Machine Learning Based Design Space Exploration and Applications to Signal Integrity Analysis of 112Gb SerDes Systems

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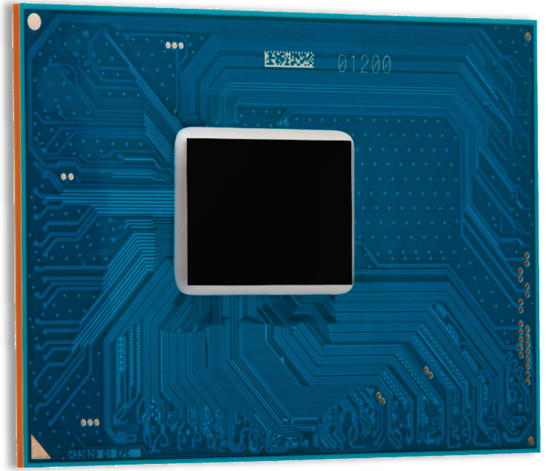
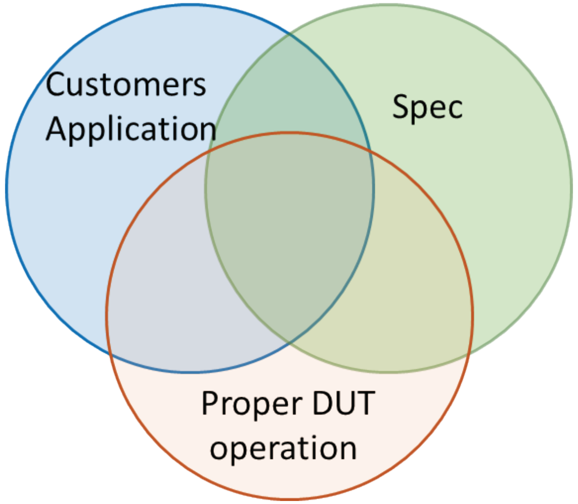
Agenda

1. **Introduction**
    1. Motivation and problem statement
    2. Proposed Method
        1. Range analysis
        2. COM Based System Analysis
        3. Channel Modeling Technics

2. **Case study : 112GB C2C link Design Space Exploration**
    1. Benchmarking- Simple link
    2. Realistic Case – Demonstration of Proposed Method

How to approach the Design Complexity and Coverage ?



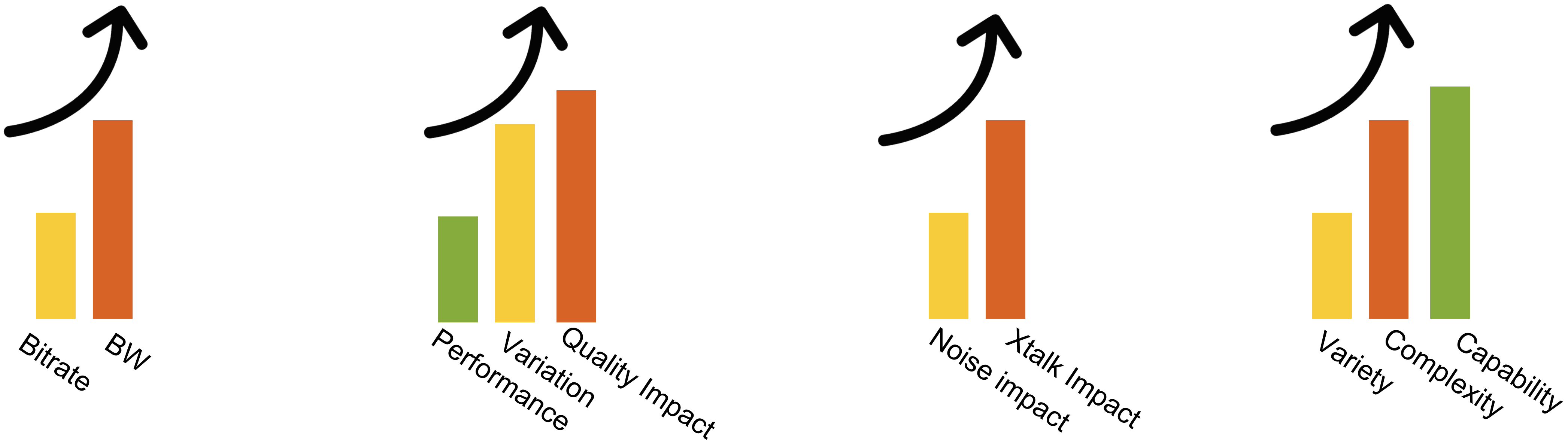


- 15 Supported protocols
- 5 Physical Interfaces
- 2 -100 Ports
- 20 Supported Use Cases

System Complexity

System Complexity

System Complexity Contributors



Signals **Interconnects** **Modulation Impact** **EQ Mechanism**

Common Design Process

1.	**Previous Project Leverage**	1.	→Limited similarity
2.	**Experts Opinion**	2.	→Intuition is misleading, this is getting harder!
3.	**Limited number scenarios analyzed**	3.	→Are we looking at the right ones? Coverage ?

The Outcome

Sub-Optimal Design = $$$ ⏱ ⚙ Penalty

A systematic approach

We need to systematically Identify:

- What are the system characteristics required for achieving good performance ?
- What are the system characteristics required for achieving excellent performance ?
- What are the system characteristics responsible for bad performance?

Design Space Exploration In 4 Steps

1. Define solution space
2. Generate link models covering the solution space
3. Analyze System performance for each case
4. Understand the results

   A. What are the important features that impact the system behavior the most?
   B. What are the ranges of each of the important features in which we are most likely to achieve desired system response?
   C. What are the combinations of feature ranges that enable us to achieve desired system response?
   D. What are the feature ranges where system is most likely to fail?

Design Space Exploration In 4 Steps

Expert Opinion
(SI Eng)

1

Define solution space

3D EM Simulator
(Simbeor)

2

Generate link models covering the solution space (1k-1M cases)

Covering:
- Design options
- PCB Manufacturing variation

COM script
(Matlab)

3

Analyze System performance for each case (x10th cases)

Covering:
- PVT corners
- EQ capabilities
- Linc partners
- OP modes

ML
(EVA tool)

4

Understand the results

A. What are the important features that impact the system behavior the most?

B. What are the ranges of each of the important features in which we are most likely to achieve desired system response?

C. What are the combinations of feature ranges that enable us to achieve desired system response?

D. What are the feature ranges where system is most likely to fail?

**System parameters are features in ML terminology*
***SerDes system response is COM metric with 3 dB pass-fail*

Feature Range Analysis

Feature Range Analysis is ML technique designed to help answering those questions and automate the decision process

Range Analysis

- Feature Range Analysis identifies combinations of *ranges* of numeric (or continuous) features and *levels* of nominal (or categorical) features that explain positive samples – samples whose characteristics and the behavior we want to explore in the data (COM>3 or COM<3)
- Algorithm resembling *Rule Learning*, *Rule Induction*, and *Subgroup Discovery* – see analysis and references in the paper

Z. Khasidashvili, A. J. Norman. *Range Analysis and Applications to Root Causing. In: 6th IEEE International Conference on Data Science and Advanced Analytics*, DSAA 2019.

Range Analysis Algorithm

1) Ranks features highly correlated to the response with 2 procedures:
   Ranking procedure uses *Ensemble Feature Selection*
   Basis procedure uses *Maximal Relevance Minimal Redundancy* (MRMR) to select a subset of features which both strongly **correlate** to the response and provide a good **coverage** of the entire variability in the response

2) Apply ***ranking*** and ***basis*** procedures to select the most relevant single ranges of the selected features, and in addition select single ranges that maximize one or more ***quality*** functions

3) Generate *range- combinations of features* and apply ***ranking***, ***basis*** and ***quality*** procedures to select the most relevant ranges for combinations of features

Implemented in Intel's EVA software

Range Analysis Quality Function

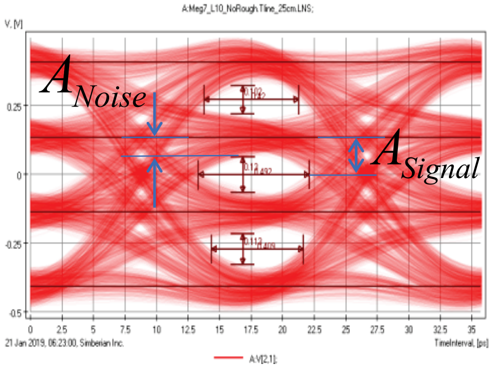
- N – count of all samples; Pos – count of positive samples; p0=Pos/N
- R – range; n(R) – count of all samples within that range;
- *True Positive Rate* (aka *sensitivity*, *recall*, or *hit rate*): TPR(R) = TP(R)/Pos
- TP(R) denotes the count *of true positive* samples - positive samples within R;
- *Predictive Positive Value* (also known as *precision*): PPV(R) = TP(R)/n(R);
- **The *lift:* Lift(R) = PPV(R)/p0** – likelihood to have more positive samples within R;
- ***Weighted Relative Accuracy****:* WRAcc(R) = (n(R)/N)*(PPV(R)–p0)

Goal of design exploration with RA is to identify ranges R that maximize Lift(R), WRAcc, and/or other quality functions that are most suitable for the application at hand

COM Based System Analysis

COM In Nutshell

Channel Operating Margin (COM) –ideal metric for RA

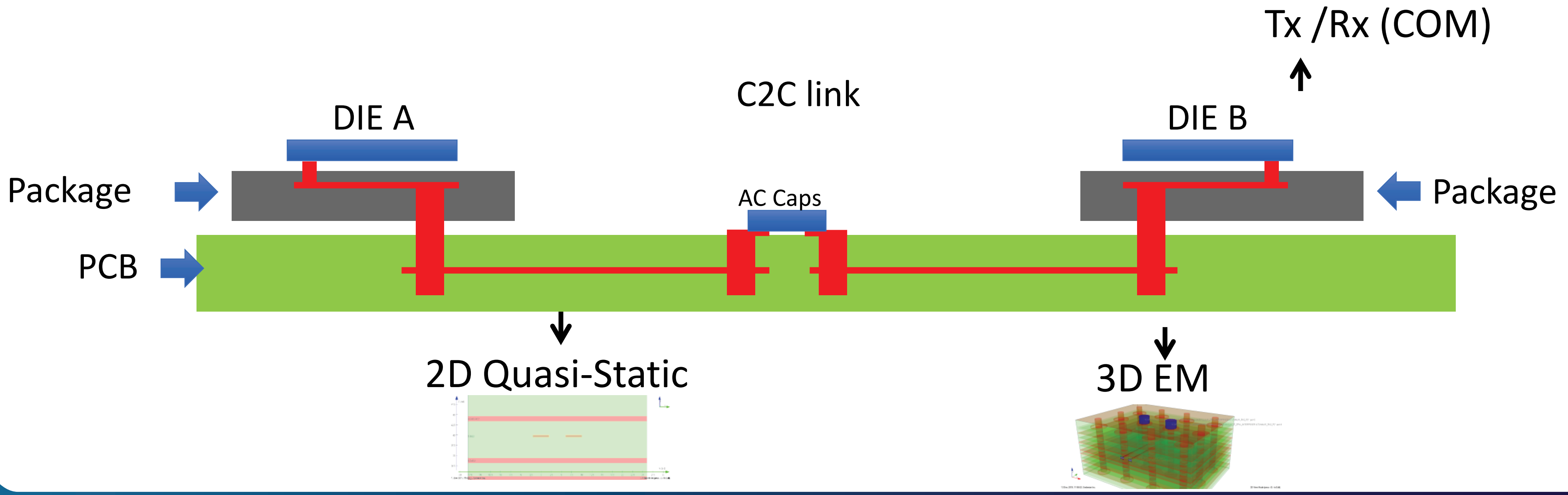


$$COM = 20 \cdot \log\left(\frac{A_{Signal}}{A_{Noise}}\right)$$

>3 dB for pass threshold
>4 dB for excellent links

A_{Signal} *Peak Signal – includes all losses accounted in model and equalization*

A_{Noise} *Peak SER Noise – includes losses, ISI, crosstalk and random noise with some assumptions and equalization*



Interconnect system Modeling

Thermal losses – dielectric and conductor effects

Reflections – characteristic impedance mismatch and discontinuities

Couplings - leaks and interference

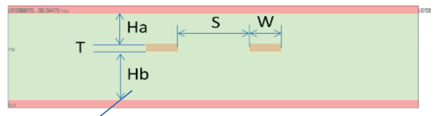
Models to compute S-parameters of links

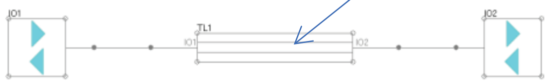
1D models or transmission line models – Telegrapher’s equations

Modal or per unit length parameters for the Telegrapher's equations (Z, Y) are computed with static or quasi-static field solver (2D problems for Laplace's equations) or an electromagnetic fields solver (3D problems for Maxwell's equations)

Lines with coupling, multimodal waveguides, periodic structures can be accurately modeled as 1D

$$\frac{\partial V(x,t)}{\partial x} = -Z_\delta(t) * I(x,t)$$
$$\frac{\partial I(x,t)}{\partial x} = -Y_\delta(t) * V(x,t)$$

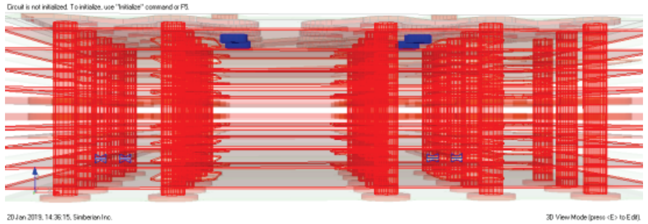




3D models or 3D full-wave models - everything described and solved with Maxwell's equations without any simplifications for 3D geometries or field components

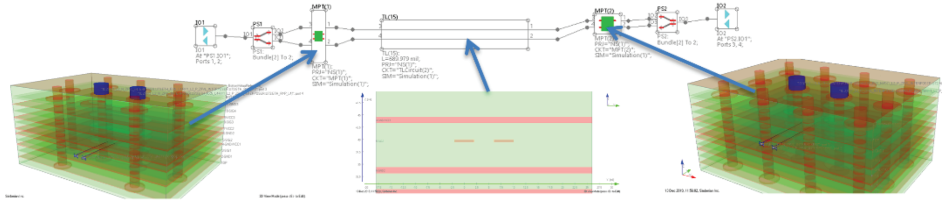
$$\nabla \times \vec{E}(\vec{r},t) = -z_\delta(\vec{r},t) * \vec{H}(\vec{r},t)$$
$$\nabla \times \vec{H}(\vec{r},t) = y_\delta(\vec{r},t) * \vec{E}(\vec{r},t) + \vec{J}$$

Analysis of discontinuities such as via-holes, connectors or any type of transitions between uniform traces



1D+3D: Hybrid de-compositional analysis with transmission line models for traces (1D) and 3D models for discontinuities or transitions (Y. Shlepnev, EMC 2013)

The best technique for the serial interconnects under the localization condition
This approach usually works for PCB and packaging problems with a relatively long traces, but may fail if trace segments are too short – complete 3D analysis is required in this case



ML Design Exploration Examples

112 Gb Chip to Chip Link

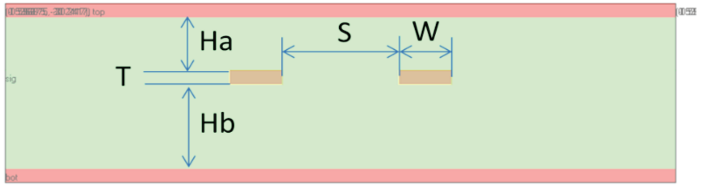
1) Simple 112 Gbps PCB link case

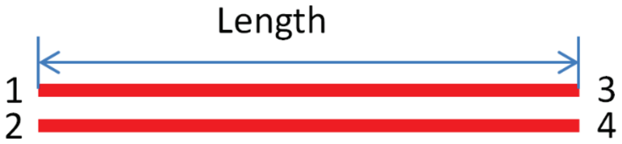
2) Realistic 112 Gbps link with PCB discontinuities and crosstalk

Simple 112 Gbps link case (PCB channel = TL model)

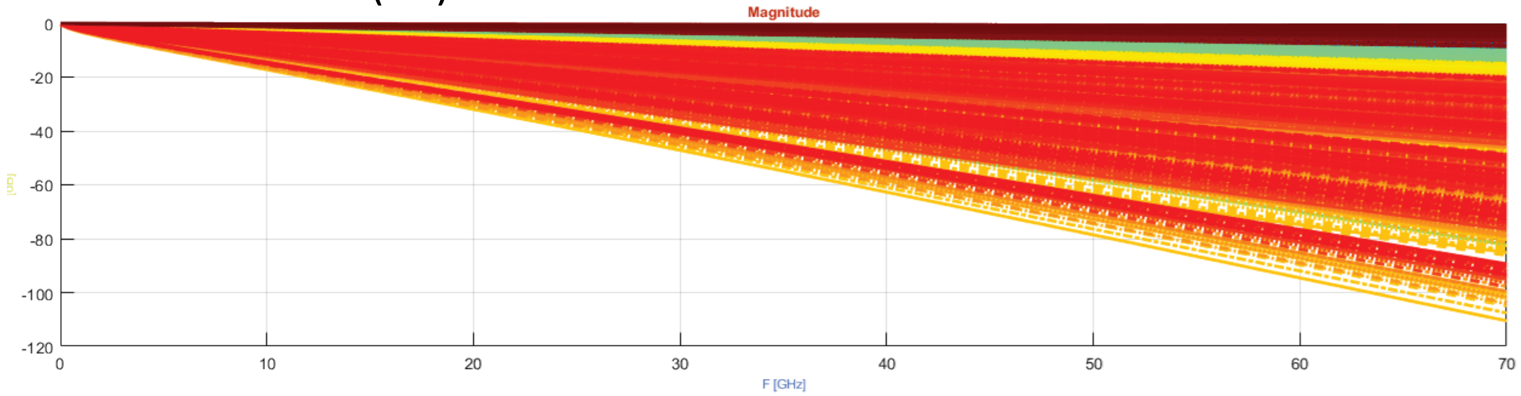
DOE Table: 5760 cases

	Feature						
1	Tx_PCB_TL_S (S/H)	1	2	3			
2	Tx_PCB_TL_L (Length) [in]	0.5	1	3	6	9	12
3a	PCB_Dk (Dk)	2.8	3.2	3.5	3.8		
3b	PCB_LT (LT)	0.001	0.002	0.004	0.009		
4	PCB_TL_H (Ha,Hb) [mil]	3	5	8	10		
5	PCB_Imp [Ω]	85	90	95	100	105	
6	PKG_Len, [mm]	1	5	12	31		





Insertion Losses (dB) for some PCB links



+Reference package parameters, 1 tap DFE

Simplest link RA results

What are the important features that impact the system behavior the most?

Results of **ranking** and **basis** procedures: strongest correlation to response and variability (coverage)

feature	score	selection
Pkg_len_RX	1.0000	correlation-coverage
Tx_PCB_L	0.3949	correlation-coverage
PCB_Imp	0.2309	correlation-coverage
PCB_Dk	0.0859	correlation-coverage
PCB_H	0.0529	correlation-coverage
Tx_PCB_DS	0.0079	coverage
Tx_PCB_S	0.0011	coverage

Single-range features maximizing **quality**

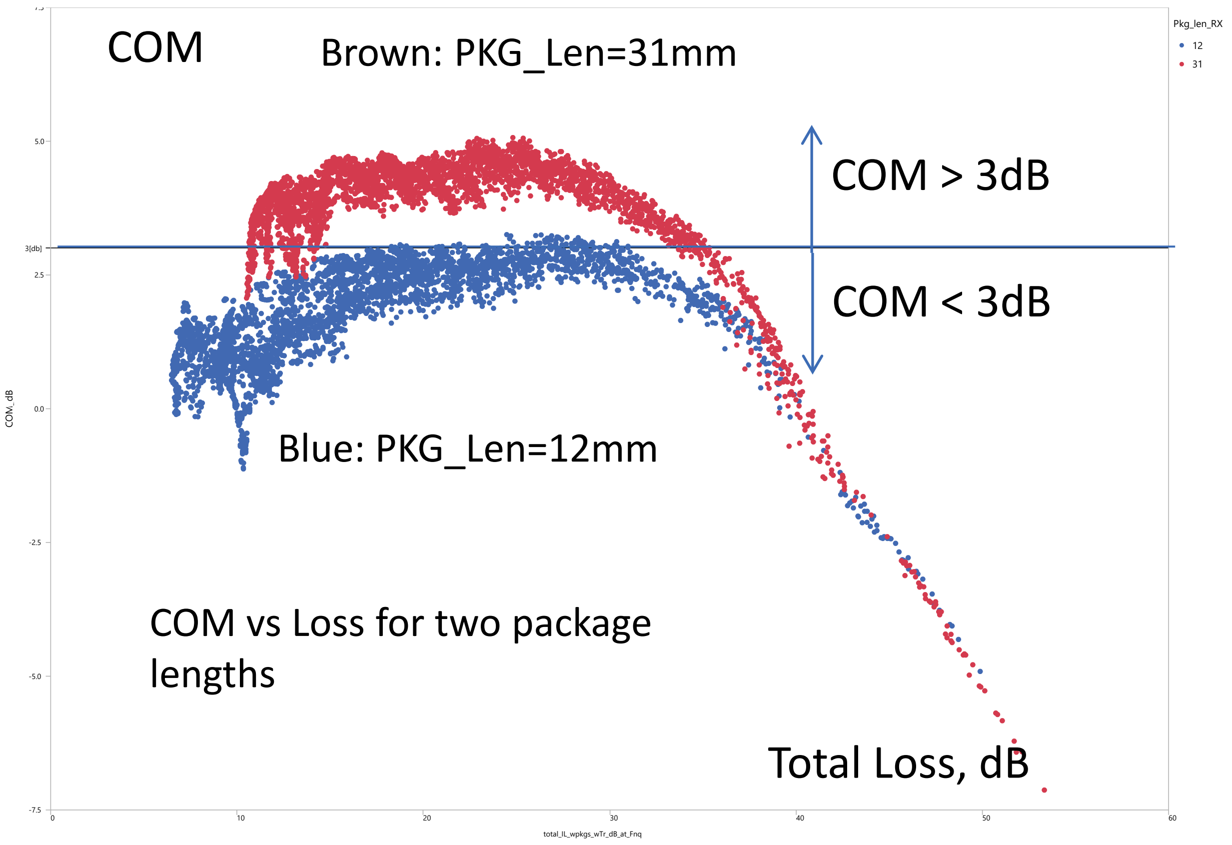
	feature	max score	max lift
0	Pkg_len_RX	1.0000	2.001159
1	Tx_PCB_L	0.3490	1.653923
2	PCB_Imp	0.1999	1.292459
3	PCB_H	0.0284	1.072431
4	Tx_PCB_S	0.0011	1.001120

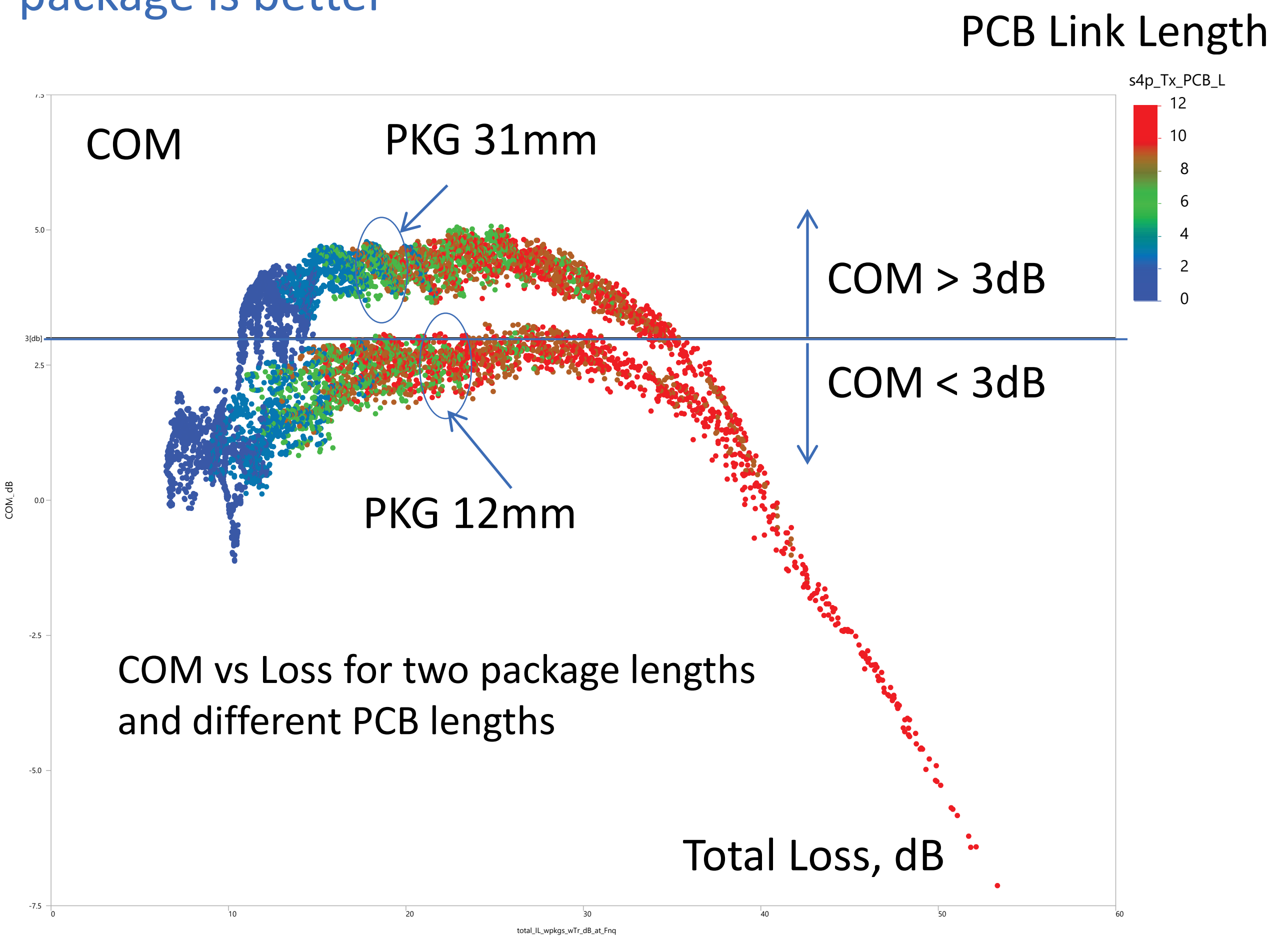
Positive: COM>=4
Negative COM<4

Package length is highly rated by both procedures – this is the most important element of the link

Simple link: Channel Length

COM vs. Total Loss at Nyquist frequency – longer package is better





Simple link: Impedance effect

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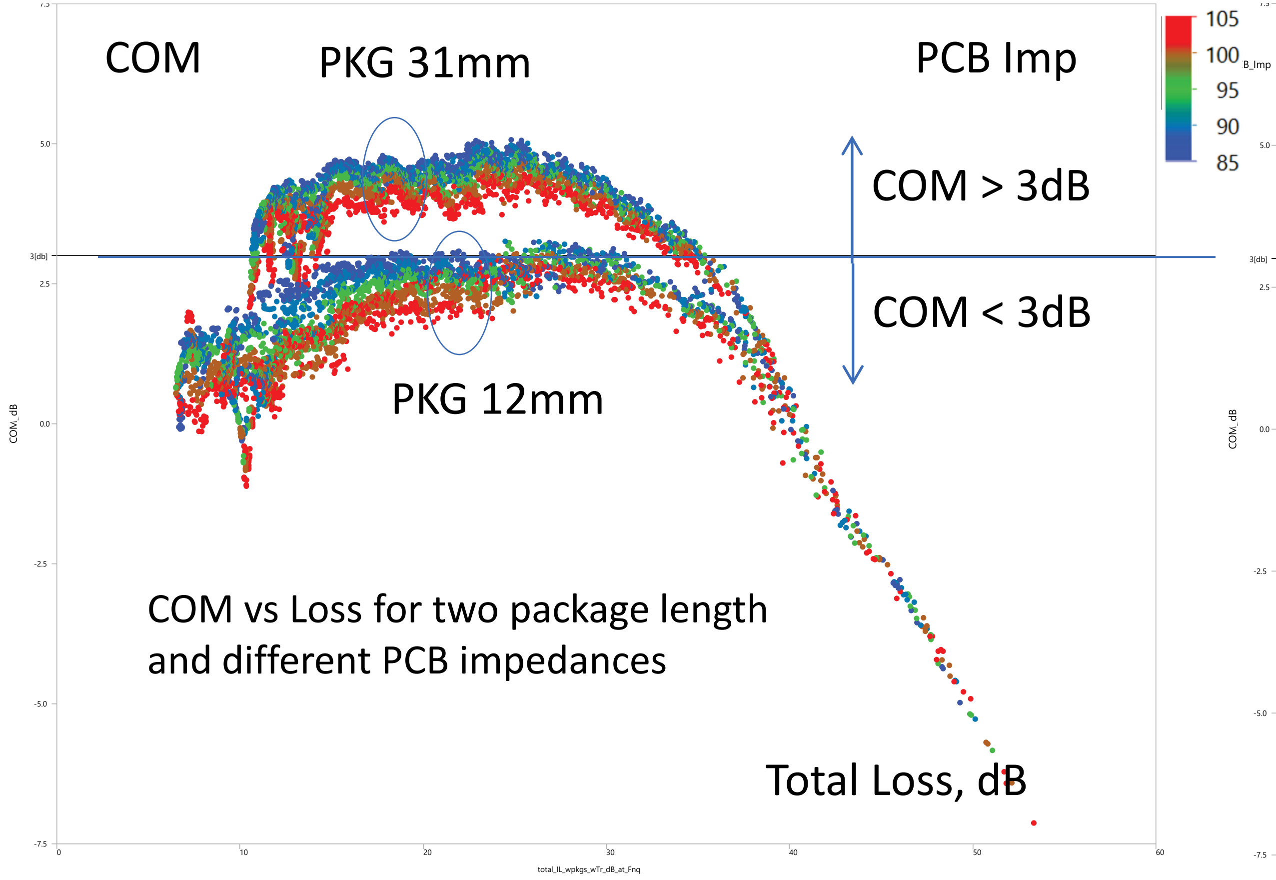
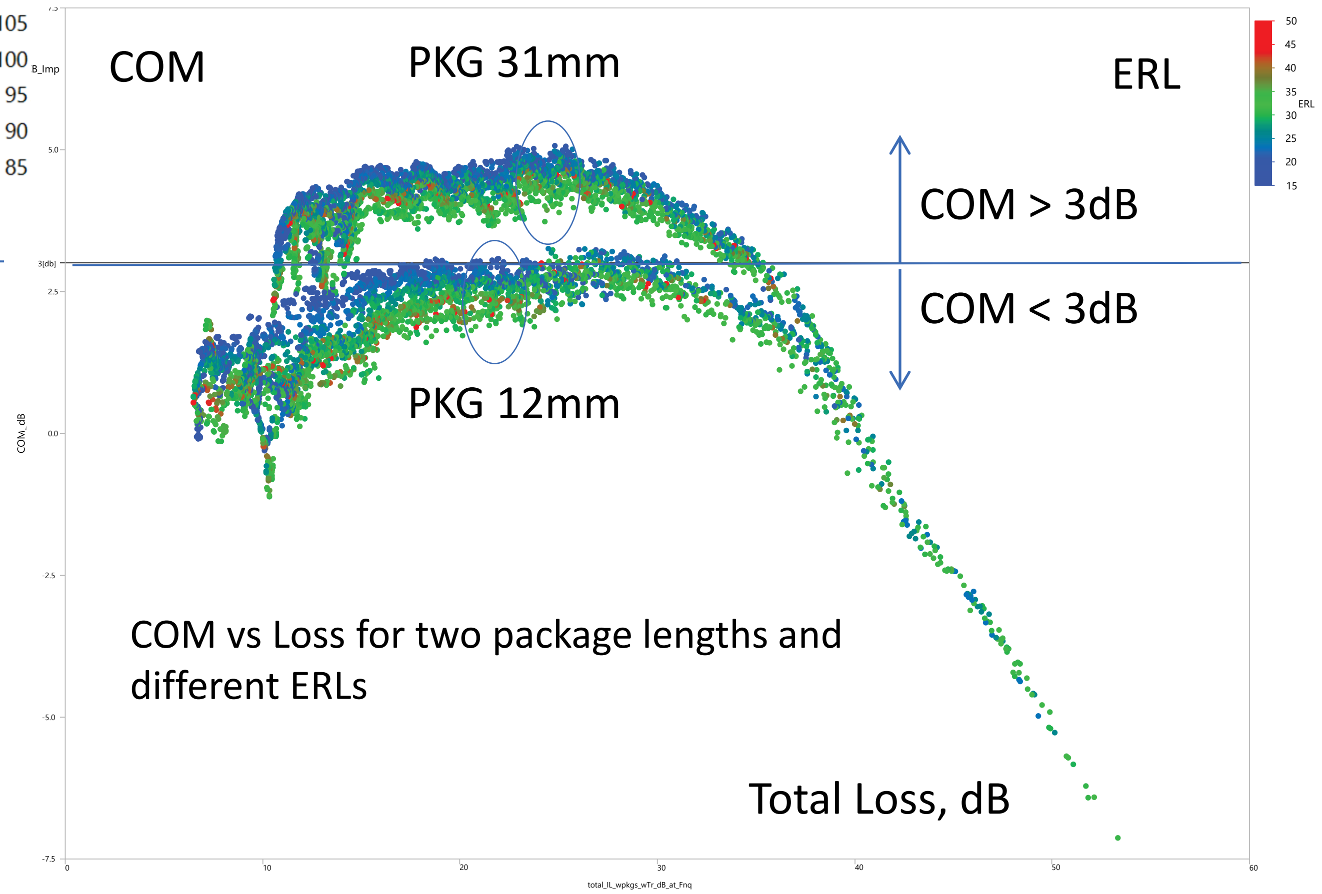
COM vs. Total Loss at Nyquist frequency – lower impedance is better





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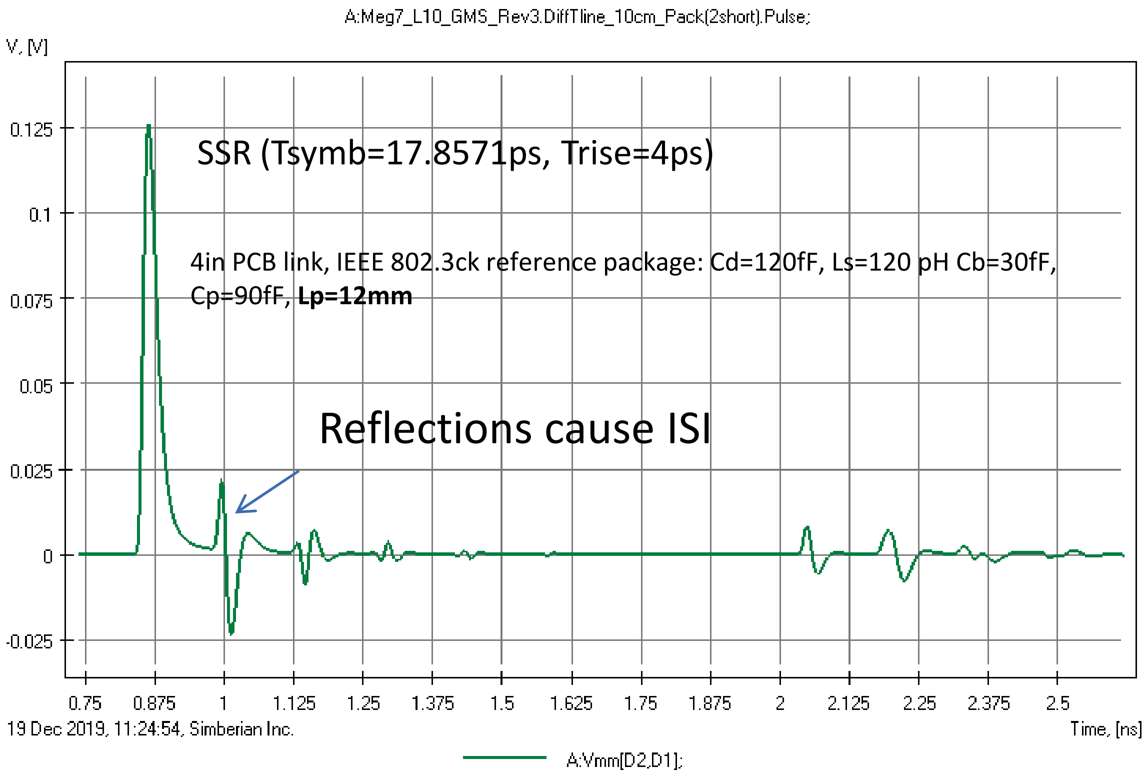
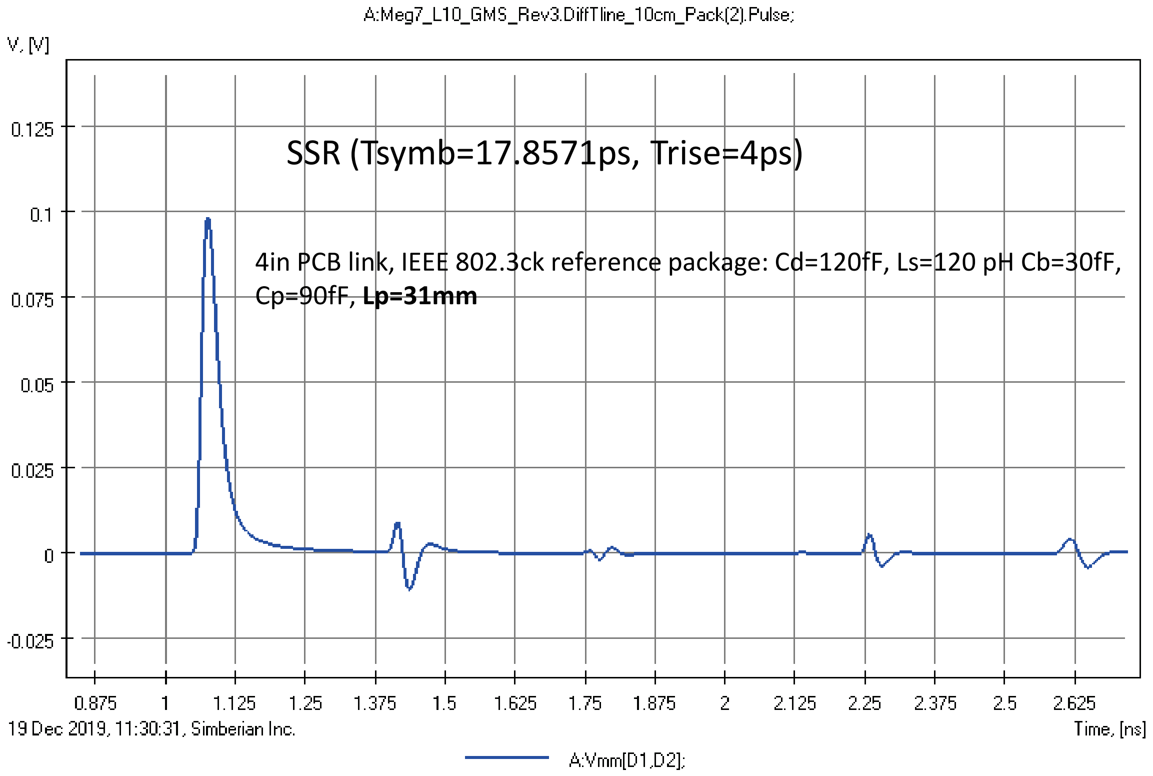
Why 12mm Rx package is a Challenge

Shorter package (12mm)



Longer package (31mm)



Reflections cannot be mitigated with 1 tap DFE

Simple link: Combination of Features

What are the combinations of feature that impact the system behavior the most?
(enabling us to achieve desired system response)

Important range-pair features

	feature1	feature2	max score	max lift
0	Pkg_len_RX	Tx_PCB_L	1.0000	3.307847
1	Pkg_len_RX	PCB_Imp	0.8773	2.586416
2	Pkg_len_RX	PCB_H	0.4797	2.136974
3	Pkg_len_RX	PCB_Dk	0.6936	2.131448
4	Tx_PCB_L	PCB_Imp	0.3344	1.453289

Important range triplet features

	feature1	feature2	feature3	max score	max lift
0	PCB_Imp	TK_PCB_L	Pkg_len_RX	0.8263	3.835184
1	Pkg_len_RX	TK_PCB_L	PCB_Imp	0.9639	3.835184
2	PCB_Dk	TK_PCB_L	Pkg_len_RX	0.8480	3.216147
3	Pkg_len_RX	Tx_PCB_L	PCB_Dk	0.7398	2.951053
4	TK_PCB_L	PCB_Imp	Pkg_len_RX	1.0000	2.907210
5	PCB_Dk	PCB_Imp	Pkg_len_RX	0.7385	2.805366
6	PCB_H	Tx_PCB_L	Pkg_len_RX	0.8333	2.766596
7	Pkg_len_RX	PCB_Imp	PCB_Dk	0.6248	2.262003

Positive: COM>=4
Negative COM<4

Combinations of features with package and PCB link length have highest lift – proper selection increases likelihood of success

Simple Link: RA Results

What are the combinations of feature ranges that enable us to achieve desired system response? (maximizing quality)

	s4p_PCB_Imp range_1	s4p_Tx_PCB_L range_2	Pkg_len_RX range_3	score	selection	Positive Out	Negative Out	Positive In	Negative In	Range1 Lift	Range2 Lift	Range3 Lift	Triplet Lift
1	-Inf:90	6:6	31:Inf	0.3600	target	1963	6382	288	0	1.282095	1.653923	2.001159	3.83518
2	-Inf:95	6:6	31:Inf	0.4577	target	1822	6379	429	3	1.220420	1.653923	2.001159	3.80855
3	-Inf:95	3:Inf	31:Inf	0.8263	correlation-coverage	888	6018	1363	364	1.220420	1.298165	2.001159	3.02684

	feature1	feature2	feature3	max score	max lift
0	PCB_Imp	TK_PCB_L	Pkg_len_RX	0.8263	3.835184
1	Pkg_len_RX	TK_PCB_L	PCB_Imp	0.9639	3.835184
2	PCB_Dk	TK_PCB_L	Pkg_len_RX	0.8480	3.216147
3	Pkg_len_RX	Tx_PCB_L	PCB_Dk	0.7398	2.951053
4	TK_PCB_L	PCB_Imp	Pkg_len_RX	1.0000	2.907210
5	PCB_Dk	PCB_Imp	Pkg_len_RX	0.7385	2.805366
6	PCB_H	Tx_PCB_L	Pkg_len_RX	0.8333	2.766596
7	Pkg_len_RX	PCB_Imp	PCB_Dk	0.6248	2.262003

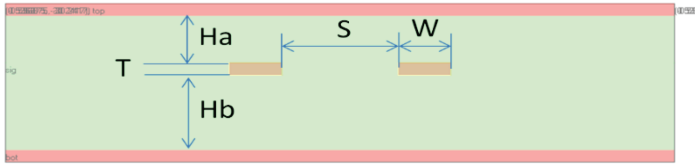
Positive: COM>=4
Negative COM<4

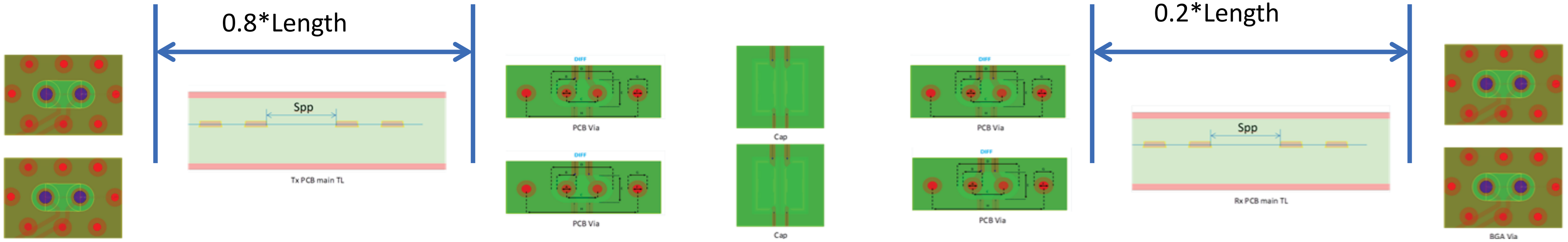
Realistic Link with crosstalk and discontinuities

DOE Table: 25920 cases

	Feature						
1	Tx_PCB_TL_S (S/H)	1	2	3			
2	Tx_PCB_TL_L (Length) [in]	0.5	1	3	6	9	12
3a	PCB_Dk	2.8	3.2	3.5	3.8		
3b	PCB_LT	0.001	0.002	0.004	0.009		
5	PCB_TL_H (Ha, Hb) [mil]	3	5	8	10		
6	PCB_Imp [Ohm]	85	90	95	100	105	
7	Tx_PCB_TL_DS (Spp/H)	3	5	10			
8	SR [um]	0.075	0				
9	PKG_Len [mm]	5	12	31			

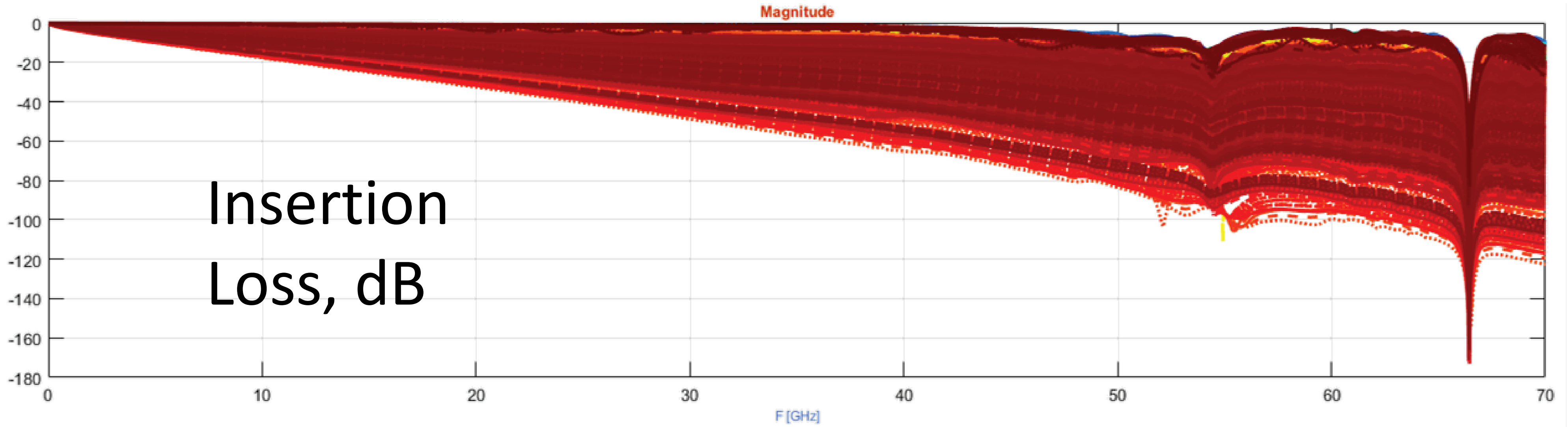
Optimized discontinuities + reference package model

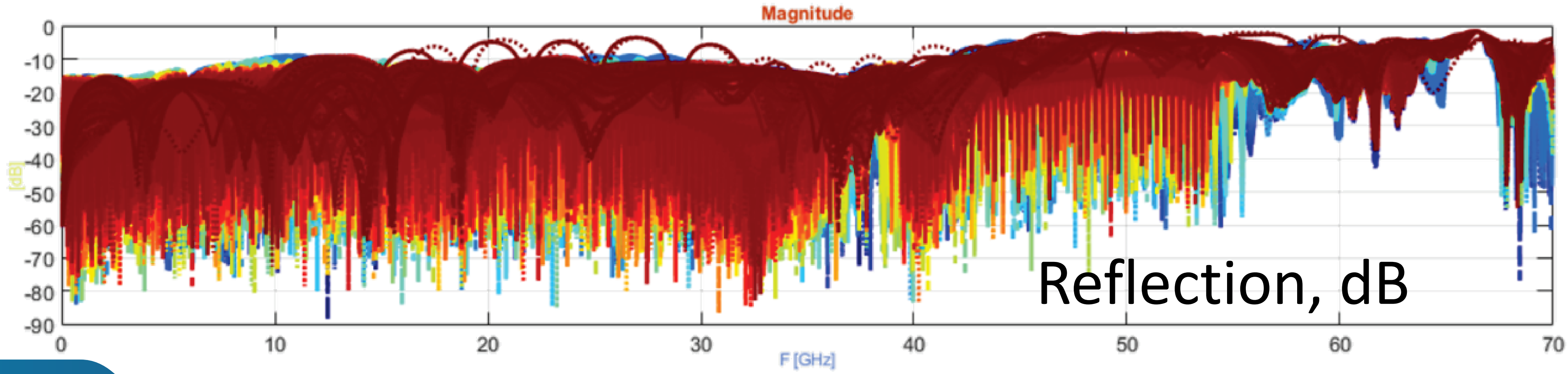




Simulated with Simbeor SDK

Realistic link S-parameters





Design Exploration Based on RA Method

Step1 - Single Feature Analysis

1. Features Ranking
2. Features Range Based Ranking
3. Important Ranges Breakdown

Step2 - Pair of features Analysis

1. Features Range Based Ranking
2. Important Ranges Breakdown

Step3 - Triplets of Feature Analysis

1. Single Range Features Ranking
2. Important Ranges Breakdown

Step 4- Etc.

…

Step N –Success (Exploration Goals Are Mett)

Step1 - Single Feature Analysis

All feature ranking results

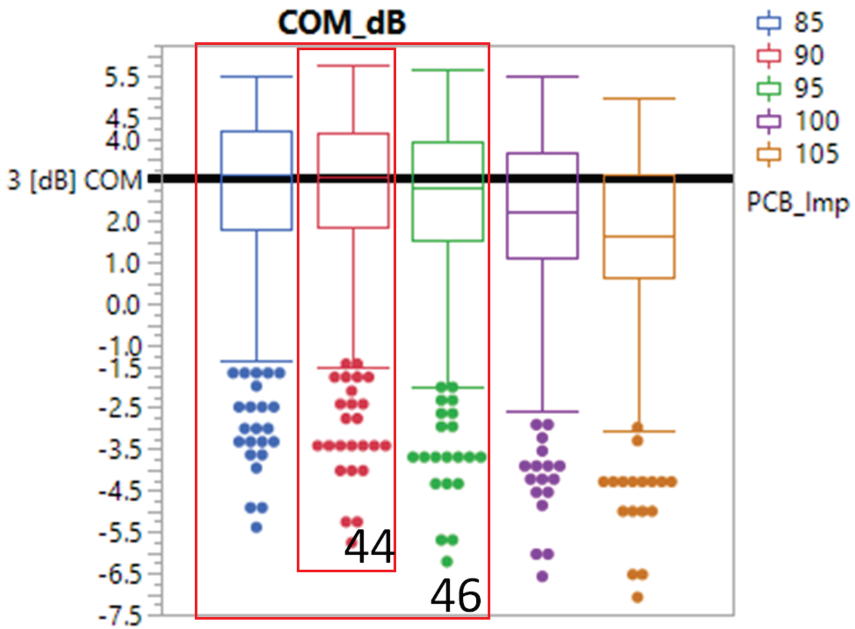
	feature	score	selection
56	Pkg_len_TX	1.0000	correlation-coverage
57	Tx_PCB_L	0.5426	correlation-coverage
58	PCB_Imp	0.2433	correlation-coverage
59	PCB_Dk	0.0544	correlation-coverage
60	PCB_LT	0.0544	correlation-coverage
61	PCB_H	0.0400	coverage
62	PCB_SR	0.0210	coverage
63	Tx_PCB_DS	0.0128	coverage
64	Tx_PCB_S	0.0064	coverage

Important single range features

	feature	max score	max lift
0	Pkg_len_TX	1.0000	1.713138
1	Tx_PCB_L	0.8063	1.482123
2	PCB_Imp	0.3451	1.229225
3	PCB_H	0.0559	1.040834
4	PCB_Dk	0.0630	1.027400
5	PCB_SR	0.0302	1.022407
6	Tx_PCB_DS	0.0093	1.009892

Example: Single ranges identified for the impedance feature

	PCB_Imp	score	selection	Positive OUT	Negative OUT	Positive IN	Negative IN	Range Lift
44	90:90	0.1672	target	8249	12449	2691	2487	1.229225
45	-Inf:90	0.2865	target	5571	9957	5369	4979	1.227204
46	-Inf:95	0.3451	coverage -target	3210	7143	7730	7793	1.177833
47	-Inf:100	0.2770	target	1401	3777	9539	11159	1.090070



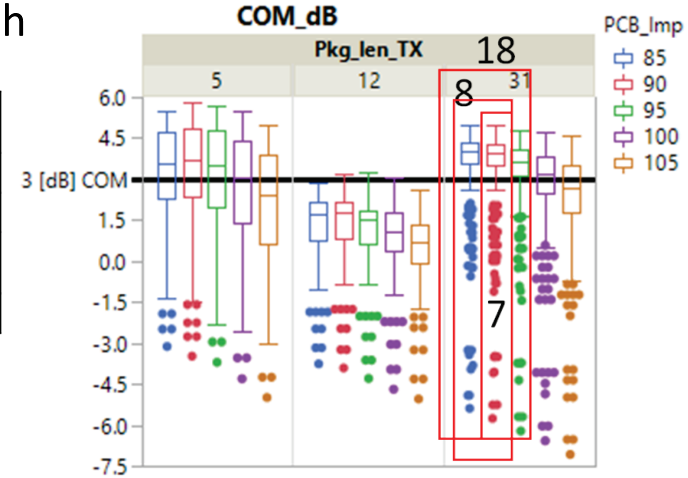
Step2 - Pair of features Analysis

Important range pair features

	feature1	feature2	max score	max lift
0	PCB_Imp	Pkg_len_TX	0.9959	2.213154
1	Pkg_len_TX	Tx_PCB_L	0.9782	2.182943
2	PCB_Dk	Pkg_len_TX	0.7254	1.882133
3	PCB_Dk	Tx_PCB_L	0.5314	1.505301
4	PCB_Imp	Tx_PCB_L	0.6828	1.390276
5	PCB_H	Tx_PCB_L	0.4950	1.323446

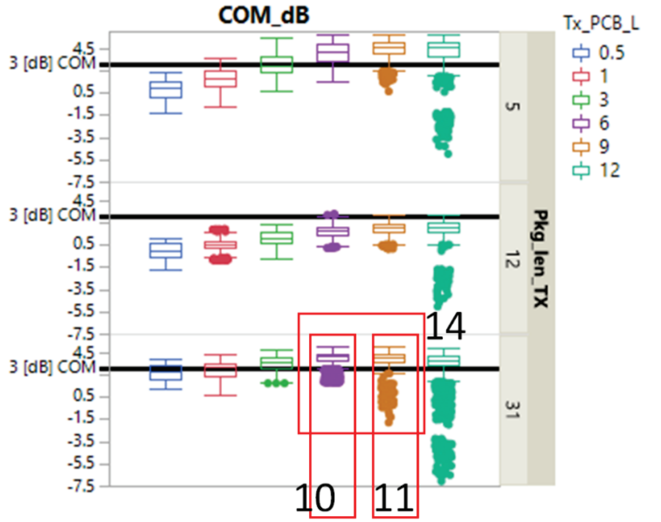
Important ranges for PCB link impedance and package length

	PCB_Imp	Pkg_len _TX	score	selection	Positive OUT	Negative OUT	Positive IN	Negative IN	Pair Lift
7	90:90	31:Inf	0.4957	coverage-target	9325	14825	1615	111	2.213154
8	-Inf:90	31:Inf	0.8086	target	7716	14711	3224	225	2.210964
18	-Inf:95	31:Inf	0.9959	correlation-coverage-target	6337	14365	4603	571	2.104236
23	-Inf:100	31:Inf	0.9741	correlation-target	5394	13583	5546	1353	1.901400



Important ranges for package length and PCB link length

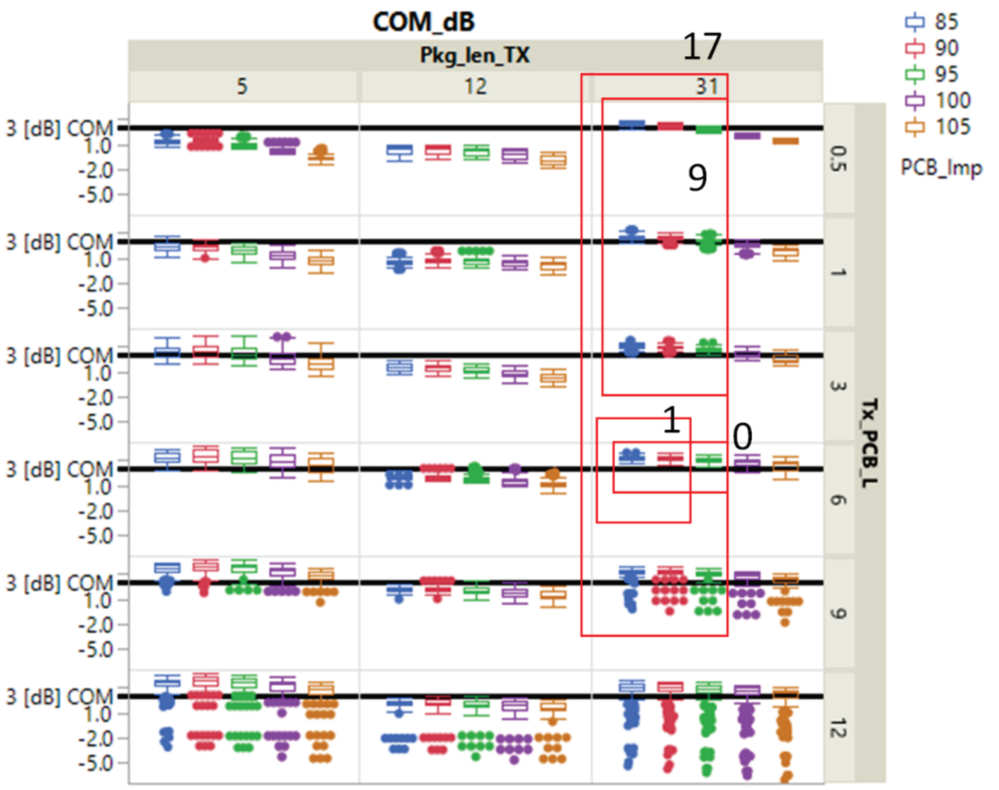
	Pkg_len _TX	Tx_PCB_L	score	selection	Positive OUT	Negative OUT	Positive IN	Negative IN	Pair Lift
10	31:Inf	9:9	0.4275	target	9611	14825	1329	111	2.182943
11	31:Inf	6:9	0.6725	target	8301	14695	2639	241	2.167338
14	31:Inf	6:6	0.4140	target	9630	14806	1310	130	2.151734
19	31:Inf	6:Inf	0.8290	coverage	7140	14416	3800	520	2.080557
20	31:Inf	3:Inf	0.9782	correlation-coverage-target	6024	14092	4916	844	2.018688



Step3 - Triplets of Feature Analysis

Important range triplet features

	feature1	feature2	feature3	max score	max lift
0	PCB_Imp	Tx_PCB_L	Pkg_len_TX	1.0000	2.365265
1	PCB_Dk	Tx_PCB_L	Pkg_len_TX	0.7511	2.365265
2	PCB_Dk	PCB_Imp	Pkg_len_TX	0.8383	2.136133
3	PCB_Dk	Tx_PCB_L	PCB_Imp	0.5385	1.414642
4	PCB_H	Tx_PCB_L	PCB_Imp	0.5225	1.404740
5	PCB_Dk	Tx_PCB_L	PCB_H	0.4255	1.360514



Four possible ranges identified for the first triplet of features (PCB link impedance and length and package length)

	PCB_Imp	Pkg_len_TX	Tx_PCB_L	score	selection	Positive OUT	Negative OUT	Positive IN	Negative IN	Triplet Lift
9	-Inf:90	31:Inf	-Inf:3	0.5050	coverage	9335	14820	1605	116	2.365265
0	-Inf:95	31:Inf	6:6	0.3789	target	10076	14936	864	0	2.365265
1	-Inf:90	31:Inf	6:6	0.2971	target	10364	14936	576	0	2.250287
17	-Inf:95	31:Inf	-Inf:9	0.9038	correlation-target	7064	14502	3876	434	2.205840

Conclusion

- Expertise-based analysis of interconnect systems with tens of features is difficult and error-prone (requires an expert to start with)
- A formal system design exploration method based on Machine Learning Range Analysis algorithms is proposed and demonstrated for 112Gb system case study – only the initial set of features and ranges should be identified by an engineer
- The proposed method allows automated analysis of the solution space and identifies the features ranges with the maximal likelihood of success
- It can be used as a decision support tool for design choices in the hands of the system architect, Si designer, SI Engineer, and more