Characterization, Optimization and Analysis of 200 Gbps Communication Channels

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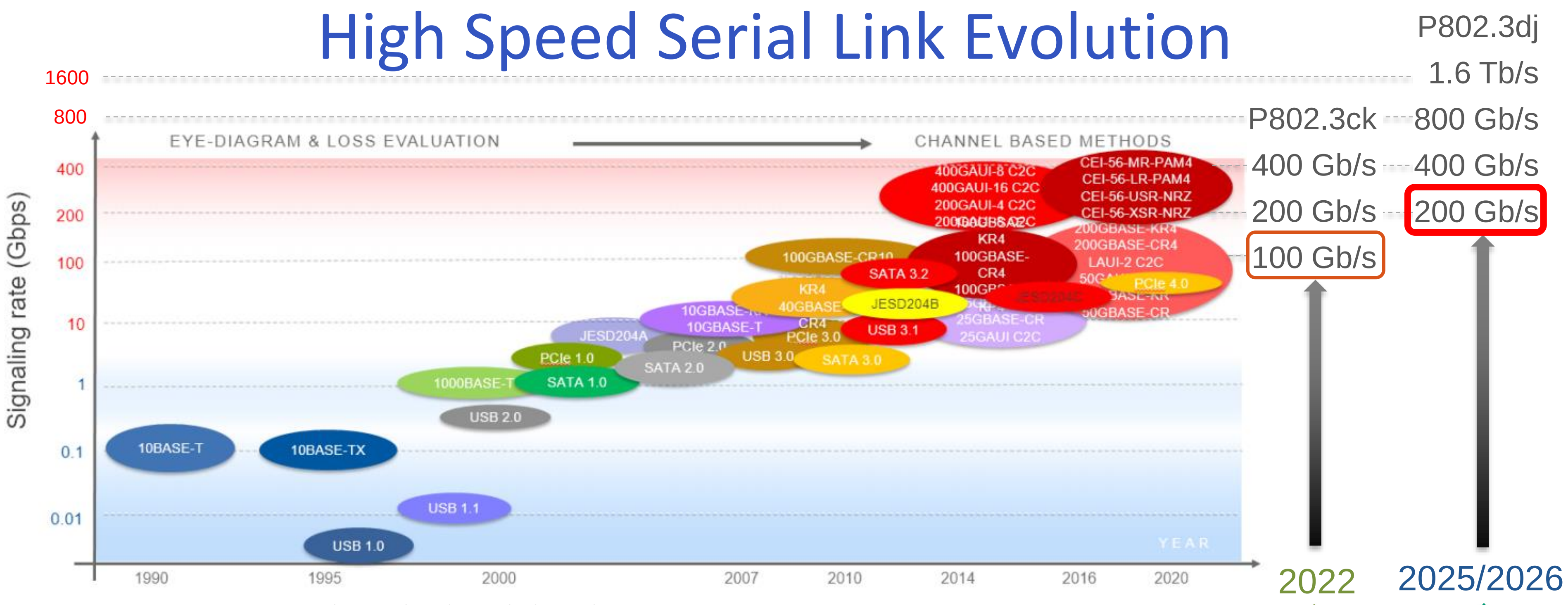
High Speed Serial Link Evolution

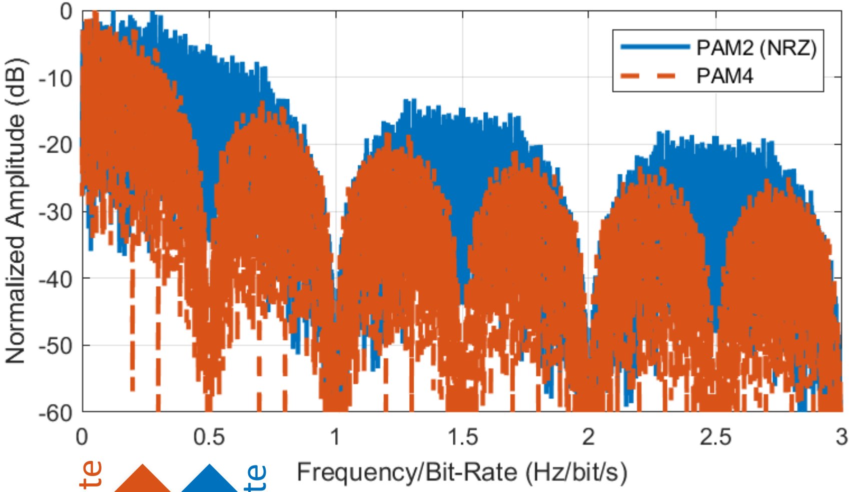


Source: *SerDes Design Part 2: Serial Protocols and SI Methods Trends*, MENTOR

- **IEEE 802.3ck (106Gbps):** Electrical C2M & C2C & CR1 & KR1 400GbE
- **OIF CEI-112G-VSR-PAM4 (112Gbps):** Very Short Reach Interface

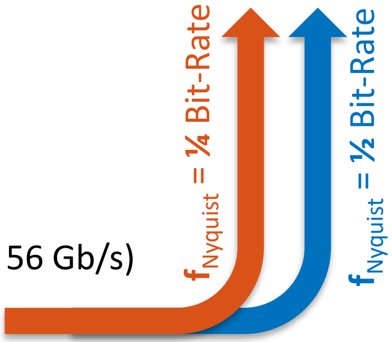
- **IEEE 802.3df* (212Gbps):** New PAR: Electrical 800 Gb/s and 1.6 Tb/s over copper
- **OIF CEI-224G (224Gbps):** New OIF Project at White-Paper start

Introduction to PAM4



PAM4 advantages:

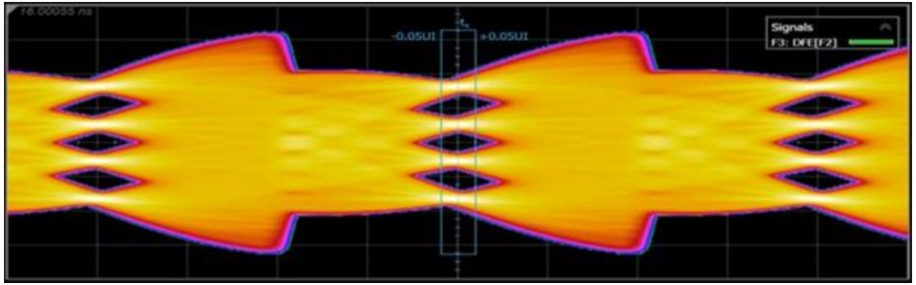
- Double bit rate:
  - Bit-rate$_{NRZ}$ = symbol rate (Gb/s=Gbaud)
  - Bit-rate$_{PAM4}$ = 2×symbol rate (i.e. 28 Gbaud = 56 Gb/s)
- or, half Nyquist (fundam.) frequency

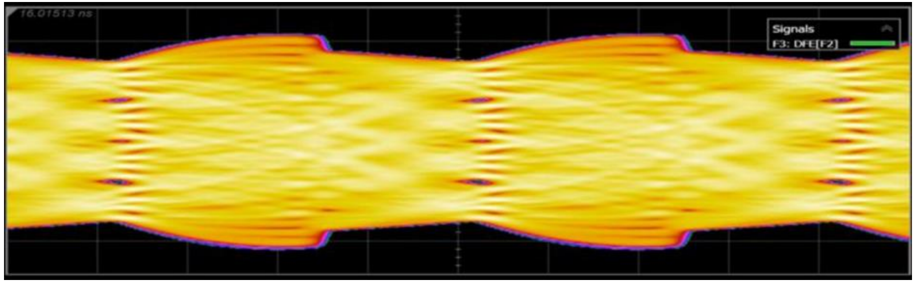


	PAM 4	NRZ
Bits for UI	2	1
Levels	4	2
Rising/Falling edges	6/6	1/1
Transitions	12	2
Eye per UI	3	1

Data Rate vs. Eye Diagram

Increasing data rate (> 200 Gbps): larger bandwidth, shorter t_r/t_f (**≈3-4 ps**), tight UI (≈ **9.4 ps**)





Closed eye

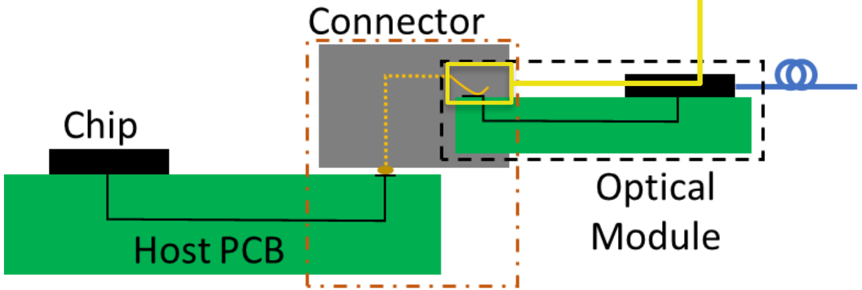
Degradation of performances:
stronger impact of jitter, noise, losses, crosstalk, ISI

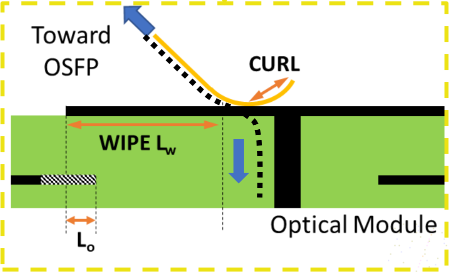
Possible solutions involving:
More complex equalization, better manufacturing (materials, assembly, tolerances)

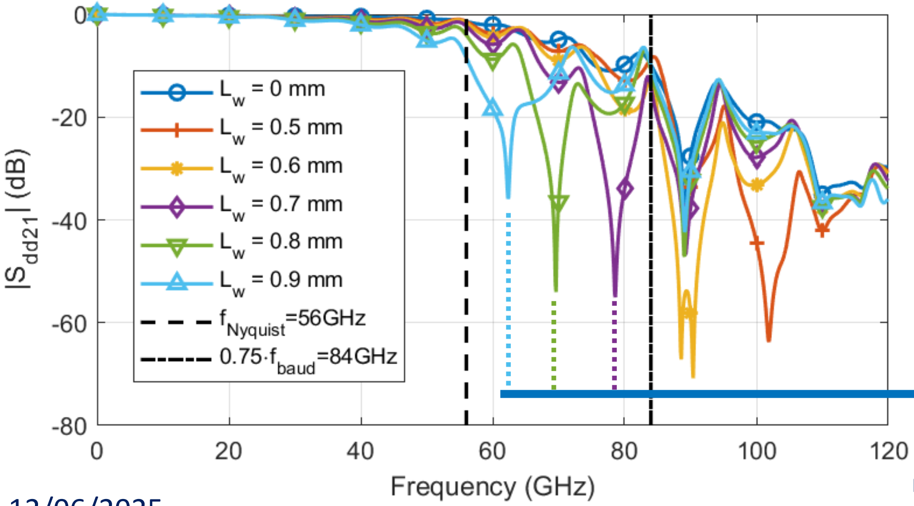
Outline

- Physical Design and Challenges
- Channel Equalization
- The Channel Operating Margin (COM) Method
- Verification at 212 Gbps
- Future Trends and Conclusions

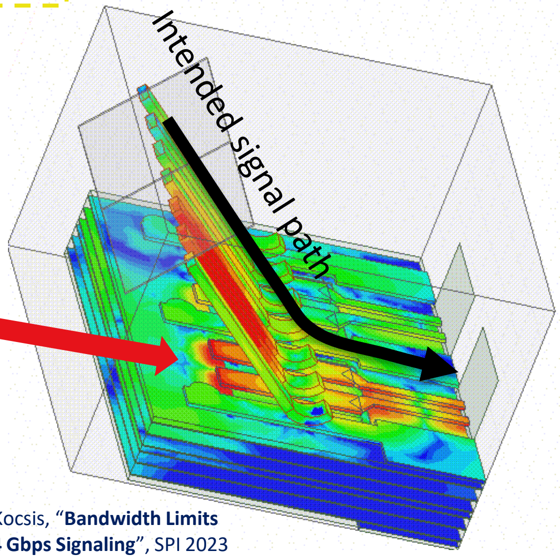
Mated Connector (OSFP, QSFP-DD)







Signal energy lost at the stub resonance

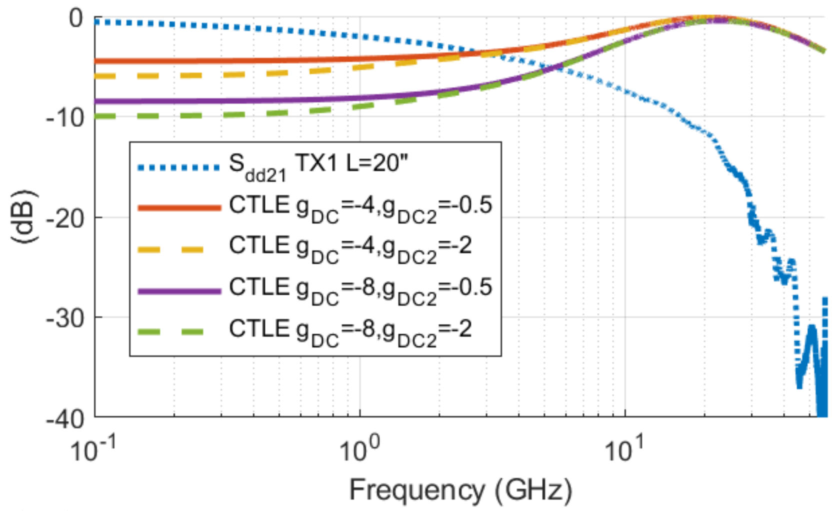


F. de Paulis, R. Rabinovich, M. Resso, S. Kocsis, "**Bandwidth Limits of Connector Wipe Stub for Reliable 224 Gbps Signaling**", SPI 2023

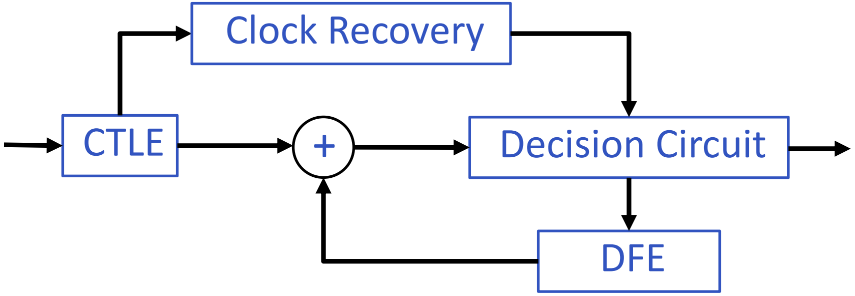
Equalization (at RX)

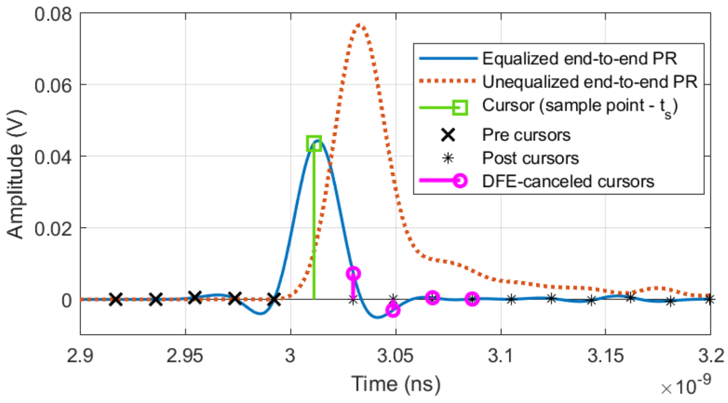
Continuous Time Linear Equalizer (CTLE)

$$H_{CTLE}(f) = \frac{\left(10^{\frac{g_{DC}}{20}} + j\frac{f}{f_z}\right)\left(10^{\frac{g_{DC2}}{20}} + j\frac{f}{f_{LF}}\right)}{\left(1 + j\frac{f}{f_{p1}}\right)\left(1 + j\frac{f}{f_{p2}}\right)\left(1 + j\frac{f}{f_{LF}}\right)}$$



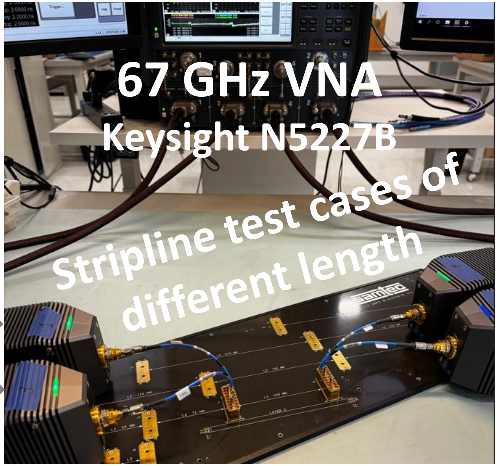
Decision Feedback Equalizer (DFE)

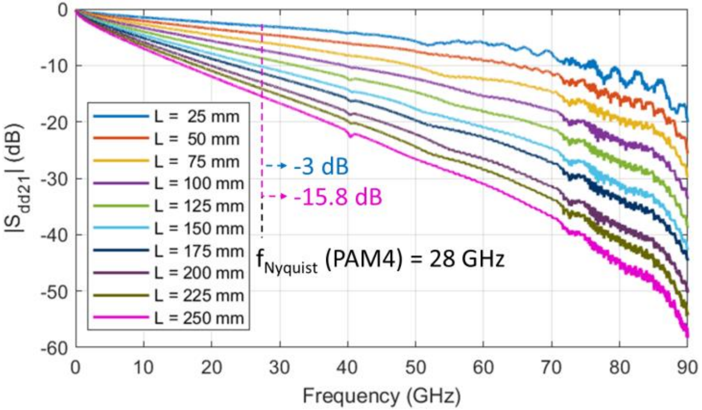




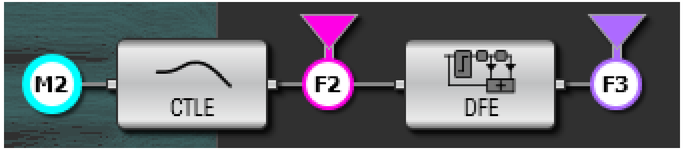
Example (at 112 Gbps PAM4)

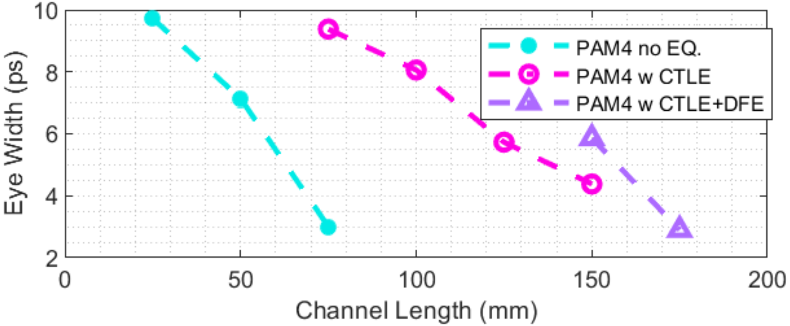
110 GHz Remote Heads
Keysight N5293AX03

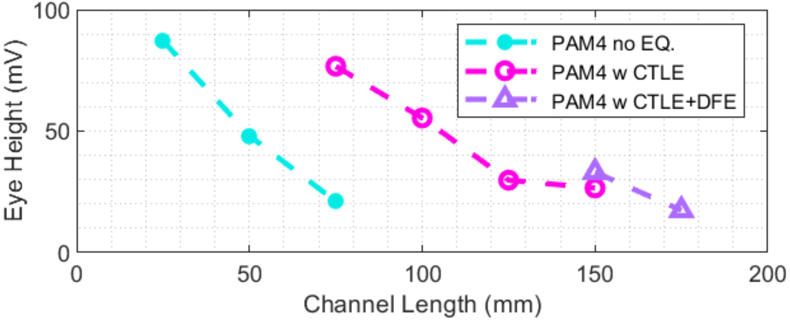




Waveform
PRBS at RX

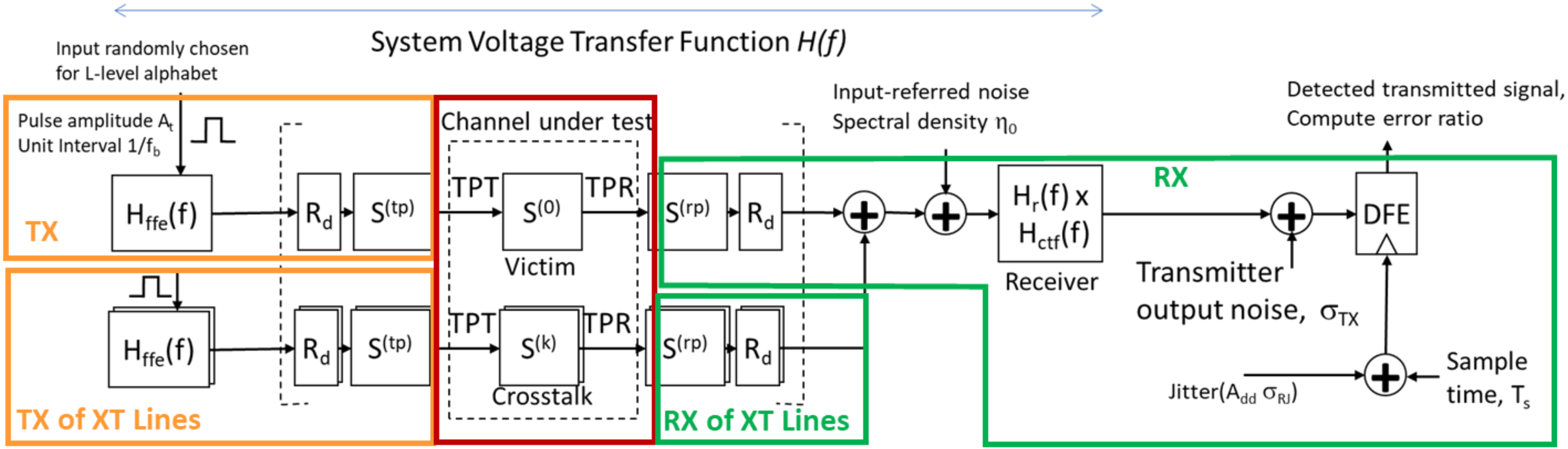






F. de Paulis, R. Mellitz, L. Boluna, M. Resso, R. Rabinovich, "**Design and Verification of Wired Channels Beyond 100 Gbps**", IEEE Trans-SIPI 2025

Channel Design and Optimization: COM

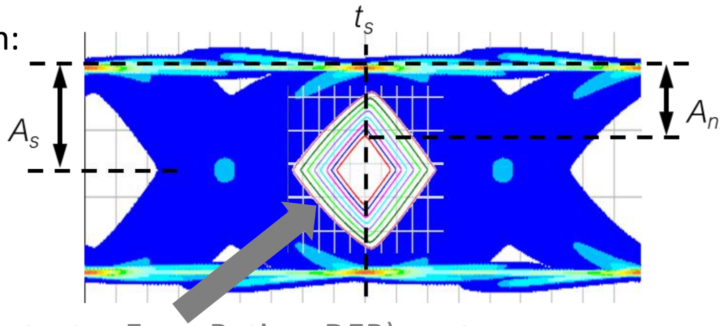


The COM metric comes out from the **Channel Operating Margin** algorithm:

$$COM = 20 \log \frac{A_s}{A_n}$$

A_s: Amplitude of signal obtained by the maximization of FOM

A_n: Combined amplitude of noise and interference (crosstalk) at a given DER value

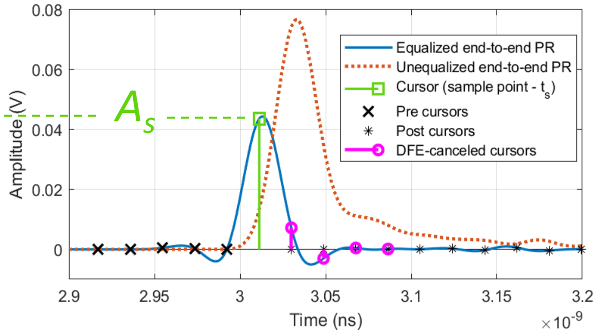


BER (Detector Error Ratio – DER) contours

The COM Algorithm

$\boldsymbol{A_s}$ obtained by maximization of **FOM** through a full-search of equalization parameters (FFE, CTLE, DFE):

$$\boldsymbol{FOM} = \mathbf{20}\log\frac{\left(h^{(0)}(t_s)\right)^2}{\sigma_{TX}^2+\sigma_{ISI}^2+\sigma_J^2+\sigma_{XT}^2+\sigma_N^2}$$



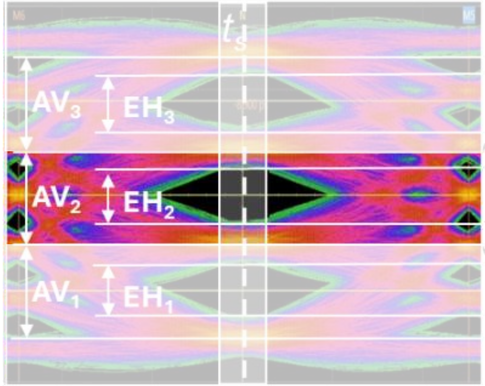
--- Computed

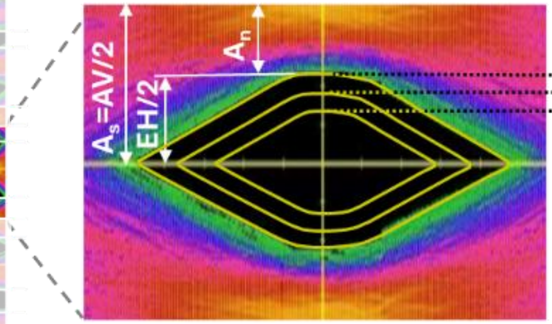
--- Given (Input)

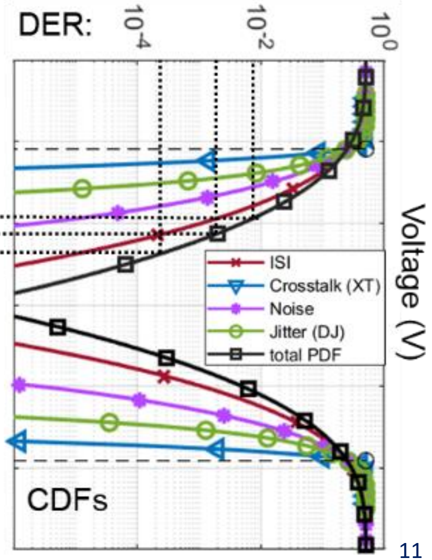
Combination, by convolution, of PDFs associated to all noise contributions:

An alternative metric from 802.3ck:
Vertical **E**ye **C**losure

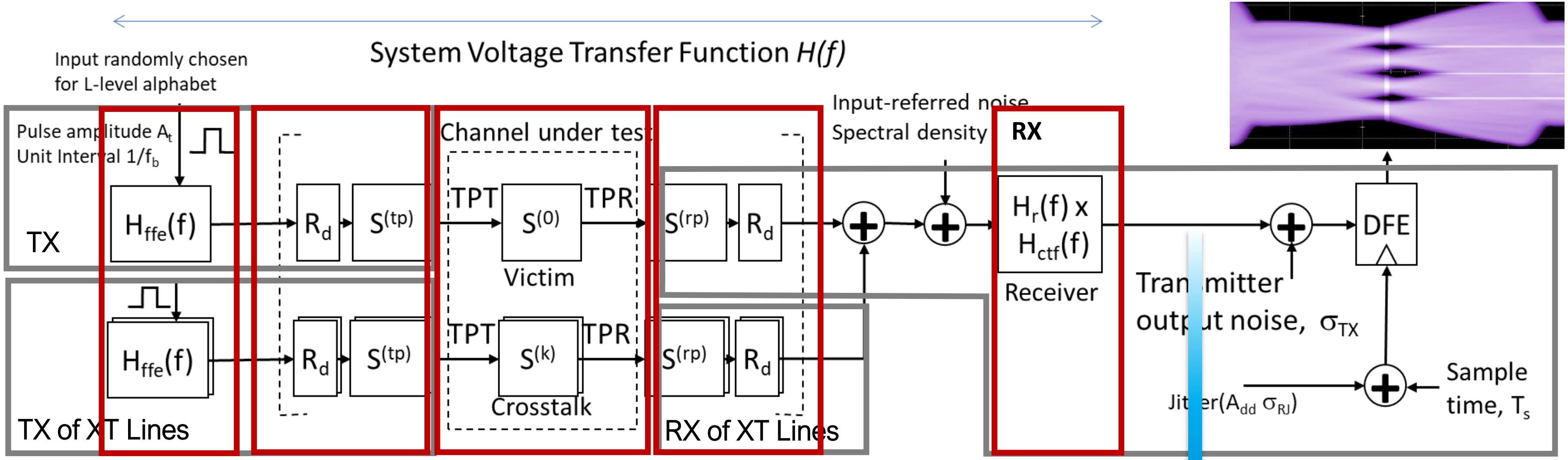
$$\boldsymbol{VEC} = \boldsymbol{min}\left(\mathbf{20}\log\frac{AV_i}{EH_i}\right)$$







The COM Algorithm in Frequency Domain



Modelled TX FFE

Modelled TX Package and Terminations

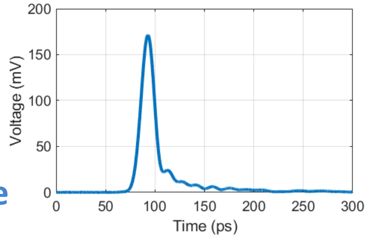
VNA **Measured** Channels (S-parameters)

Modelled RX Package and Terminations

Modelled RX $H_r(f)$ and CTLE

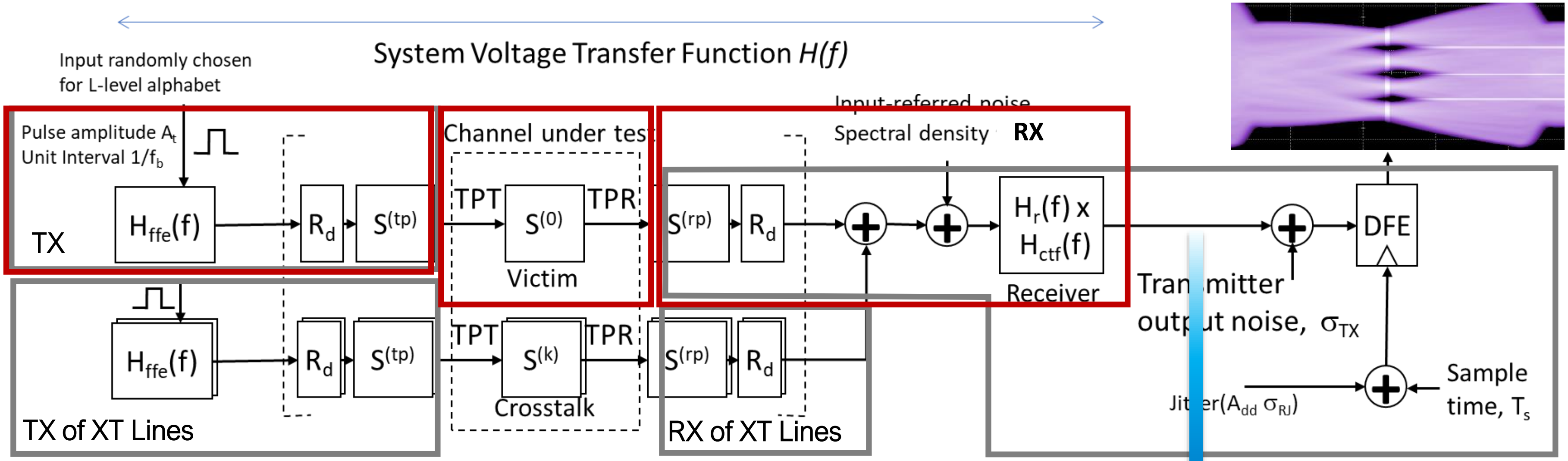
Frequency Domain

Calculation of Pulse Response



TX parameters (**A_{TX}, t_r, jitter σ_{RJ} and A_{DD}, SNDR, R_{LM}**) needs to be measured in advance

PR-Based COM Algorithm (**T**ime **D**omain)

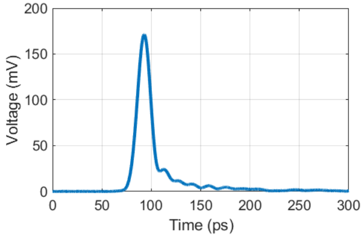


Hardware TX:
Instrumentation or
Silicon source

Channel

Instrumentation RX:
$H_r(f)$, w/wo CTLE

Extraction of Pulse Response from Measured PRBS13Q Waveform

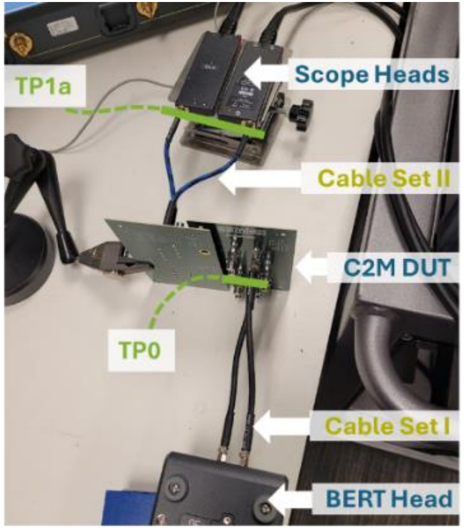


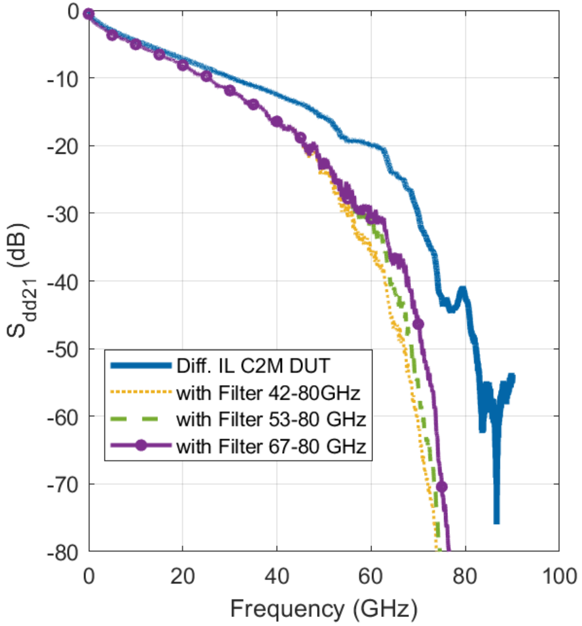
Several assumptions for FD-COM set uncertainties that are not acceptable for time domain conversion while moving toward the edge of applicability of the method for > 200 Gbps

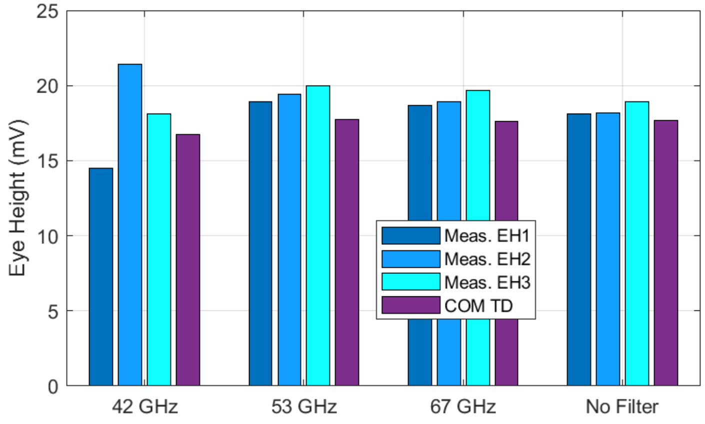
F. de Paulis, M. Resso, L. Boluna, J. Calvin, R. Mellitz, R. Rabinovich, "**A Novel Approach to 224 Gb/s Reference Receiver Design Using Raised Cosine Response for Noise Mitigation**", DesignCon 2023.

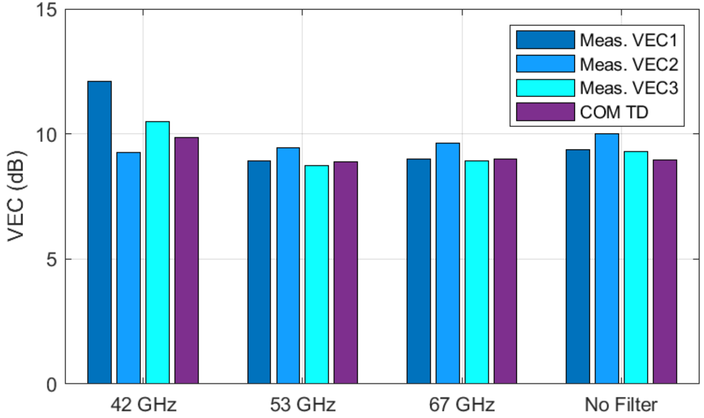
Verification of COM at 212.5 Gbps

DUT (PCB + Conn + PCB) representative of expected C2M interface losses @ $f_{Nyquist}$







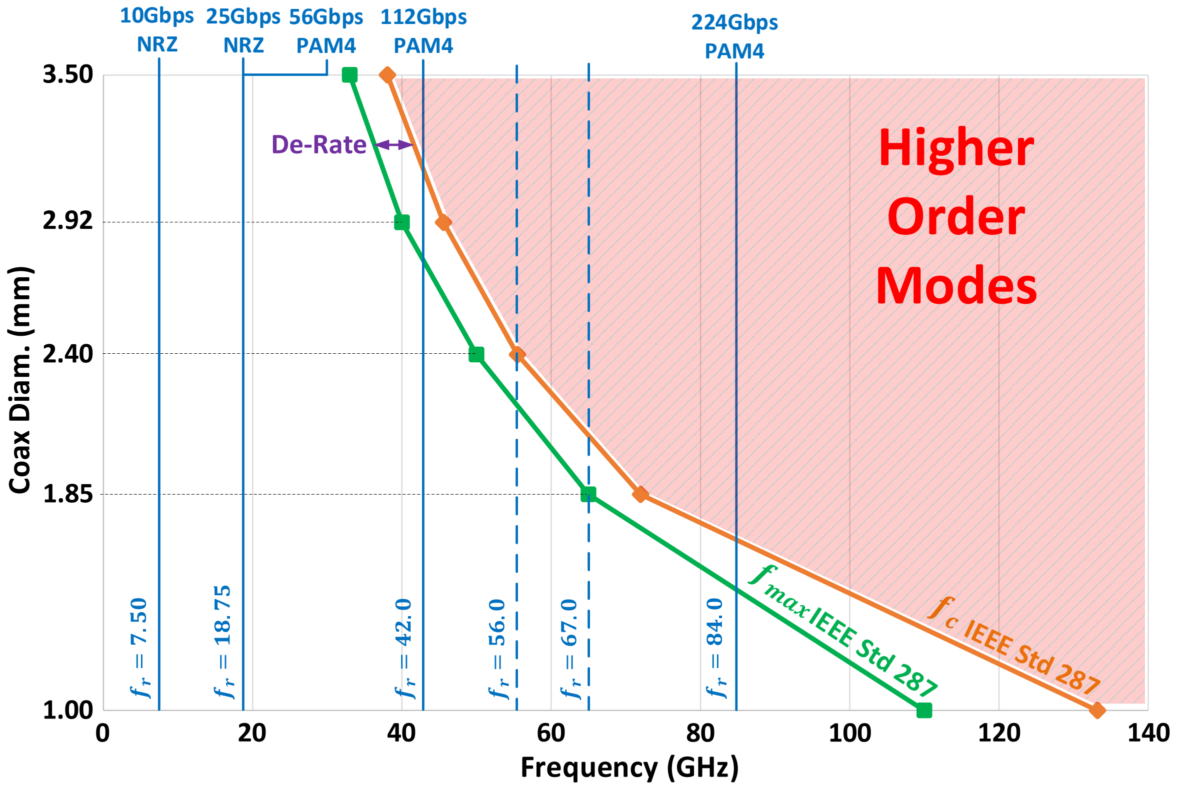


Experimental setup fully equipped with 1.00 mm interfaces

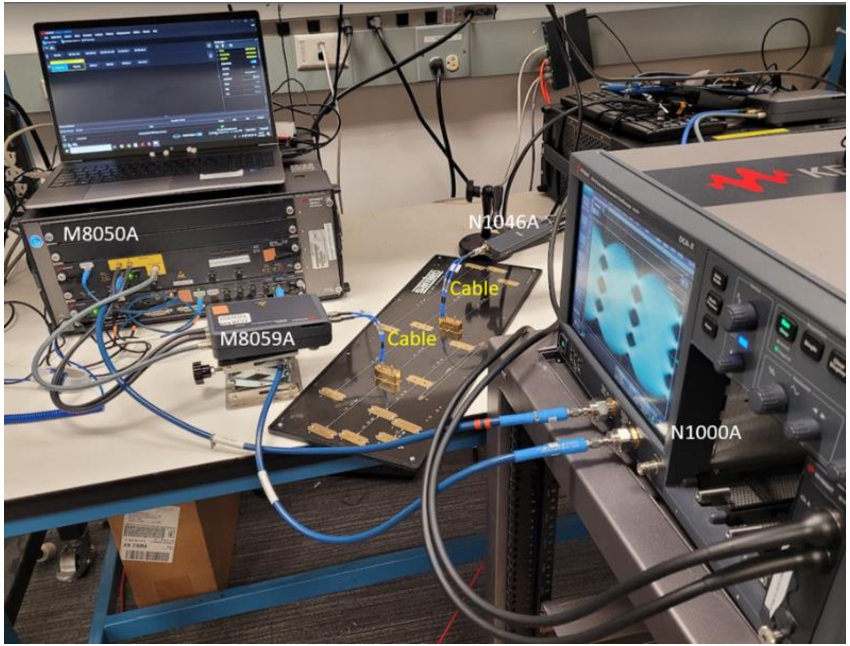
F. de Paulis, M. Resso, L. Boluna, J. Calvin, R. Mellitz, R. Rabinovich, "**A Novel Approach to 224 Gb/s Reference Receiver Design Using Raised Cosine Response for Noise Mitigation**", DesignCon 2023.

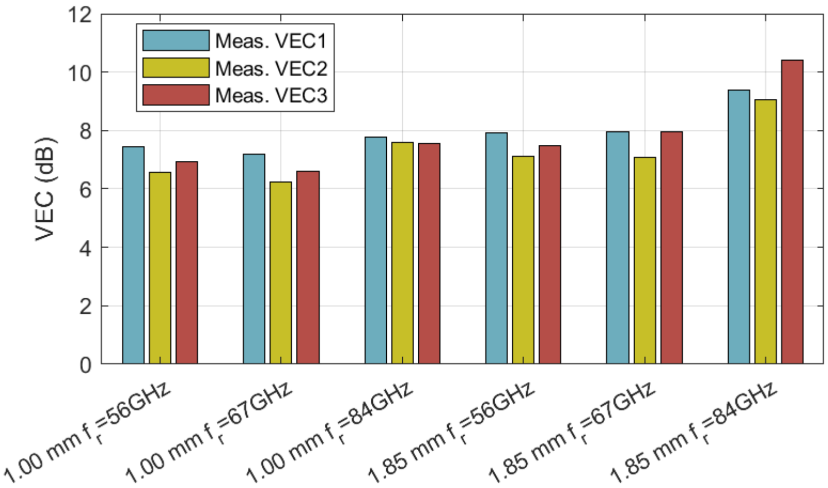
Testability

- IEEE Std 287 modal cutoff frequencies (f_c) from mechanical interface specification
- De-rated (f_{max}) for margin and interoperability per coax connector diameter
- Butterworth filter cutoff (f_r) traditionally 1.5x fundamental frequency for signaling rates 112 Gbps



Uncertainties by 1.00 mm vs 1.85 mm Setups





- A 4th order Butterworth filter is applied f_r (@ -3dB) = 56, 67, 84 GHz
- Both 1.0 mm and 1.85 mm cases show little VEC difference for f_r = 56, 67 GHz
- Worst VEC for the 1.85 mm setup

B. Gore, R. Mellitz, A. Josephson, F. de Paulis, L. Boluna, J. Calvin, Rabinovich, M. Resso, "**Are 1.0 mm Precision RF Connectors Really Required for 224 Gbps-PAM4 Verification?**", DesignCon 2024.

Conclusions

- The feasibility and design process of communication rates above 200 Gbps for short channels of C2M type are demonstrated
- Technological limits set by the 100 Gbps previous data rate generation are successfully overcome by investigating new solutions for channel design, optimization, and testing for 200 Gbps signaling
- Such solutions that may be taken into account toward the definition of the next Ethernet and OIF Standards foreseen for late 2025 (or in 2026)
- The 400 Gbps are under the radar screen of major technology players targeting the best trade-off among modulation scheme (i.e. PAM6), channel BW (to be kept < 100 GHz)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Thank you