Addressing the challenges of PAM-3 USB 4.0 - Design and Analysis

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Agenda

- **USB4 Challenges**
- **USB4 Compliance Kit**
- **USB4 AMI Model parameters**
- **Requirements to pass USB4 Gen 4 Compliance**
- **USB4 Spec**
  - This presentation refers to tables and sections defined in the USB4 Specification V2.0
  - https://www.usb.org/document-library/usb4r-specification-v20
- **TX/RX AMI Optimization**
- **TX/RX AMI and Channel Co-Optimization**
- **Conclusions**

USB4 Gen 4 Compliance Challenges

- **USB4 PAM3**
- **Equalization**
  - Tx AMI Model
    - 42 presets
    - 2 precursor taps
    - 1 postcursor tap
  - Rx AMI Model
    - 2 stage CTLE
    - 12 tap DFE
- **SNDR (Signal to Noise Distortion Ratio)**
  - Not a standard serial link measurement

PAM3 Overview

- MLT-3 was included in patent (#5280500) which was filed by Mario, Luca, and Maurilio in 1991
- Multi-Level Transition (MLT-3) was used on 100Base-TX (802.3u) in 1995.
- PAM3 (8b/6t) was adopted into 100BASE-T4 (100 Mbit/s over four-pair UTP cable) in 1995 as well
- USB4 V2.0 adopted PAM3 to support 40Gbps/lane speed for USB4 Gen4
- PAM3 offers larger vertical eye openings compared with PAM4 and less bandwidth requirement than NRZ (PAM2)
- Key technical details
  - **25.6Gtps** to support 40Gbps
  - **11b/7t** (1.57 bits per symbol) encode/decode scheme
  - **2048/2187** offers better overhead vs USB 3.1/3.2 and USB4 128b/132b and 8b/10b USB3.0 encoding schemes
  - Pre-coding scheme is adopted to reduce the burst errors due to RX DFE (Decision Feedback Equalization)
  - Forward Error Correction (FEC) for PAM-3 is required for USB4 V2.
  - Reed-Solomon (480,504) FEC detects and corrects up to 12 errors per block
  - Combined with precoding, the resulting BER of 1E-19 is significantly better than 1E-12 for USB4 Gen3 20Gbps.

Figure 4-43. Description of Pre-coding Operation

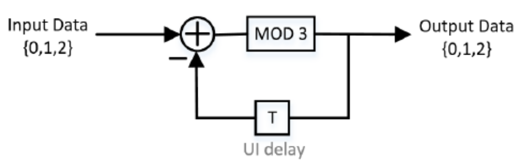
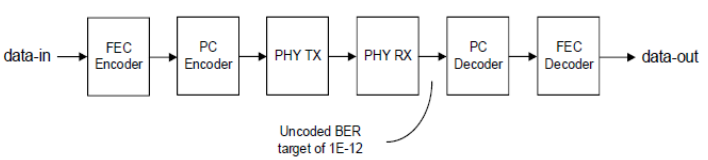
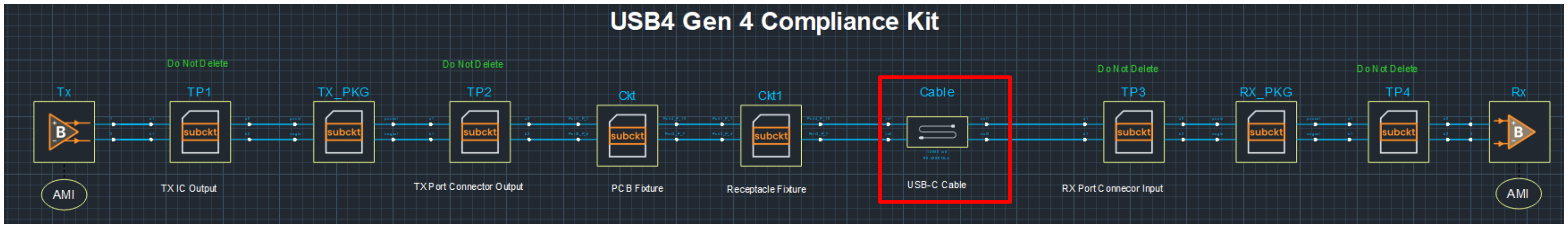


Figure 3-1. Combined Forward-Error-Correction and Pre-Coding Scheme



USB4 Compliance Kit Setup



Simulation Properties:

Data Rate (Gbps)	Log BER	Ignore Time (ns)	Minimum # of Bits	Bit Sampling Rate	BER Floor
38.4	-8	200	100000	32	1e-8

- **25.6GBaud/S PAM3 Signaling (40 Gbps)**
- **42 Preset TX AMI Model**
- **Dual Stage CTLE with 12 Tap DFE RX AMI Model**
- **Users can replace all Rx, Tx, PKG, and interconnect models with their own**

Figure 3-27. Gen 4 Compliance Test Point Definitions

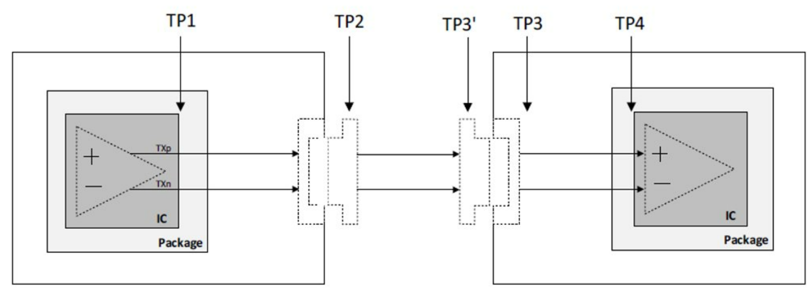


Table 3-21. Electrical Compliance Test Points

Test Point	Description	Comments
TP1	Transmitter IC output	Not used for Gen 4 electrical testing.
TP2	Transmitter port connector output	Defined at the output of a compliance plug fixture.
TP3	Receiver port connector output	Defined at the receptacle side of the connector. All measurements at this point shall be done while applying the reference equalization function.
TP3'	Receiver port connector input	Defined at the output of a compliance plug fixture.
TP4	Receiver IC input	Not used for Gen 4 electrical testing.

Compliance Tests

- **Tx Tests**
  - Tx Level
  - Tx Differential Return Loss (Figure 3-31)
  - Tx Signal to Noise Distortion Ration (SNDR) (Section 3.2.3.4)

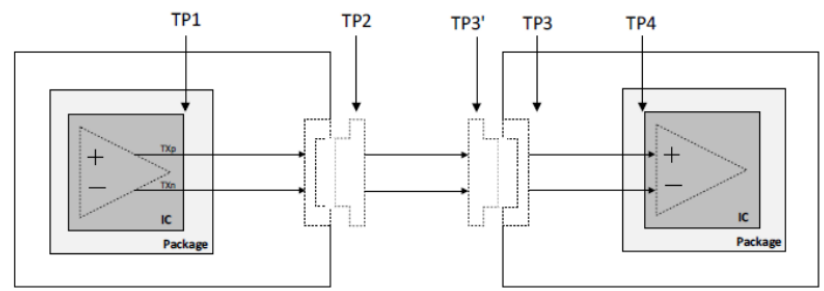
- **Rx Tests**
  - End to End Channel Differential Insertion Loss @12.8 GHz
  - Differential Return Loss Mask (Figure 3-35)
  - Receiver Tolerance Test (Section 3.2.4.2)

USB 4 - Gen 4 Compliance Kit

Choose Compliance Items

No.	Parameter	Values	■
Transmitter Tests (Table 3-22)			
1	Tx Level		■
2	Tx Differential Return Loss		■
3	Tx Signal to Noise Distortion Ratio (SNDR) (Section 3.2.3.4)	32.5 dB	■
Receiver Tests			
4	End to End Channel Differential Insertion Loss @ 12.8 GHz	28.5 dB	■
5	Rx Differential Return Loss		■
6	Receiver Tolerance Test (Section 3.2.4.2)		■

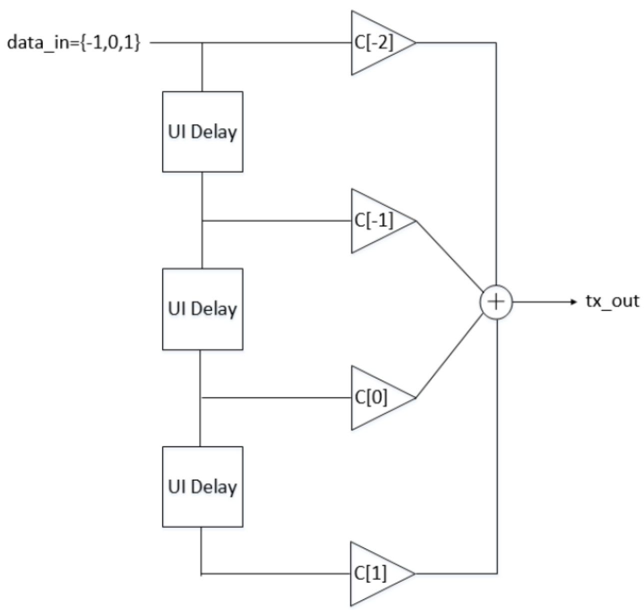
Figure 3-27. Gen 4 Compliance Test Point Definitions



Tx AMI

- **Tx Equalization**
  - 42 presets defined in USB4 Spec
  - Default preset of Tx shall be configured to setting that obtains lowest data dependent jitter

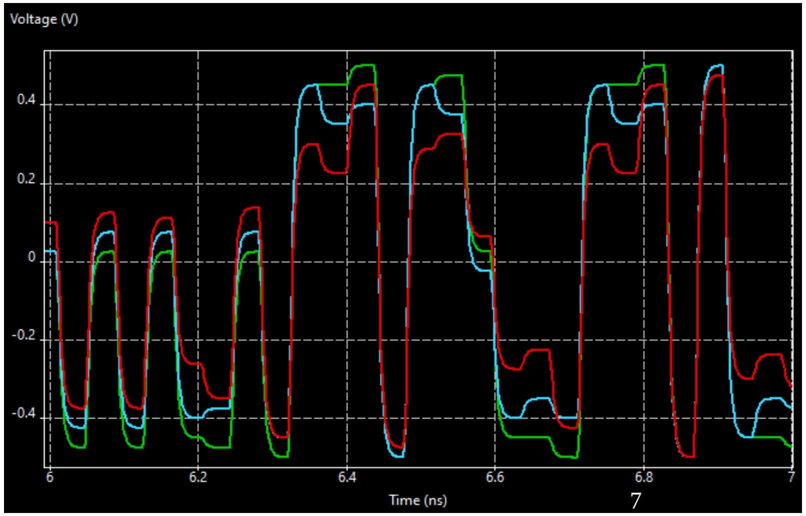
Figure 3-32. Transmitter Equalizer Structure



USB4 Gen4 TXAMI Model

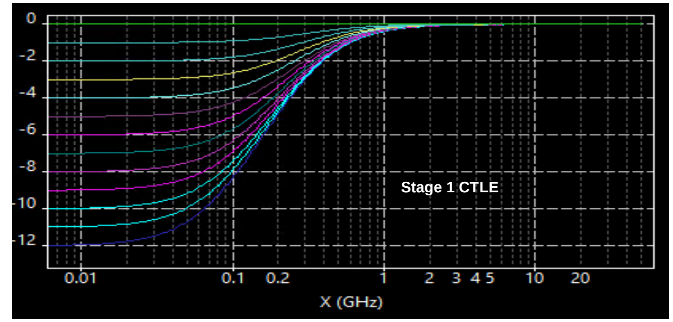
Table 3-24. Transmitter Equalization Presets

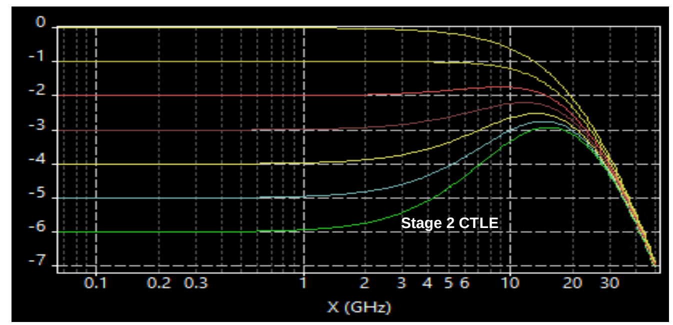
Preset Number	C[-2]	C[-1]	C[0]	C[1]
0	0	0	1	0
1	0	0	0.95	-0.05
2	0	0	0.9	-0.1
3	0	0	0.85	-0.15
37	0.05	-0.25	0.65	-0.05
38	0.075	-0.25	0.675	0
39	0.075	-0.25	0.625	-0.05
40	0	-0.10	0.40	0
41	0	0	0.50	0



Rx AMI

- **Rx Equalization**
- **Dual stage CTLE with 12 tap DFE**
  - All measurements at TP3 shall be taken while applying the reference equalization function





CTLE:

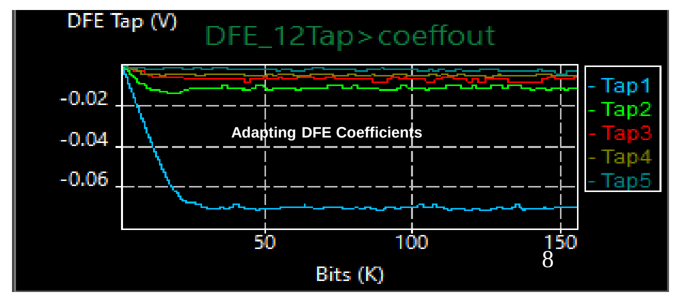
$$H(s) = \frac{(s + 2\pi f_{LP} \cdot A_{DC\_LP})}{(s + 2\pi f_{LP})} \cdot \frac{f_{p1} \cdot (s + 2\pi f_{z1} \cdot A_{DC\_1})}{f_{z1} \cdot (s + 2\pi f_{p1})} \cdot \frac{2\pi f_{p2}}{(s + 2\pi f_{p2})}$$

Nominal setting: $f_{LP}=F_{baud}/80$

Nominal setting: $f_{p1}=f_{z1}=F_{baud}/2.5$

Nominal setting: $f_{p2}=F_{baud}$

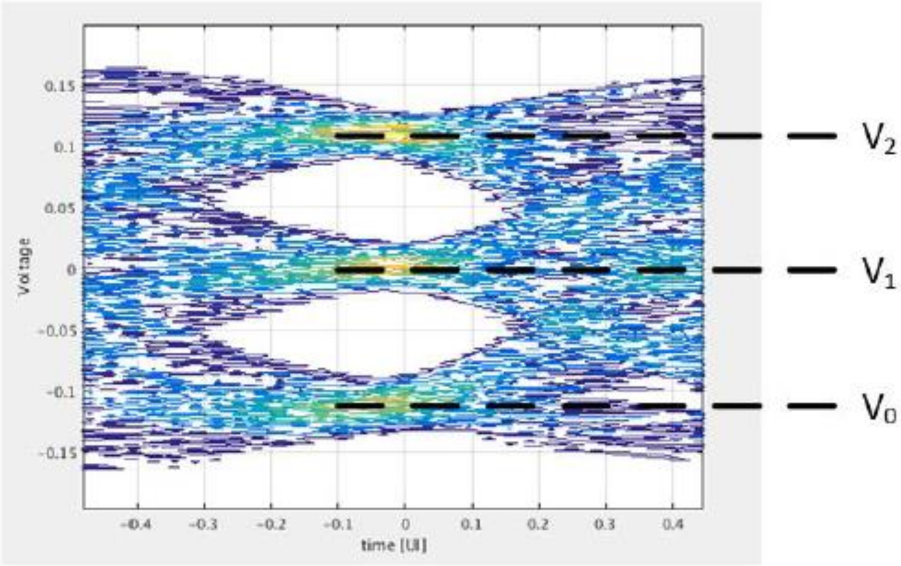
RX EQ Settings			
g_DC	[-12:1:0]	dB	CTLE stage1 (high pole) DC attenuation
g_DC_HP	[-6:1:0]		CTLE stage2 (low pole) DC attenuation
f_HP_PZ	0.32	GHz	CTLE stage2 pole location
f_z	10.24	GHz	CTLE stage1 zero location
f_p1	10.24	GHz	CTLE stage1 first pole location
f_p2	25.6	GHz	CTLE stage1 second pole location
N_b	12	UI	Number of DFE taps
b_max(1)	0.75		Dynamic range limitation for the DFE first tap (referenc
b_max(2..N_b)	0.2		Dynamic range limitation for the DFE taps 2 and above



Tx Level

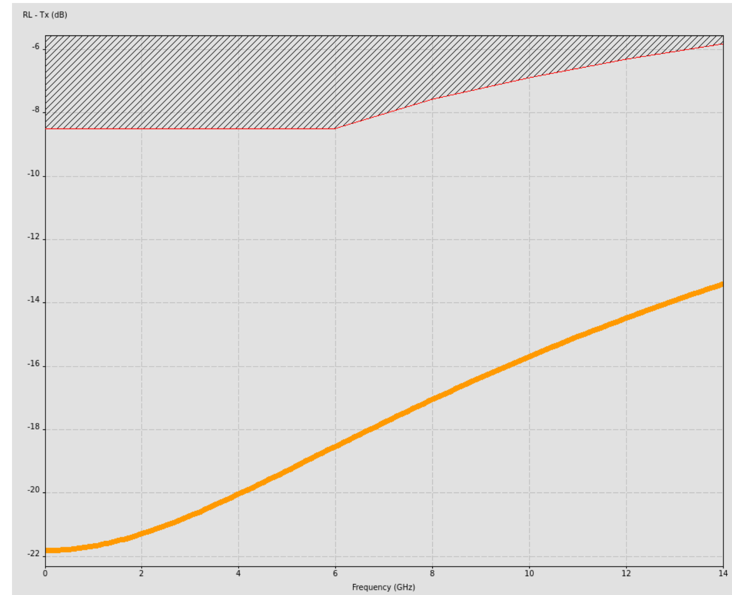
- **Tx levels mismatch ratio is calculated as a function of the mean PAM3 constellation levels**
- **TX_LEVELS_MISMATCH = min{(V2-V1)/Δ, (V1-V0)/Δ}**
- **TX_LEVELS_MISMATCH >= 0.975**

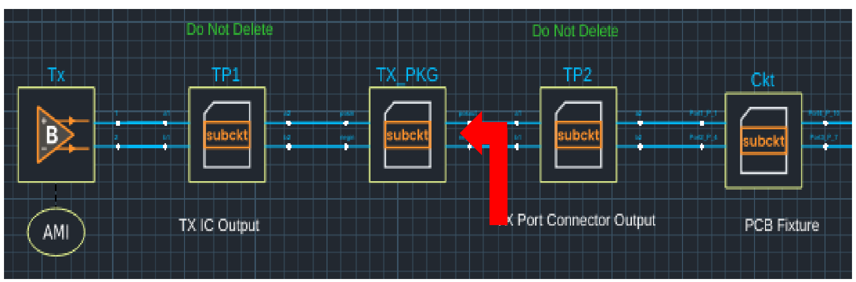
Figure 3-29. PAM3 Constellation Levels



Tx Differential Return Loss – 3.2.3.7

- **Tx Return Loss should only include Tx and PKG**
- **IBIS File usage**
  - Calculate output impedance and use C_Comp
  - Will use external model if pointed to in IBIS





$$\mathrm{SDD22}(f) = \begin{cases} -8.5 & 0.05 < f_{GHz} \leq 6 \\ -5.84 + 7.2 \cdot \log 10\left(\frac{f_{GHz}}{14}\right) & 6 < f_{GHz} \leq 14 \end{cases}$$

Tx Signal to Noise and Distortion (SNDR) – 3.2.3.4

- **Ratio between linear fit pulse peak and the root square sum of linear fit error and additive noise**
  - SNDR is the variation between the ideal signal and the measured signal
  - Same as IEEE Ethernet standards
- **TX_SNDR >= 32.5dB**

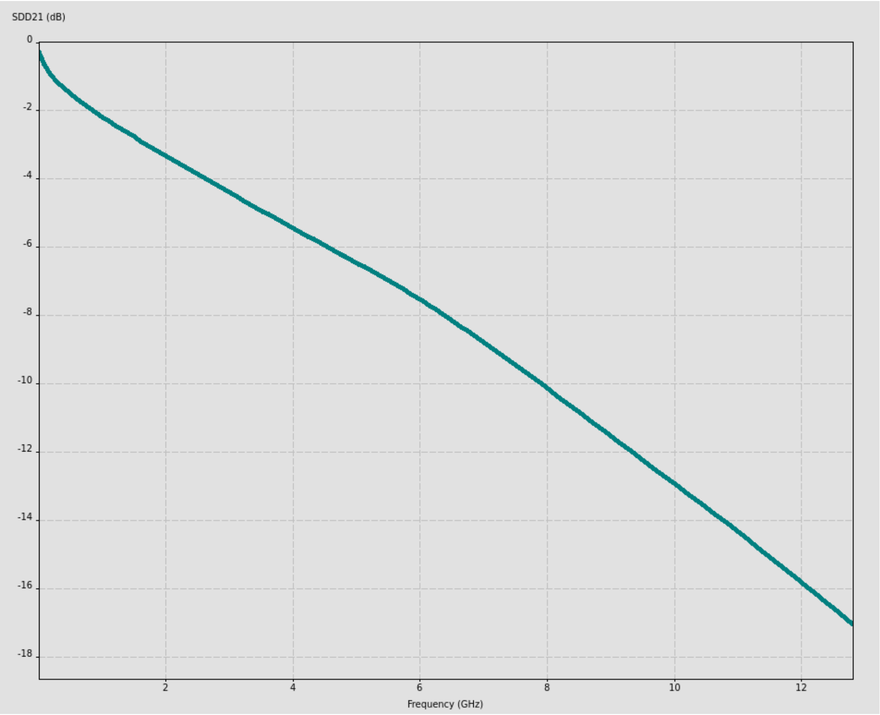
The TX_SNDR is defined as follows:

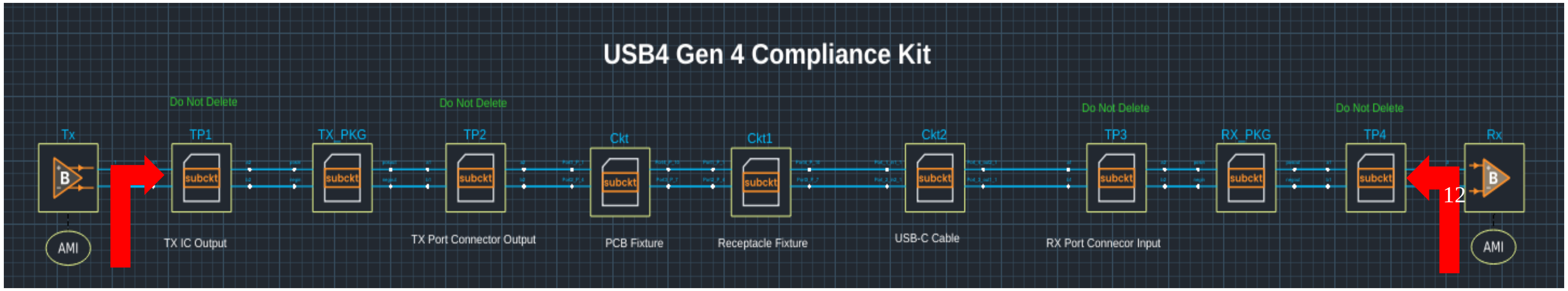
$$TX\_SNDR = 20 \cdot log_{10}\left(\frac{P_{max}}{\sqrt{\sigma_e{}^2 + \sigma_n{}^2}}\right)$$

where, P_{max} is the maximum value of the linear fit pulse response p(k).

End to End Channel Diff Insertion Loss – 3.2.4.2

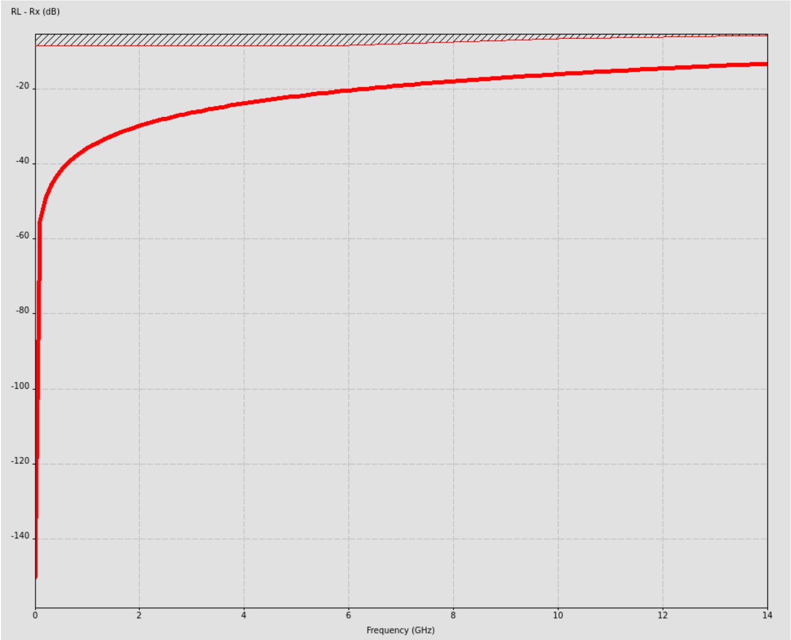
- **Single point test at 12.8GHz**
  - IL < -28.5 dB @ 12.8GHz
  - Die to Die

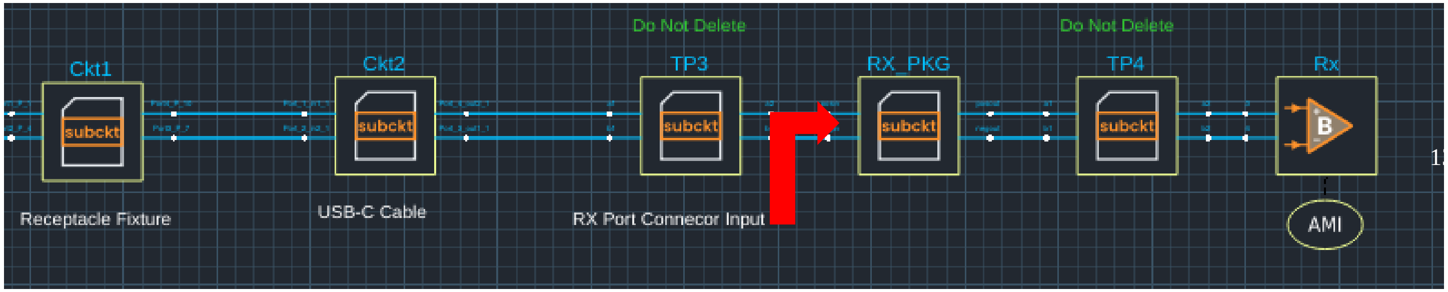




Rx Differential Return Loss – 3.2.4.1.2

- **Rx Return Loss should only include Rx and PKG**
- **IBIS File usage**
  - Calculate input impedance and use C_Comp
  - Will use external model if pointed to in IBIS



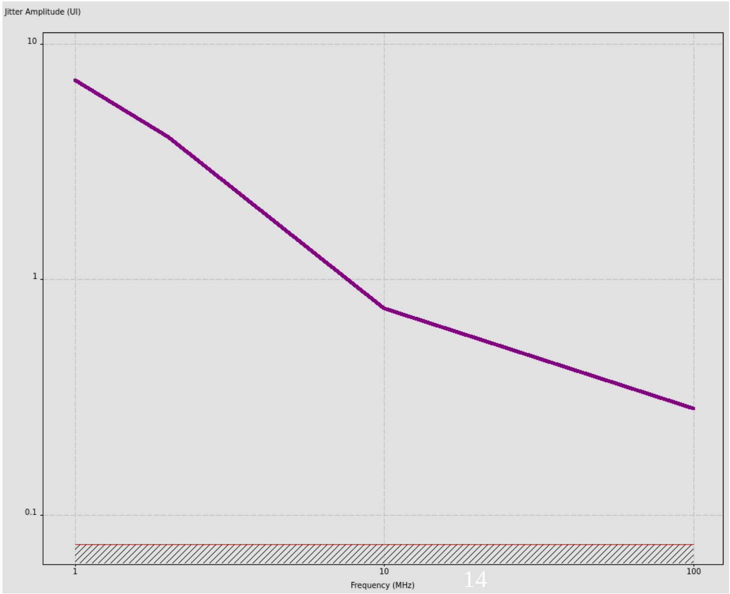


Receiver Tolerance Testing – 3.2.4.2

- **Receiver tested by injecting different sinusoidal jitter (SJ) one at a time.**
  - Jitter frequencies 1 MHz, 2 MHz, 10 MHz, 50 MHz, and 100 MHz
- **Tx parameters configured to Table 3-27**
- **Operate at BER of 1E-8 or lower**

Table 3-27. Stressed Signal for Gen 4 Receiver Compliance Testing

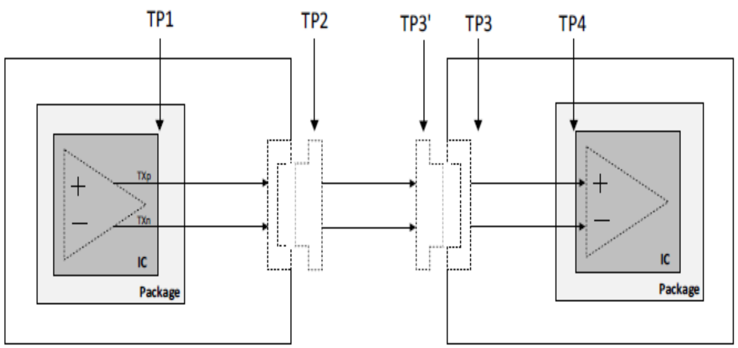
Test Case	Voltage Swing [mV pk-pk]	SNDR [dB]	Level Mismatch	ACCM Noise [mV Pk-Pk]	PJ [UI Pk-Pk]	RJ [UI RMS]
1	1000	32.5	0.975	100	0.085	0.0085
2a+2b	800	32.5	0.975	100	0.075	0.0085



USB4 Compliance Report

USB 4 - Gen 4 Compliance Report

Figure 3-27. Gen 4 Compliance Test Point Definitions



General Information

- **Project File:** usb4_compliance.topx
- **Circuit Simulator:** SPDSIM

Summary of Results

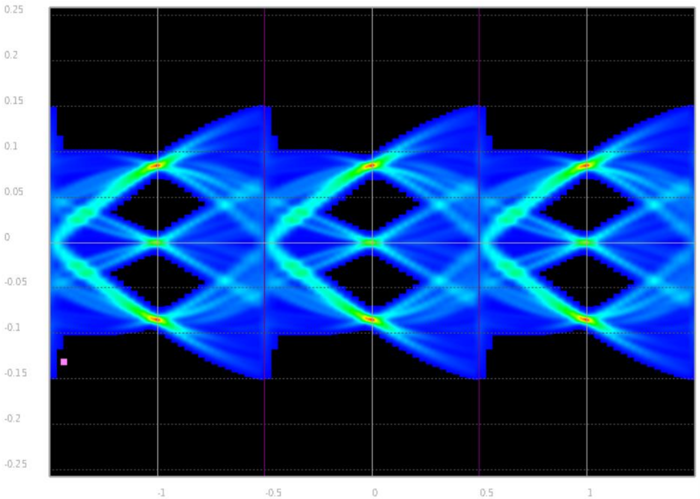
Transmitter Tests (Table 3-22)

Item	Value	Simulation Results	Pass/Fail
Tx Level	800 mV	800.009	Pass
Tx Differential Return Loss		RL - Tx	Pass
Tx Signal to Noise Distortion Ratio (SNDR) (Section 3.2.3.4)	32.5 dB	83.692	Pass

Receiver Tests

Item	Value	Simulation Results	Pass/Fail
End to End Channel Differential Insertion Loss @ 12.8 GHz		SDD21	Pass
Rx Differential Return Loss		RL - Rx	Pass
Receiver Tolerance Test (Section 3.2.4.2)		Jitter	Pass

USB4 Simulation Results



Eye Density

******* pam0 *******

Eye Contour Measurements:

Eye Height = 53 mV
Eye Height Measured at = 0.5 UI
Eye Jitter = 0.65 UI
Eye Jitter Measured at = -42 mV
Eye Norm Jitter and Noise (NJN) = 0.92
Channel Operating Margin (COM) = 8.70 dB

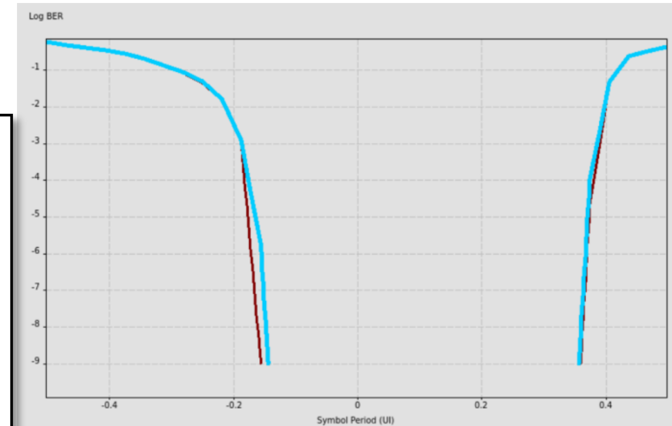
Eye Density Signal to Noise Ratio (SNR) = 152.12

BER Measurements:

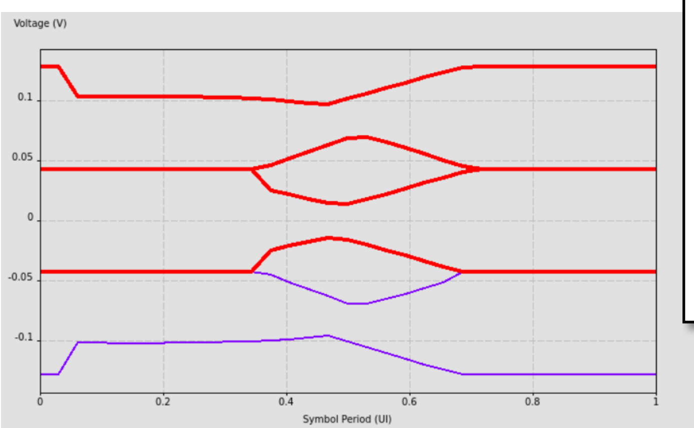
LBER(log BER)	Eye Width(UI)
-9	0.24
-8	0.26
-7	0.27
-6	0.30
-5	0.33
-4	0.37
-3	0.41

mV BER Measurements:

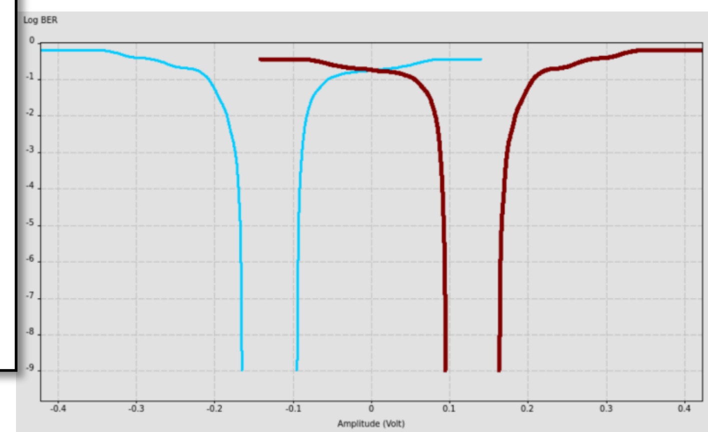
LBER(log BER)	Eye Height(mV)
-9	38
-8	41
-7	45
-6	50
-5	54
-4	60
-3	65



Bathtub Curve



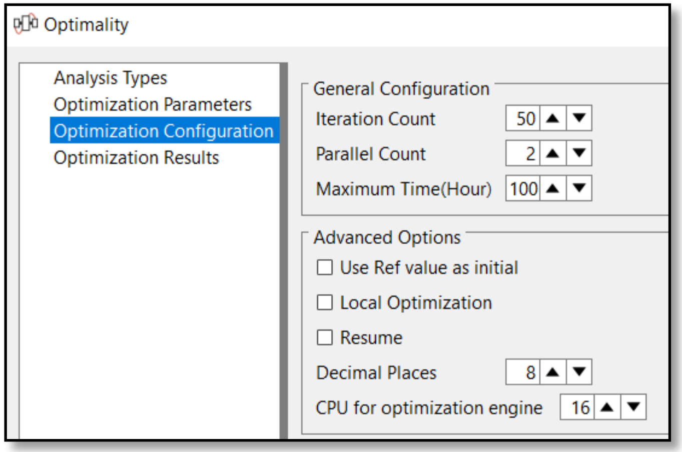
Eye Contours

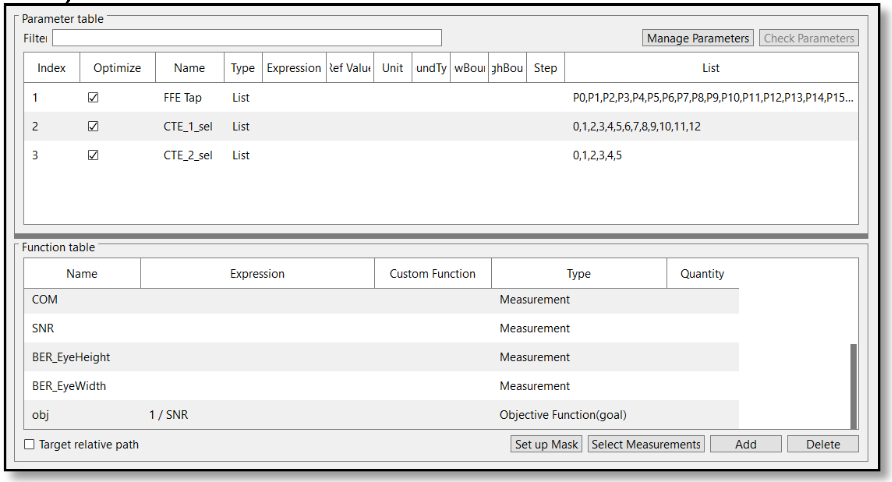


Noise Bathtub

TX/RX AMI Optimization

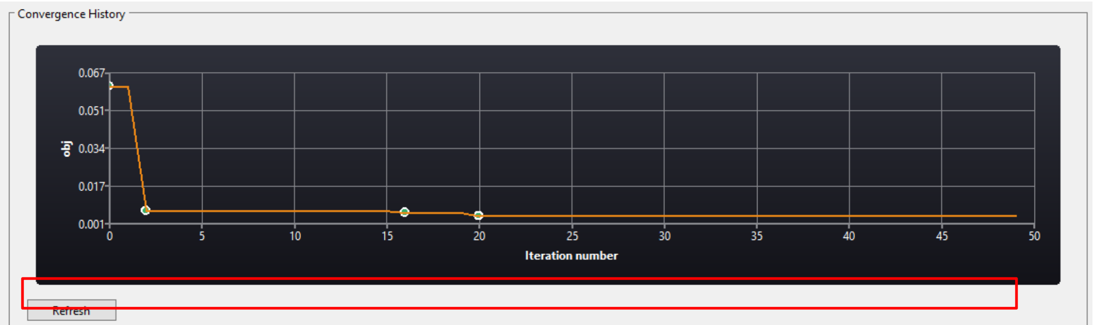
- **Setup parameters for optimization**
  - FFE Tap
  - CTE_1 select
  - CTE_2 select
- **Objective function**
  - Optimize to maximize SNR
  - Sweeps required: 3276 (42x6x13)





TX/RX AMI Optimization Results

- **Convergence history and Results Table. View waveforms directly from Results Table**
- **Sweeps required: 3276 (42x6x13)**
- **AI-empowered optimization with less than 100 iterations**

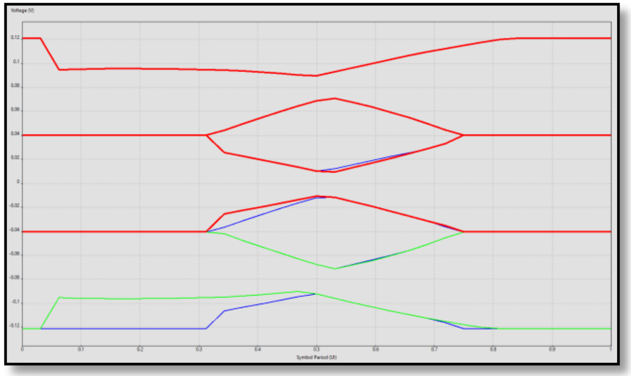


Result Table

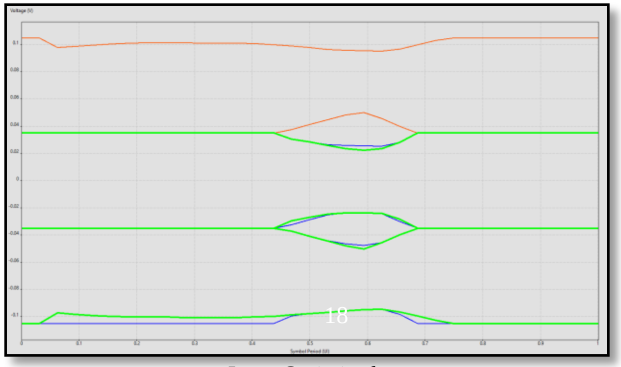
Index	obj	BER_EyeHeight	BER_EyeWidth	COM	CTE_1_sel	CTE_2_sel	EyeContourHeight	FFE Tap	SNR
20	0.00381098	44	0.33	10.13	6	0	55	P16	[illegible]
16	0.0052829	35	0.3	8.31	8	0	45	P16	189.29
48	0.00546568	35	0.29	8.54	8	3	45	P16	182.96
2	0.00608643	37	0.3	8.07	6	3	48	P16	164.3
18	0.00608828	43	0.3	8.97	6	0	53	P12	164.25
17	0.00642013	36	0.29	8.16	8	0	45	P12	155.76
13	0.00662559	49	0.31	8.19	0	0	62	P18	150.93
15	0.00809848	44	0.32	10.66	8	0	53	P9	123.48

Save | Generate HTML Report

RMB > Show Result

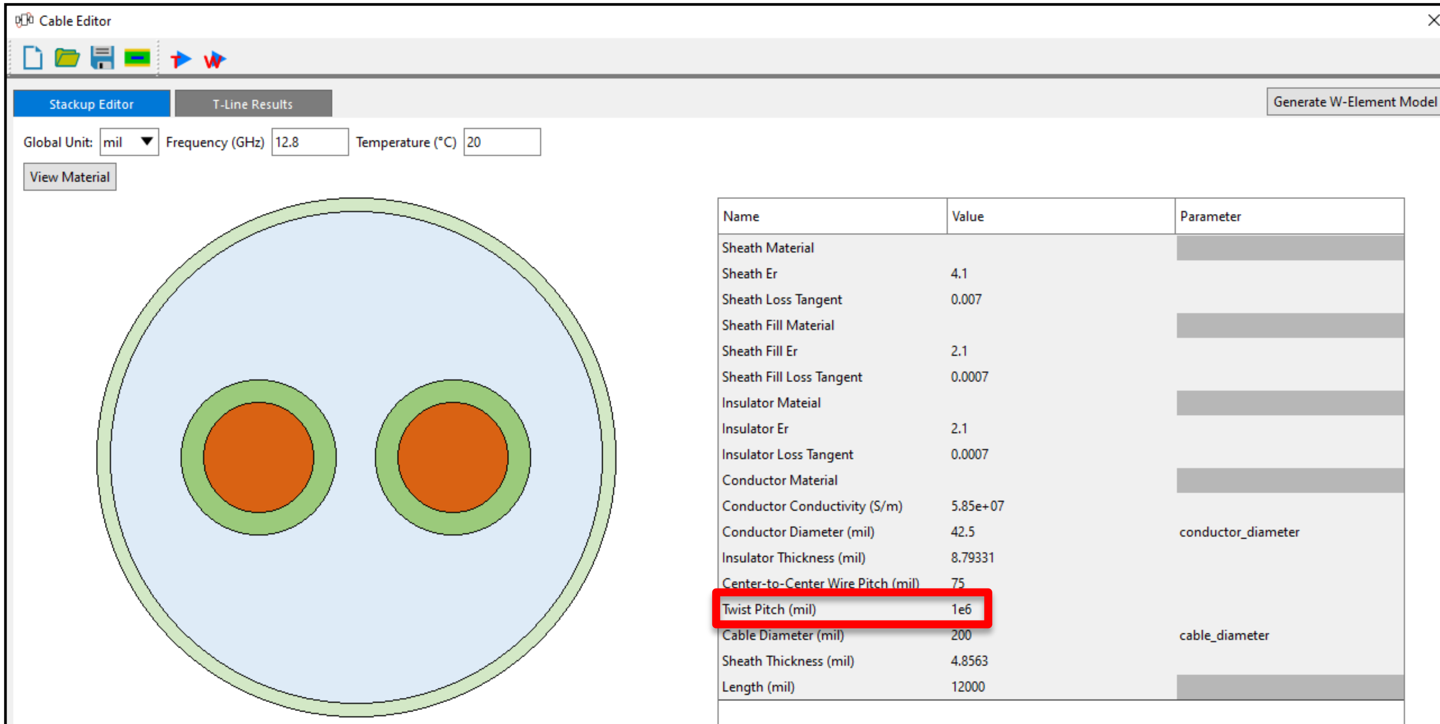


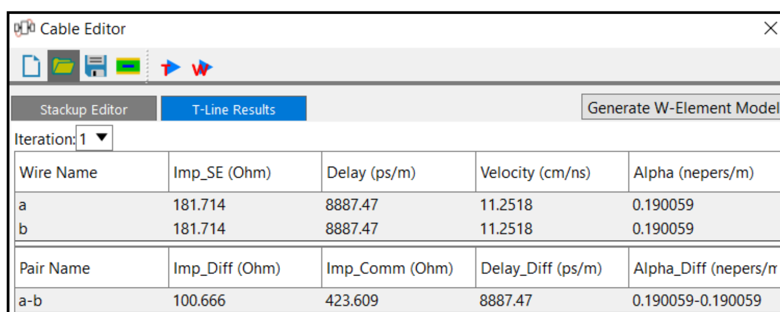
Most Optimized



Least Optimized

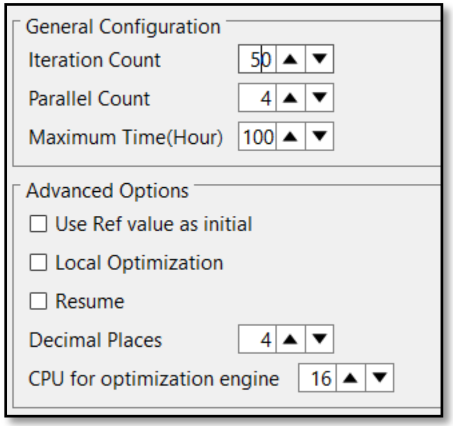
Cable Modeling Tool

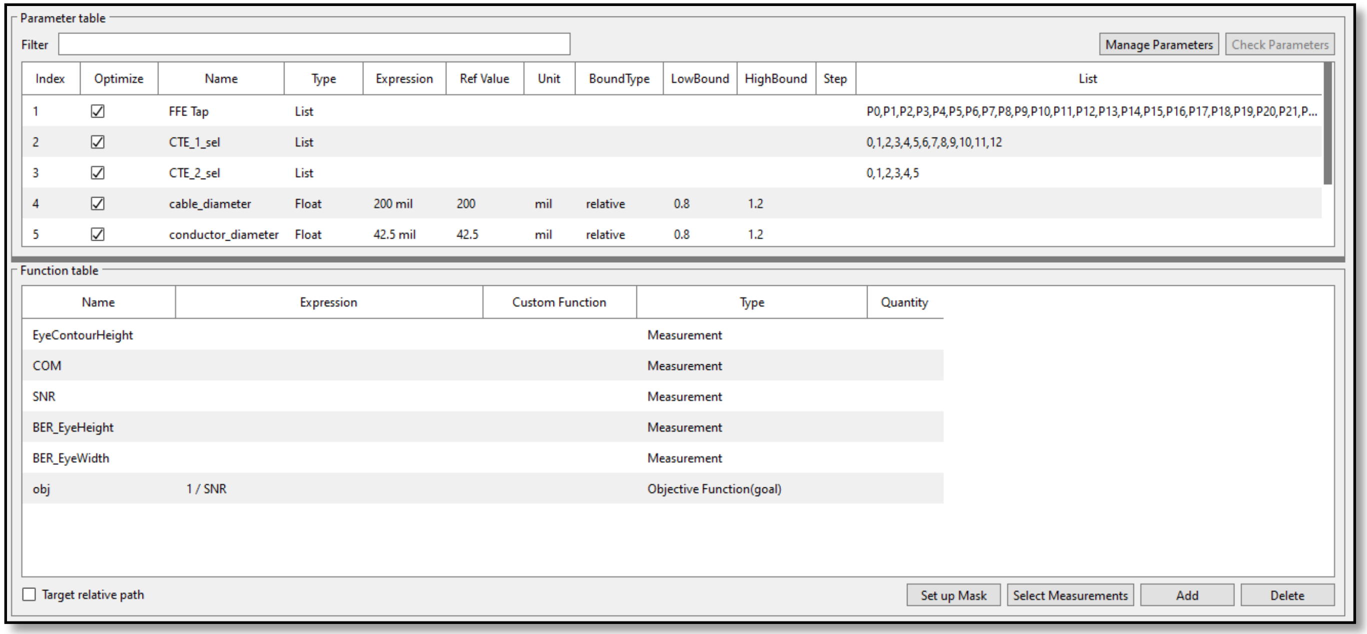




TX/RX AMI and Channel Co-Optimization

- **Optimize around Cable Diameter and Tx, Rx AMI parameters**
  - Simulate +/-20% manufacturing tolerances
    - Lowbound 0.8
    - Highbound 1.2
  - Ability to optimize any cable parameter that you wish
  - Discrete and continuous parameters
  - Sweep Iterations Required (1 mil steps):>4.7M





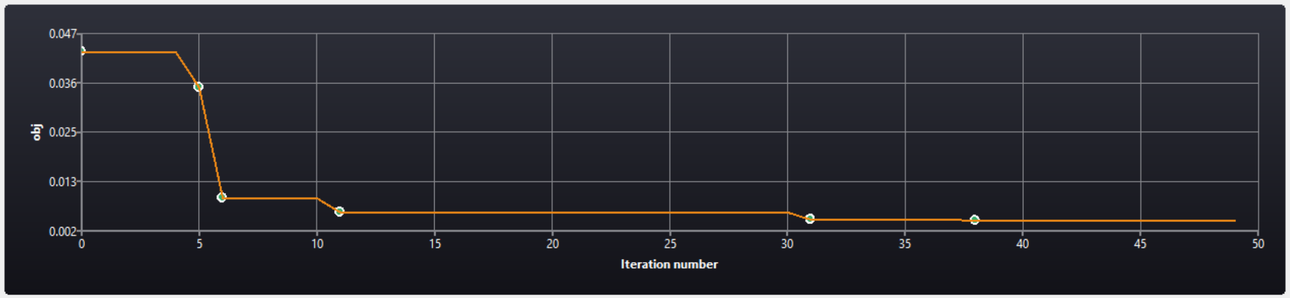
Index	Optimize	Name	Type	Expression	Ref Value	Unit	BoundType	LowBound	HighBound	Step	List
1	☑	FFE Tap	List								P0,P1,P2,P3,P4,P5,P6,P7,P8,P9,P10,P11,P12,P13,P14,P15,P16,P17,P18,P19,P20,P21,P...
2	☑	CTE_1_sel	List								0,1,2,3,4,5,6,7,8,9,10,11,12
3	☑	CTE_2_sel	List								0,1,2,3,4,5
4	☑	cable_diameter	Float	200 mil	200	mil	relative	0.8	1.2		
5	☑	conductor_diameter	Float	42.5 mil	42.5	mil	relative	0.8	1.2		

Name	Expression	Custom Function	Type	Quantity
EyeContourHeight			Measurement	
COM			Measurement	
SNR			Measurement	
BER_EyeHeight			Measurement	
BER_EyeWidth			Measurement	
obj	1 / SNR		Objective Function(goal)	

TX/RX AMI and Channel Co-Optimization Results

- **Convergence history and Results Table. View waveforms directly from Results Table.**
  - Optimize taps, and +/-20% at the same time (>4.7M sweeps)
  - AI-empowered optimization with less than 50 iterations

Convergence History

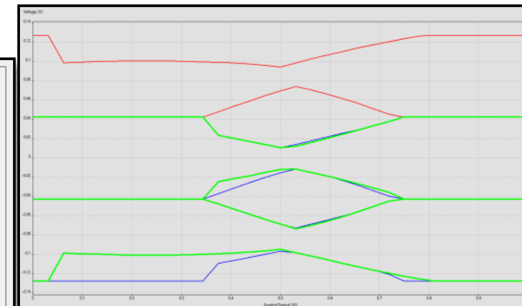


Refresh

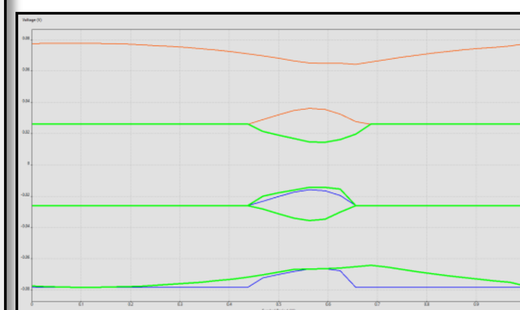
Result Table

Index	obj	BER_EyeHeight	BER_EyeWidth	COM	CTE_1_sel	CTE_2_sel	yeContourHeight	FFE Tap	SNR	cable_diameter	conductor_diameter
38	0.00453823	42	0.31	8.55	4	1	53	P17	220.35	198.373	43.5869
40	0.0046436	40	0.32	8.16	4	1	51	P17	215.35	198.412	49.6672
39	0.00467596	40	0.32	8.03	4	1	51	P17	213.86	198.417	50.393
49	0.00474563	41	0.32	8.53	4	1	53	P17	210.72	198.812	48.4337
42	0.00475398	42	0.32	8.82	4	1	53	P17	210.35	198.818	37.6688
31	0.00479547	43	0.33	8.87	4	1	54	P17	208.53	198.832	51
33	0.00498281	43	0.33	8.99	4	1	54	P17	200.69	198.854	51
34	0.00498281	43	0.33	8.99	4	1	54	P17	200.69	198.854	51
35	0.00533646	39	0.32	9.83	6	1	51	P17	187.39	198.854	51

Save   Generate HTML Report



Most Optimized – Diff Impedance of cable = 98Ω



Least Optimized - Diff Impedance of cable = 108.9 Ω

Conclusion

- **USB4 Challenges simulating next-gen interfaces**
  - Unique measurements
  - Higher speeds and PAM-3 encoding
- **USB4 Compliance Kit**
  - Tx & Rx Checks
  - Interconnect, Channels Checks
  - IBIS, AMI Models
- **USB4 optimization functions**
  - TX/RX AMI parameter optimization
  - Channel design optimization & manufacturing tolerance simulations
  - TX/RX and Channel co-optimization

THANK YOU!
&
QUESTIONS?

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