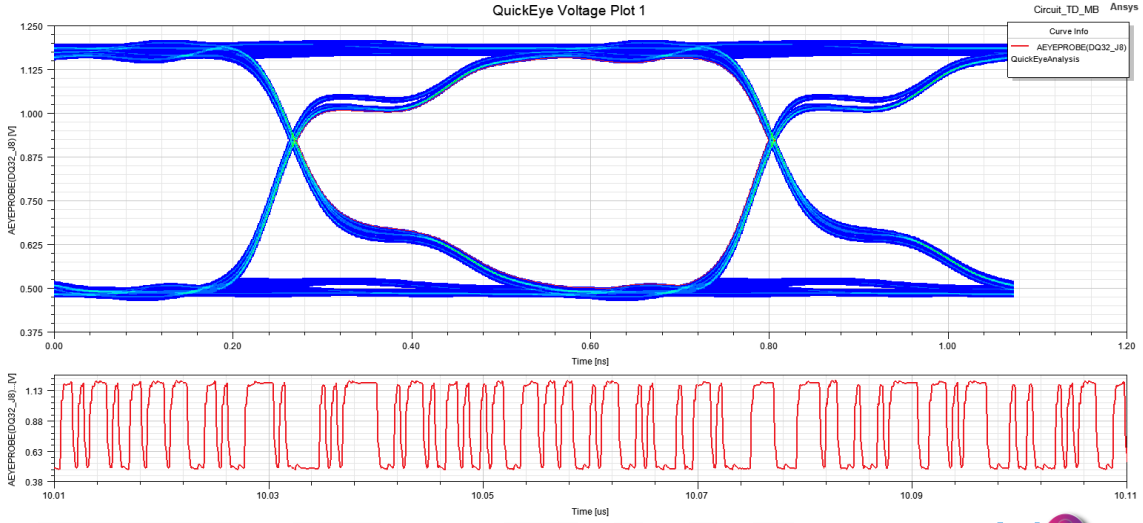
Broader Trend: Design Exploration

- **Example: DDR SODIMM connectors**



Swap connectors or change stackup to get past 1866 MHz





Analytical Methods

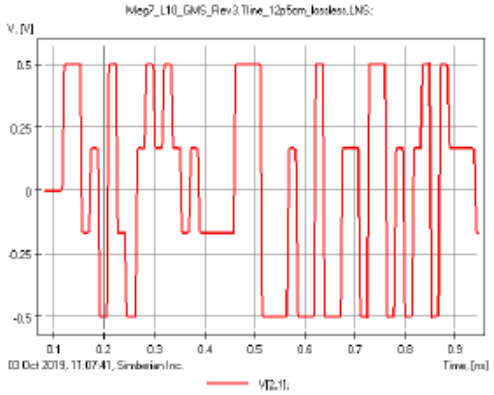
- **Deriving analytical models**
  - Objective function: Signal integrity (S/Z-parameters), possibly EMI
  - Design variables: Channel geometry
  - Parameters: Roughness, Dk/Df, stackup, etc.

- **Procedure:** Calculate objective directly, optimize for geometry and dispersion
- **Drawbacks:** Difficult to consider parasitics and complex layouts

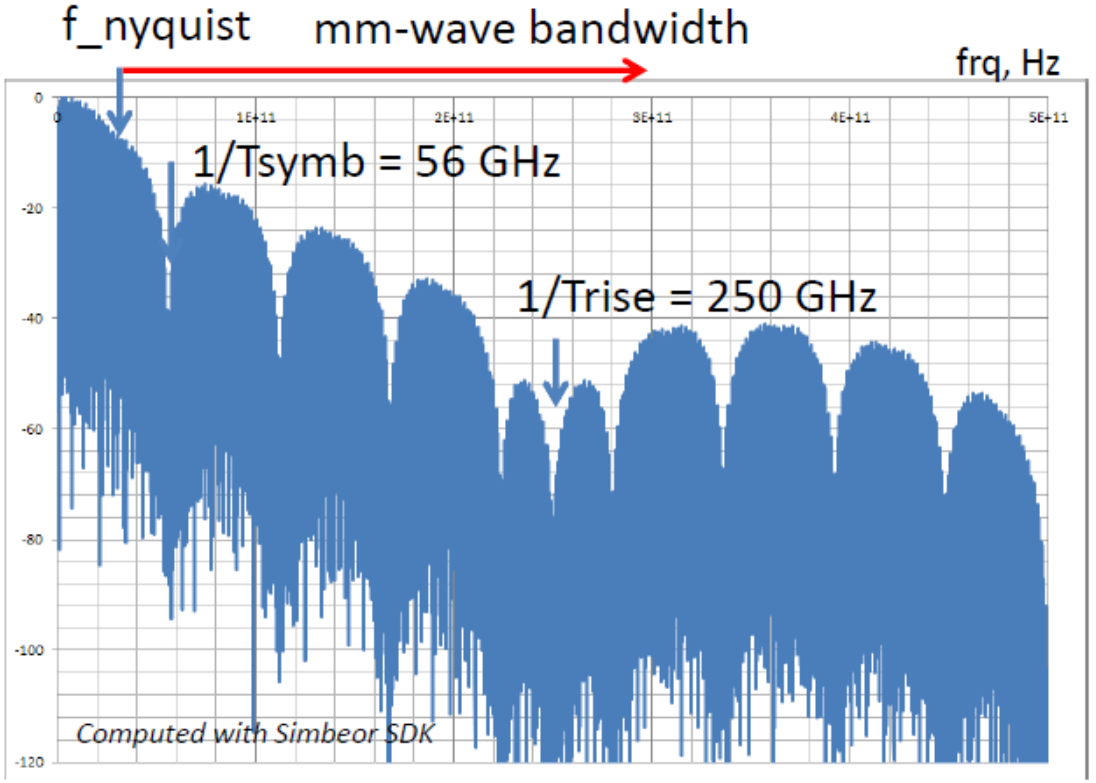
Analytical: Wideband Interconnect Design

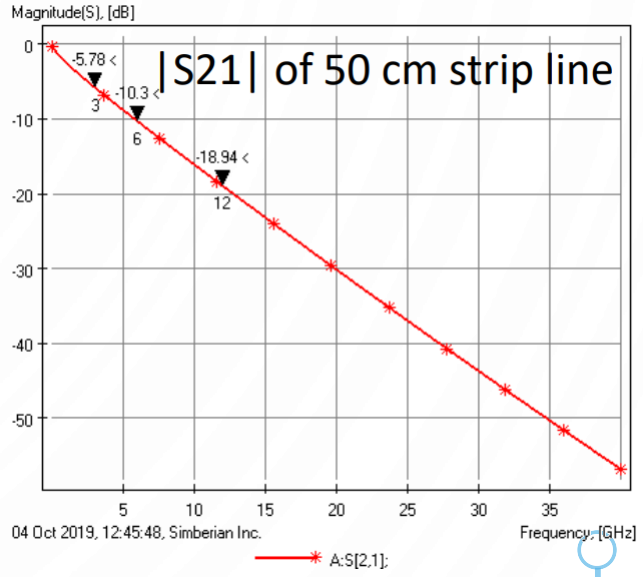
- **Example: 112 Gbps PAM4 signaling**

112 Gbps: Trise=4ps;
Tsymb=17.8571ps;
f_nyquist = 28 GHz



PSD of PRBS7



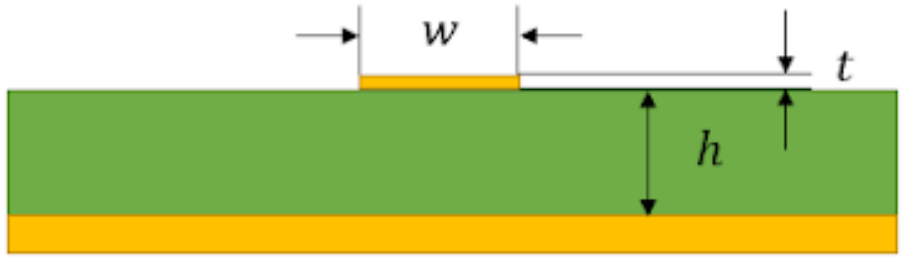


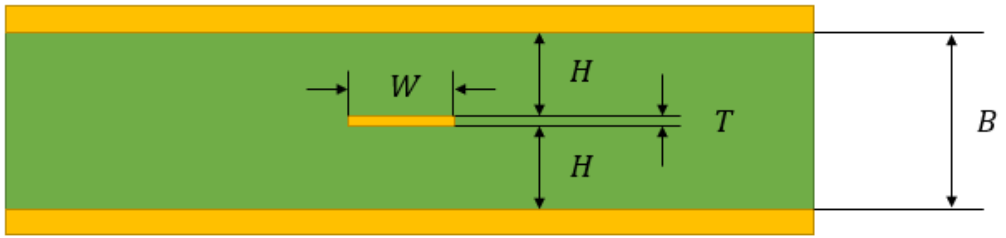
What is the bandwidth?
0.5/Trise looks unrealistic...

Heyfitch, V., and Shlepnev, Y. "Design insights from electromagnetic analysis and measurements of PCB and Package interconnects operating at 6-112 Gbps and beyond." *DesignCon 2020*.

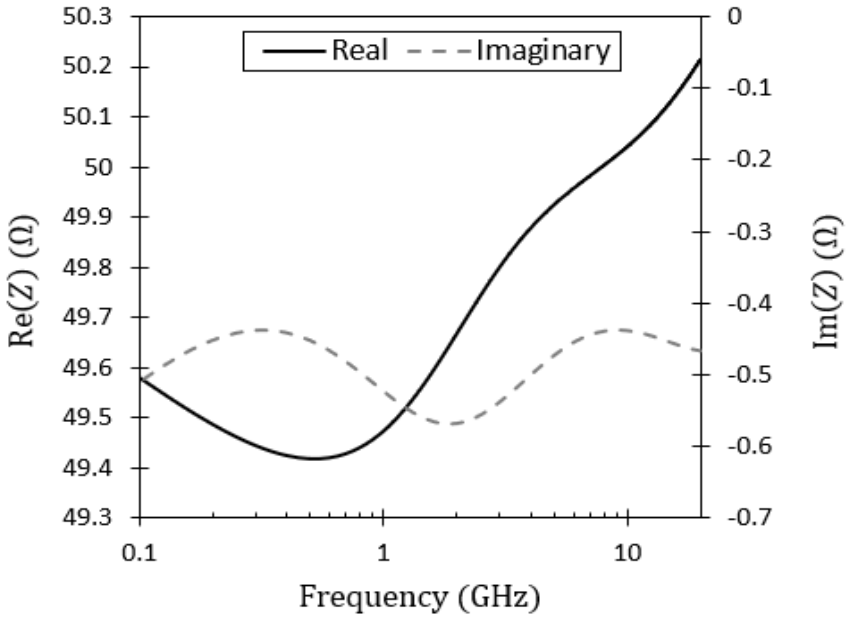
Interconnect Optimization

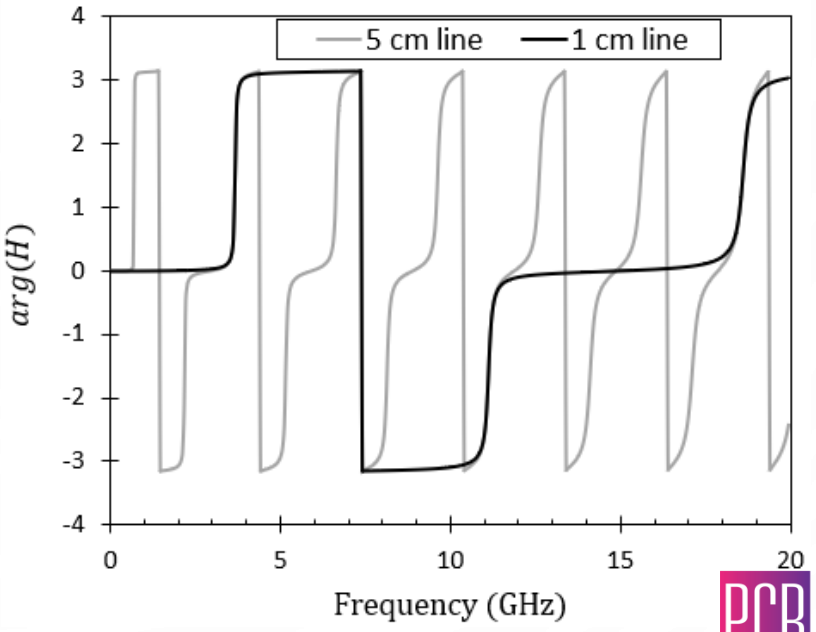
- Many parameters: geometry, via count, length,…





- Allowed impedance mismatch, dispersion, crosstalk…





Transmission Line Optimization: RLCG model

- TL characteristic impedance: $Z_0 = \sqrt{\frac{R+i\omega L}{G+i\omega C}}$

$$R(\omega) = R_{DC} + \sqrt{\omega} R_s \qquad L(\omega) = L_\infty + {R_s}/{\sqrt{\omega}}$$

$$G(\omega) = \omega C(\omega) \tan\delta\,(\omega) \qquad C(\omega) = K_g \varepsilon_R(\omega) \varepsilon_0$$

- Dielectric constant: $\varepsilon = \varepsilon_R(\omega) + i\varepsilon_I(\omega)$, $tan\delta = \frac{-\omega\varepsilon_I(\omega) - \sigma_{sub}}{\omega\varepsilon_R}$
- Need causal models or data for:

Dielectric constant: $\varepsilon(\omega)$

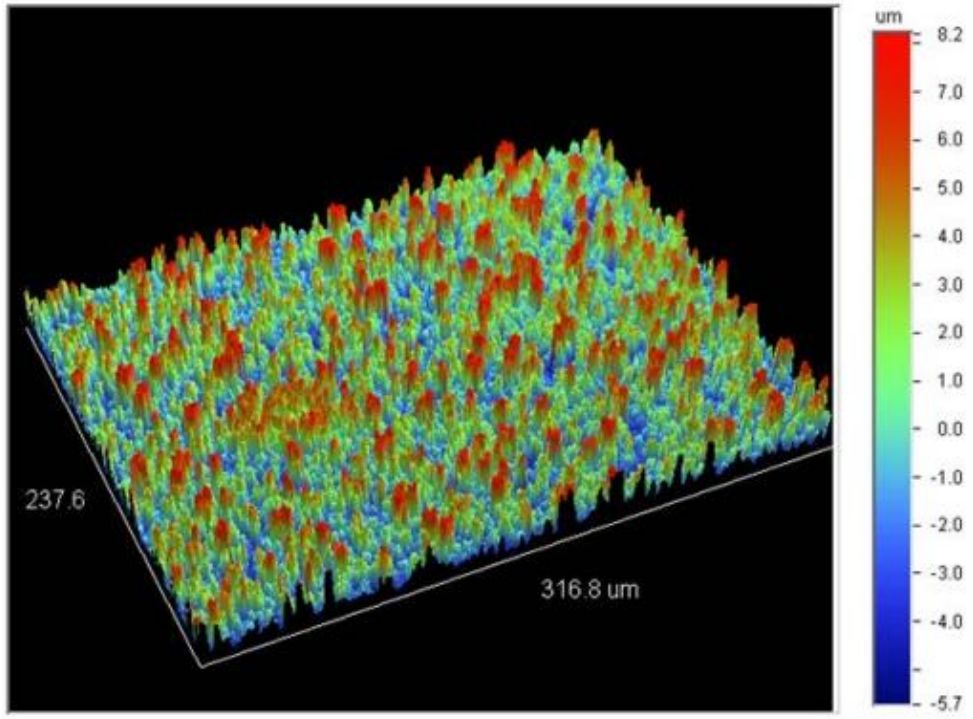
Copper roughness: $K(\omega)$

Electrical parameters: $R(\omega), L(\omega)$

Copper Roughness

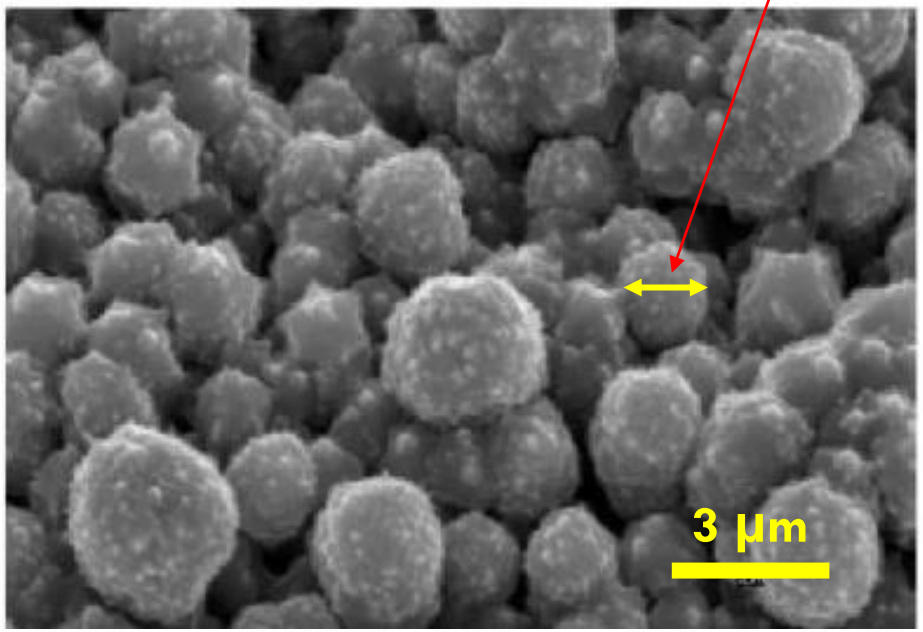
- Copper roughness increases R_S: **non-resonant random scattering and absorption/relaxation**

H_{RMS} ~5.6 µm on 2116 core



SEM image

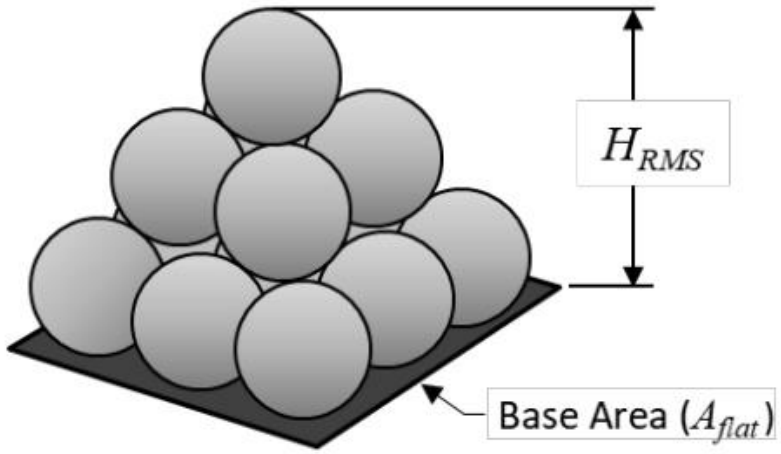
a ~1.5 µm

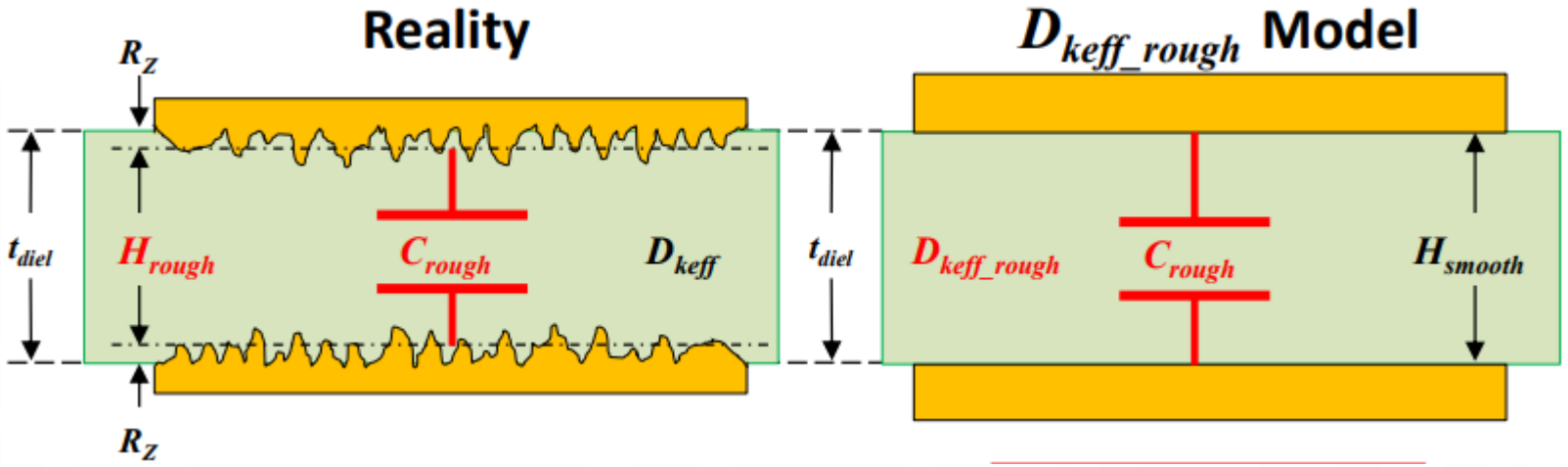


Shlepnev, Y. "Practical methodology for analyzing the effect of conductor roughness on signal losses and dispersion in Interconnects," *DesignCon 2012*.

Causal Copper Roughness Correction

- Cannonball-Huray (Other models: Hammerstad, Snowball Huray, etc.)





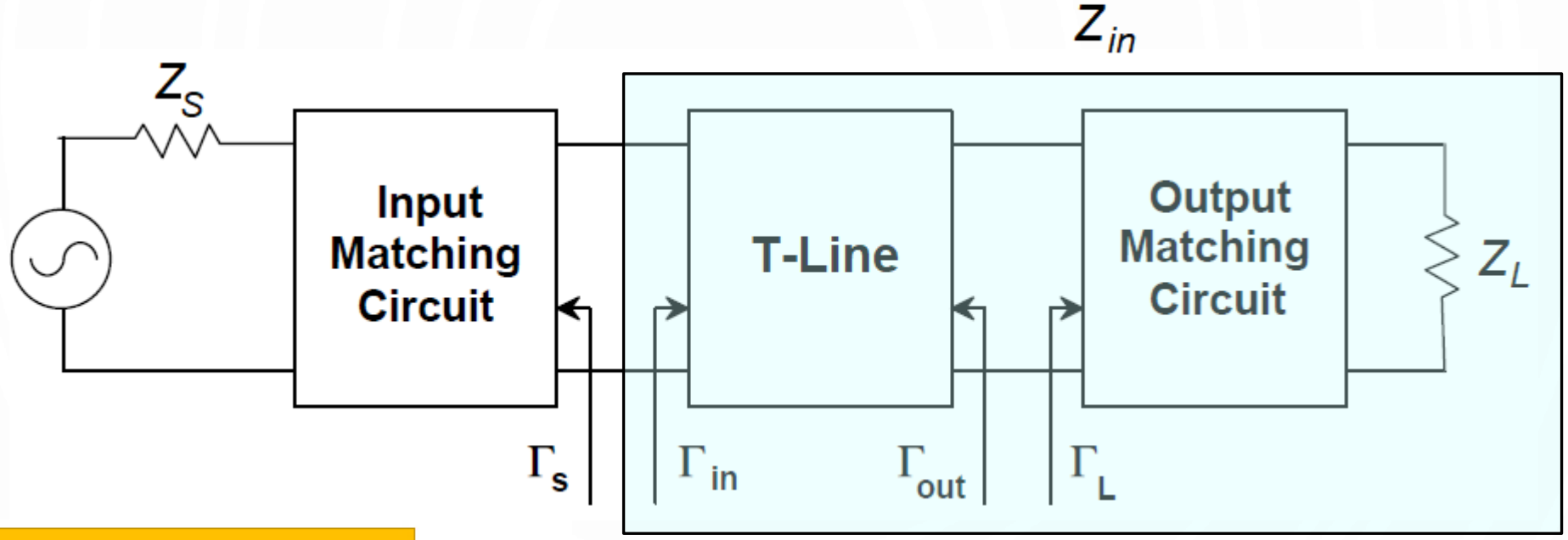
$$\varepsilon_c(\omega) = \varepsilon(\omega)\frac{t_{diel}}{t_{diel} - 2H_{10}}$$

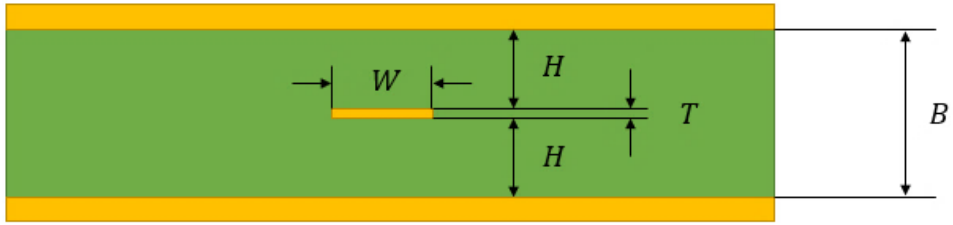
$$R_s \rightarrow K(\omega)R_s$$

	Cannonball-Huray
Normalized frequency	$s = i\omega\mu_0\sigma a^2$ (a = cannonball radius)
Correction factor K	$1 + \frac{\sqrt{s}}{1+\sqrt{s}}$

Dmitriev-Zdorov, V. "A Causal Conductor Roughness Model and its Effect on Transmission Line Characteristics," *Signal Integrity Journal*, November 2018.
Simonovich, B. "PCB Interconnect Modeling Demystified," *DesignCon 2019*.

Stripline Problem





- Lorentzian Parameters for ε:

ε_{s1}	ε_{s2}	ε_{∞}	τ_1 (ps)	τ_2 (ps)	σ ($\Omega^{-1}m^{-1}$)
4.081	4.068	3.95	82.12	5.712	$5.81 \cdot 10^7$

- Single objective: $\min L^2 \left| Z - Z_{target} \right|$

Zhang, J., et al. "Planar transmission line method for characterization of printed circuit board dielectrics," *Progress In Electromagnetics Research*, 102, pp.267-286 (2010).

Analytical Approach (Dispersion + Roughness)

- Start with Wadell's dispersion-less impedance formulas, use the definitions:

$$v^{-1} = {}^{k}/_{\omega} = \sqrt{L_{\infty} K_g \varepsilon_0 \varepsilon_{c,R}(\omega)} = {}^{\sqrt{\varepsilon_{c,R}(\omega)}}/_{c_0}, \text{ and}$$

$$Z_0 = \sqrt{{}^{L_{\infty}}/_{K_g \varepsilon_0 \varepsilon_{c,R}(\omega)}}$$

- Use N-pole Lorentzian model for $\varepsilon_c(\omega) = \frac{\varepsilon(\omega)H}{H-2H_{10}}$, causal $K(\omega)$

- Skin effect: $R_s(\omega) = \sqrt{\frac{\mu_0}{\sigma A}}\left(\sqrt{1+\left(\rho\omega\varepsilon_0\varepsilon(\omega)\right)^2} + \rho\omega\varepsilon_0\varepsilon(\omega)\right)^{-\frac{1}{2}} \approx \sqrt{\frac{\mu_0}{8\sigma(T+W)^2}}$

Analytical Approach (Dispersion + Roughness)

- Include losses with linear transformation:

$$L_\infty = {Z_0\sqrt{\varepsilon_{c,R}(\omega)}}/{c_0}$$, apply transformation:

$$i\omega L_\infty \rightarrow \frac{i\omega Z_0\sqrt{\varepsilon_{c,R}(\omega)} + (R_{DC} + \sqrt{\omega}(1+i)R_s)c_0}{c_0} = i\omega L_\infty + R_{DC} + \sqrt{\omega}(1+i)R_s$$

- For capacitance, $K_g\varepsilon_0\varepsilon_{c,R}(\omega) = \frac{\sqrt{\varepsilon_{c.R}(\omega)}}{Z_0 c_0}$, apply transformation $C \rightarrow G + i\omega C$
- Therefore, $G + i\omega C = i\omega K_g\varepsilon_0\varepsilon_{c,R}(\omega)(1 - itan\delta) = i\omega\frac{\sqrt{\varepsilon_{c.R}(\omega)}}{Z_0 c_0}(1 - itan\delta)$

Analytical Approach (Dispersion + Roughness)

- Define $Z = {i\omega L_\infty + R_{DC} + \sqrt{\omega}(1+i)R_S} / {i\omega K_g \varepsilon_0 \varepsilon_{c,R}(\omega)(1 - itan\delta)}$

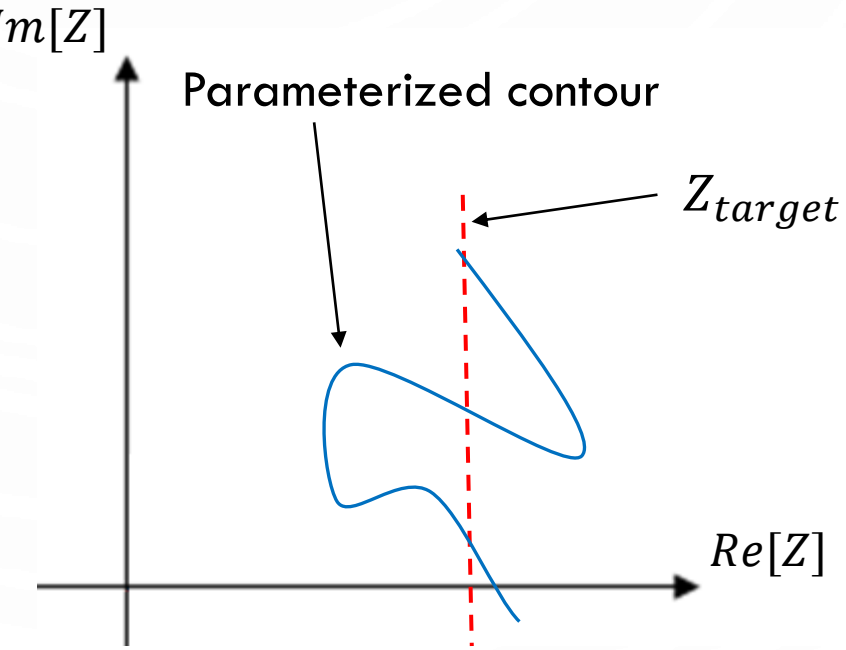
$$Z(\omega) = \sqrt{\frac{i\omega Z_0^2 \sqrt{\varepsilon_{c,R}(\omega)} + Z_0 c_0 (R_{DC} + (1+i)K(\omega)R_s\sqrt{\omega})}{i\omega\sqrt{\varepsilon_{c,R}(\omega)}\left(1 - itan\delta(\omega)\right)}}$$

- Define $\gamma = (i\omega L_\infty + R_{DC} + \sqrt{\omega}(1+i)R_s)(i\omega K_g \varepsilon_0 \varepsilon_{c,R}(\omega)(1 - itan\delta))$

$$\gamma(\omega) = \sqrt{\frac{-\omega^2 Z_0 \varepsilon_c(\omega) + i\omega c_0 \sqrt{\varepsilon_{c,R}(\omega)}(1 - itan\delta(\omega))(R_{DC} + K(\omega)(1+i)\sqrt{\omega}R_s)}{Z_0 c_0^2}}$$

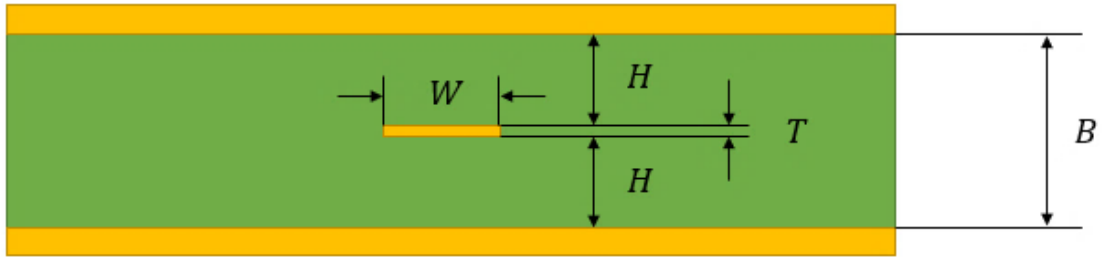
Impedance Deviation Minimization

- Impedance is function of frequency → **consider entire bandwidth**
- Use the L^p norm: $$\min\left[\int_{\omega_1}^{\omega_2} \left|Z(\omega) - Z_{target}\right|^p d\omega\right]^{1/p}$$
- For $p = 2$, equivalent to minimizing RMS deviation from a mean (target) value



Example: Stripline Problem

- 8-layer stackup (equal layers), 0.5 oz./ft.^{2} Cu, 25 cm line
  $H_{10} = 5\ \mu\text{m}, a = 2\ \mu\text{m}$



- 50 Ohm target, 1 pF load capacitance
- Constraints: $0 < {}^{W}/_{H} < 6$, T and H fixed to stackup

- Lorentzian Parameters for ε:

ε_{s1}	ε_{s2}	ε_{∞}	τ_1 (ps)	τ_2 (ps)	σ ($\Omega^{-1}\text{m}^{-1}$)
4.081	4.068	3.95	82.12	5.712	$5.81 \cdot 10^7$

- Single objective: $\min L^2 \left| Z - Z_{target} \right|$

Zhang, J., et al. "Planar transmission line method for characterization of printed circuit board dielectrics," *Progress In Electromagnetics Research*, 102, pp.267-286 (2010).

Optimization Algorithm (Single Objective)

Input: K, J, Z_T, N_{max}

00. **While** $N < N_{max}$
01. **Generate initial solution** $Z(\omega)$ and W/H
02. **If** $N < N_{max}$
03. GenerateNew ${}^{W'}/_{H'}, Z'$
04. **If** $L^2|Z'(\omega) - Z_T| < L^2(Z(\omega) - Z_T)$
and ConstraintCheck = True
05. $Z(\omega) = Z'(\omega), N = 0$
06. **Go to 02**
07. **Else**
08. ConstraintMod
09. $N \rightarrow N + 1$
10. **Go to 04**
11. **Else**
12. **End**

Mutate w/ procedure in Storn & Price (1997).

Check against constraints with method in Lampinin (2002).

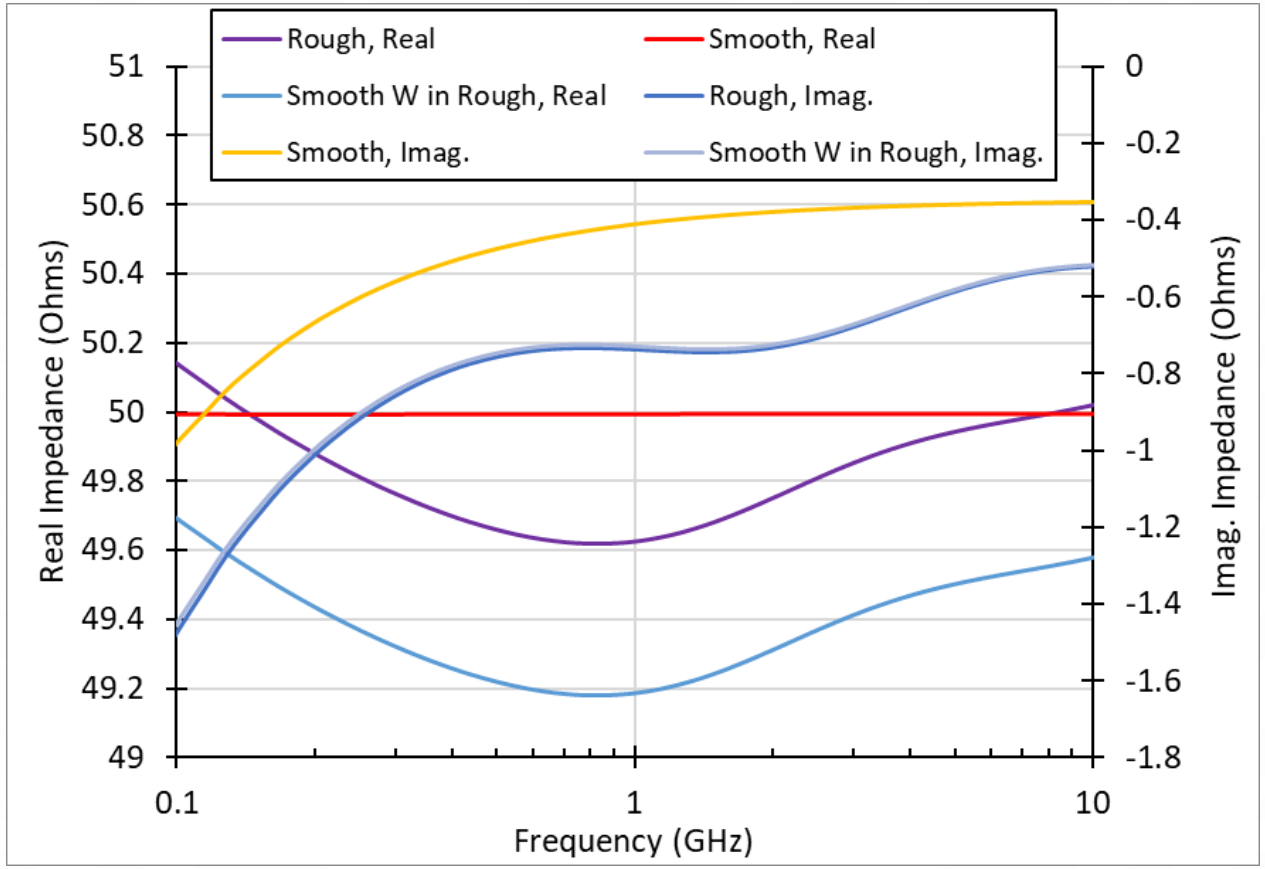
Select new $Z(\omega)$ with method in Lampinin (2002).

Storn, R., & Price, K. "Differential Evolution - A Simple and Efficient Heuristic for Global Optimization over Continuous Spaces," *Journal of Global Optimization*, 11, pp.341-359 (1997).

J. Lampinen, "A constraint handling approach for the differential evolution algorithm," *Proceedings of the 2002 Congress on Evolutionary Computation*, CEC'02 (Cat. No.02TH8600), Honolulu, HI, USA, vol. 2, pp.1468-1473 (2002).

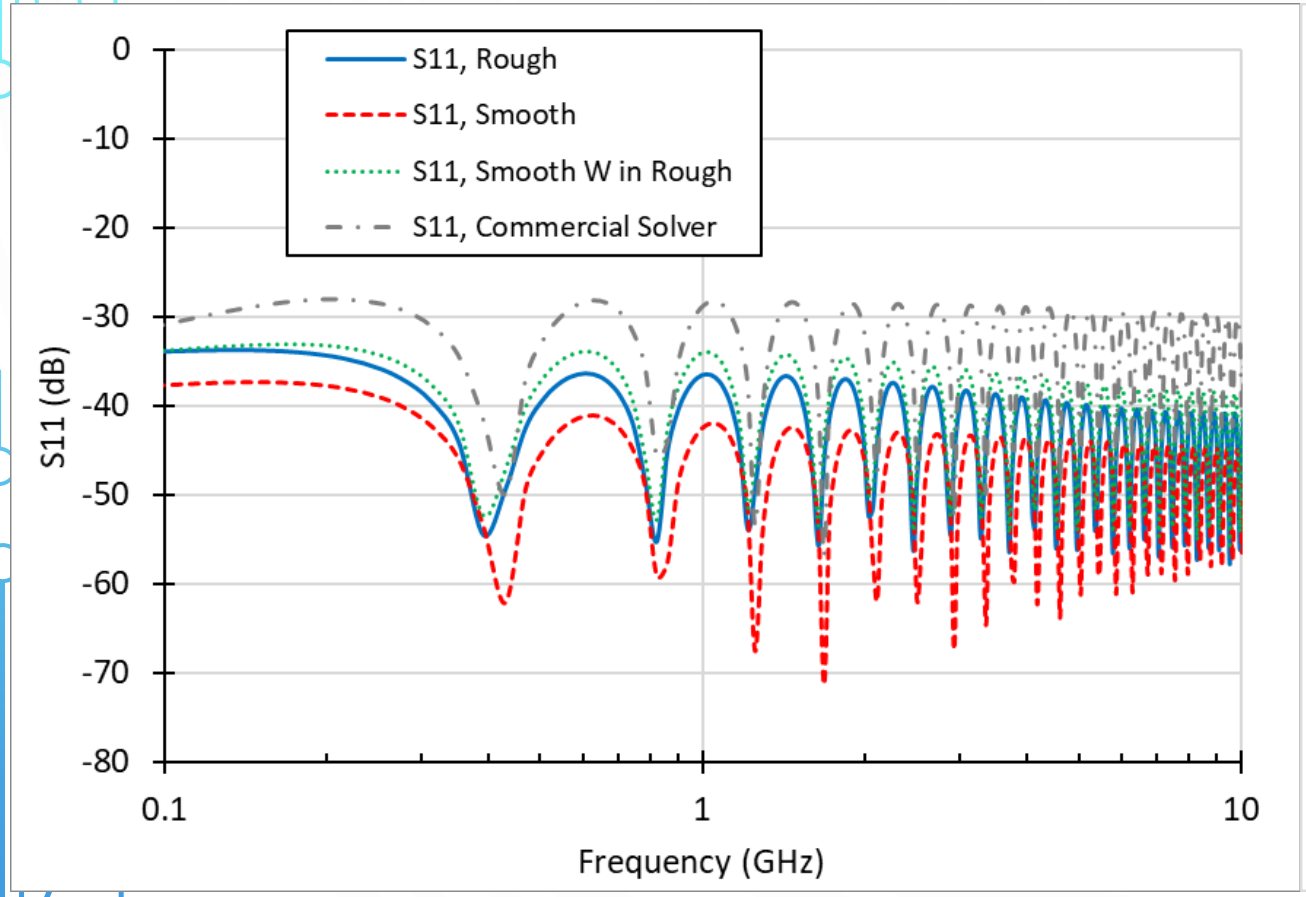
Optimization Results

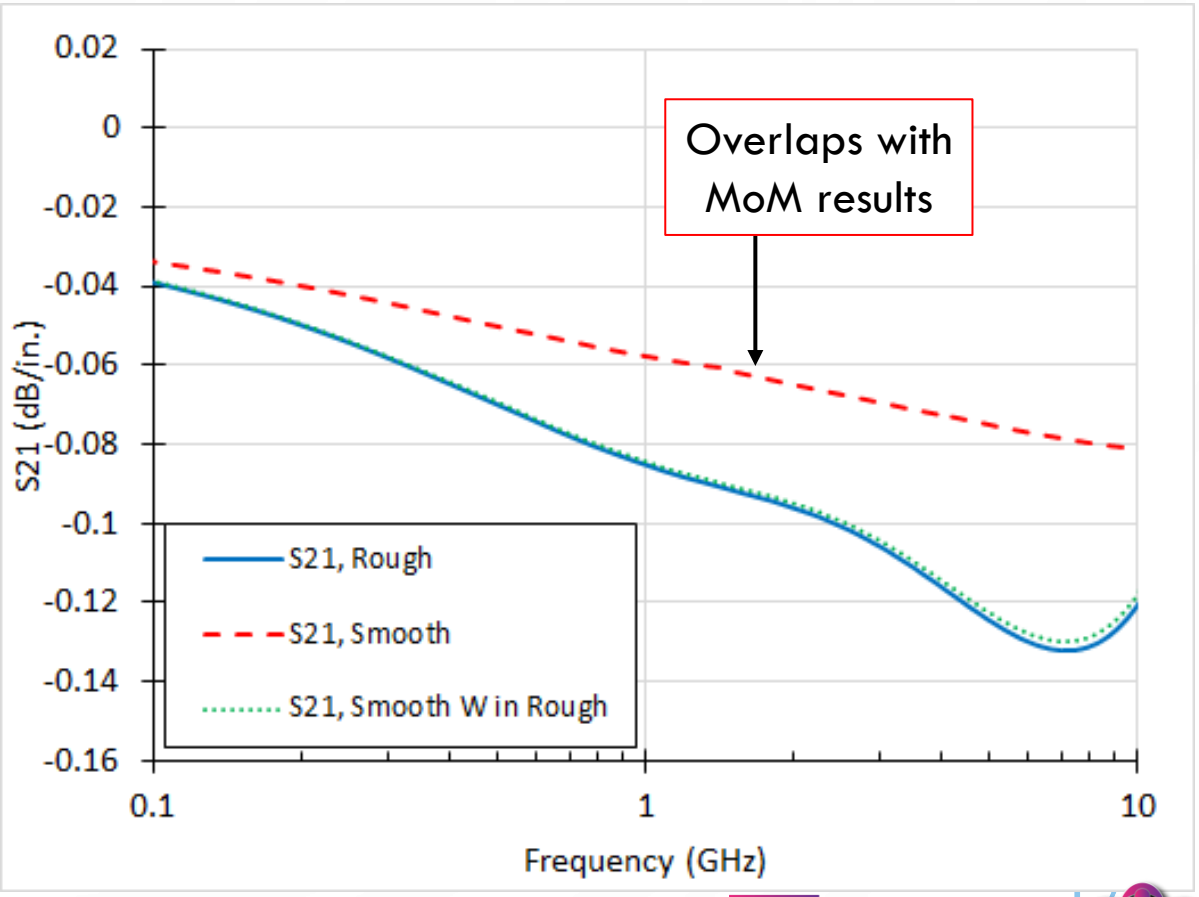
- Rough line: W = 0.178 mm (6.996 mil)
- 50 Ω Smooth line: W = 0.180 mm (7.085 mil) → No dispersion or skin effect
  - Smooth dispersion-less line: $\varepsilon = 4.171 + 0.0576i$ (@ 1 GHz)
  - Commercial MoM solver says 49.99 Ohms at 7.614 mils



Optimization Results

- Very similar return loss, very different insertion loss
- Note the commercial field solver results for return loss



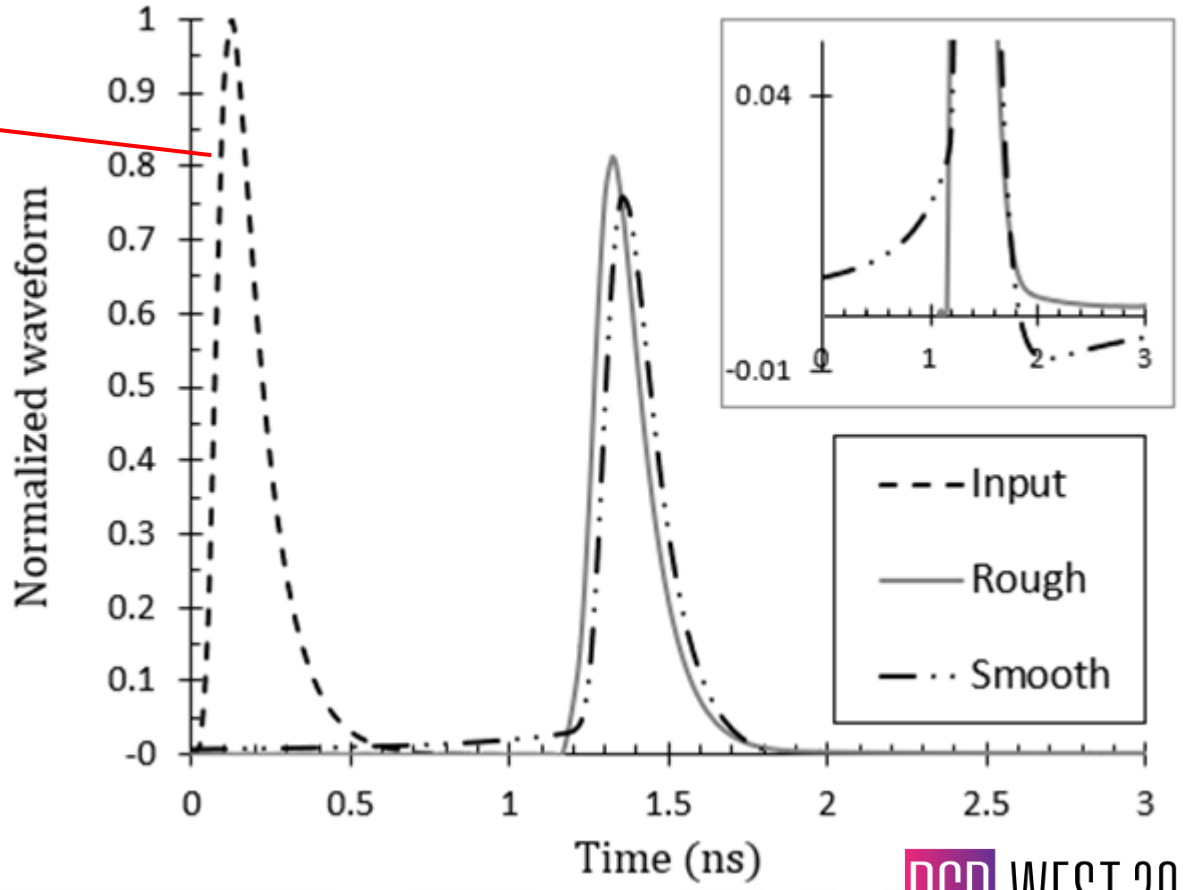


Optimization Results - Causality

- Load capacitance arises in the line's transfer function
- Use a standard procedure for RLCG models to enforce causality (see ref.)

$$y(t) = \frac{10\left(\frac{t}{\tau_0}\right)^4}{1+\left(\frac{t}{\tau_0}\right)^4} e^{-\left(\frac{t}{\tau_0}\right)}$$

1. Calculate transfer function $H(\omega)$
2. Enforce causality to get $H_c(\omega)$
3. Calculate $h(t) = IFT[H_c(\omega)]$
4. Calculate $h(t) * y(t)$



Zhang, J., et al. "Causal RLGC(*f*) Models for Transmission Lines From Measured *S*-Parameters," *IEEE Transactions on Electromagnetic Compatibility*, 52(1), pp.189-198 (2009).

Drawbacks

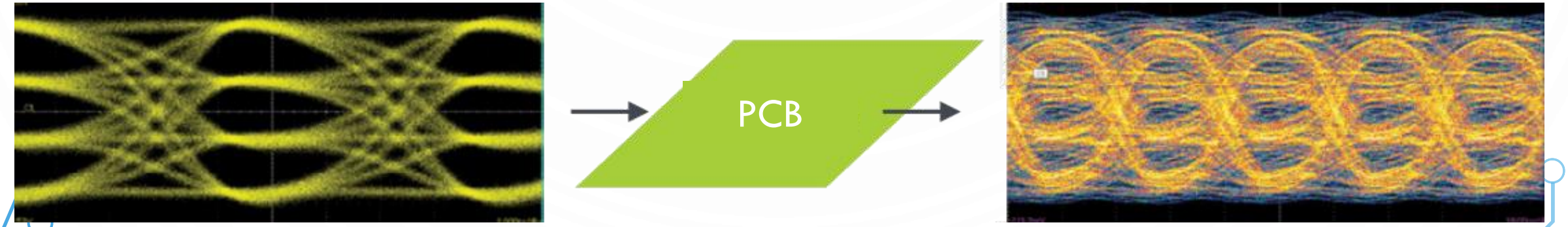
- Analytical models:
  - Difficult to account for things like differential impedance, fiber weave effects
  - Often need to incorporate numerical models

- Typically need to balance crosstalk, routing density, impedance control, and distortion → 4 objectives!
  - **Numerical model:** Wu, R.-B. and Yang, J.-C., "Boundary integral equation formulation of skin effect problems in multiconductor transmission lines," *IEEE Transactions on Magnetics*, *25*(4), 3013-3015 (1989).

Looking Ahead

- Upcoming tech demands extremely precise interconnect designs

- **Examples:** 112+ Gbps PAM4, quantum computing, 5G/6G, radar, microwave photonics, IEEE 802.11ad (Multiple Gigabit Wireless System)

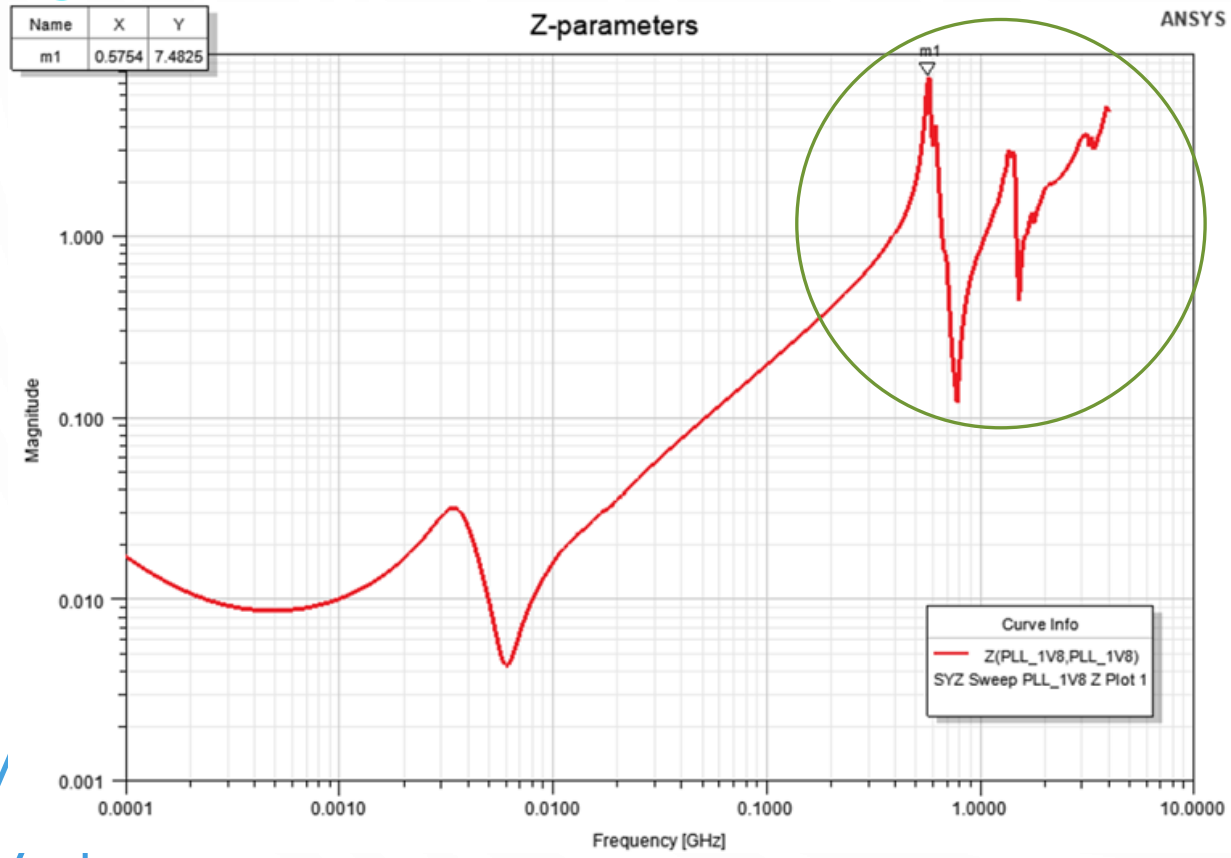


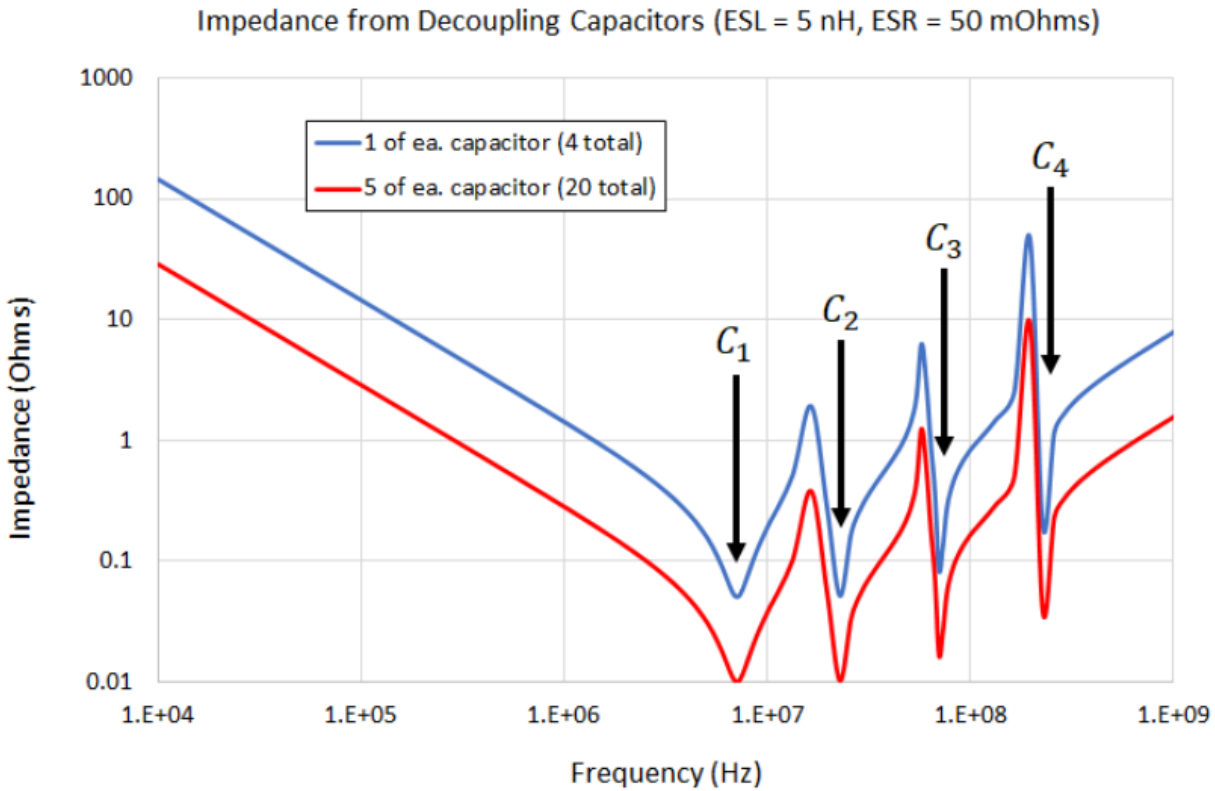
- **Constraints:** Insertion loss, ISI, crosstalk, impedance matching…

PAM4 Signaling in High-Speed Serial Technology: Test, Analysis, and Debug. Tektronix Application Note, July 2018.

Power Integrity

- Power integrity also critical in advanced designs





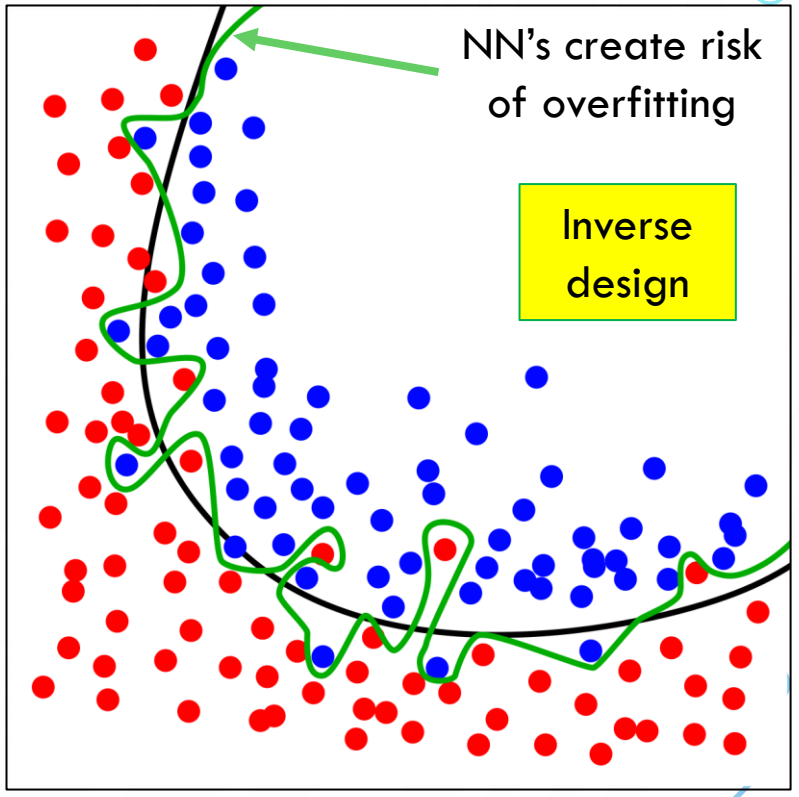
Machine Learning in Interconnect Design

- ML models already being used for interconnect and device design:
  - Transmission lines/waveguides
  - Commercial 100 GHz-1 THz oscillators and interconnects
  - SerDes adaptive equalization
  - Power and thermal integrity (on-die, SiP, applies to boards)
  - Nanophotonics device design, including PICs

- Multivariate ML models for predicting Z, S-parameters, γ, L & C, $H(\omega)$, etc.

Machine Learning in Interconnect Design

- Inverse design approach
- Optimization algorithms for specific systems and models



- Neural networks for prediction
  - Training → build numerical model from measurements (Z, S, γ, K etc.)
  - Specific to routing topology, materials, geometry, manufacturing process etc…

Roy, K., et al. "Inverse design of transmission lines with deep learning." In *2019 IEEE 28th Conference on Electrical Performance of Electronic Packaging and Systems (EPEPS)*, pp. 1-3. IEEE, 2019.

THANK YOU!

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Thank you!