Time-domain performance analysis for recently contributed channels using PAM4 signaling

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Outline

- Follow-up on ran_01_0511
  - System performance depends heavily on channel, but also on TX/RX and the interactions between them
  - Equalization is assumed – its effects (such as decreased signal level) should be taken into account
  - Jitter and imperfect terminations (e.g. pad capacitance) were shown to have a large effect on SNR
- In this presentation:
  - Newly contributed channels will be analyzed with "reference" receiver and transmitter models
  - Increased attention to sensitivity to jitter and termination effects
  - New performance measure – Normalized Eye Vertical Opening at 10^{-12}
    - Equivalent to voltage margin divided by signal level spacing – range is 0 to 1
    - Represents margin for non-idealities, especially in the receiver

Assumptions

- Adaptive equalization
  - Analog DFE at the receiver
  - 3-tap FFE at the transmitter
    - FFE tap values set to maximize Signal-to-ISI (not using all noise sources) – not strictly MMSE but close and realizable
- Crosstalk channels have the same TX amplitude, equalization, termination and frequency (clock-synchronous) as the thru channel
  - Worst phase of each crosstalk source is used
- TX/RX terminations modeled as $(50\ \Omega + \Delta R)\ ||\ C_{pad}$ single-ended
  - Sensitivity to ΔR and C_{pad} will be analyzed

Assumptions (cont.)

- Jitter modeled as Dual-Dirac, DJ and RJ
  - Represents untracked jitter (outside of the CDR bandwidth) from both TX and RX clocks
  - No HF jitter that would create distortion (e.g. DCD)
  - Jitter is translated into effective voltage noise at the sampling instant
- Noise sources are uncorrelated to each other
  - Can be summed by PDF convolution
  - Noise PDFs are used throughout the analysis – without assuming Gaussian distribution anywhere (except for RJ)
  - This analysis is much more accurate than power-summing and comparing SNRs
- Target BER is 10^{-12} before FEC
  - FEC can be used to get a lower BER
  - Or to make channels work at 10^{-12} when the unprotected BER is higher
  - Or enable a simpler PHY implementation
  - To facilitate FEC, Baud rate is taken as 13e9

TX and RX models

- PAM4, 13 GBaud
- Transmitter BW: 0.8 * 13e9 = 10.4 GHz (2^{nd} order Butterworth)
- Receiver BW: 0.6 * 13e9 = 7.8 GHz (4^{th} order Butterworth)
- DFE length: 16
- Impedance matching: ΔR span (0, ±5, ±10 Ω), C_{pad} span (0, 100, 200, 400 fF) (single ended, both TX and RX)
- TX Jitter: RJ RMS from 0 to 0.7 ps, DJ PTP from 0 to 7 ps
  - TX jitter is specified; RX jitter assumed to be the same
  - Effective DJ is 2x the TX spec, effective RJ is 1.4x the TX spec

New performance metric: Normalized Eye Vertical Opening

- Motivation:
  - With non-Gaussian noise distribution, SNR is not a useful metric (classical analysis yields over-pessimistic results)
  - Eye width is an ill-defined concept for a DFE receiver; but eye height is still useful
  - Eye height (EH) in voltage units is misleading, since the receiver typically amplifies the signal (and the noise); the receiver gain (or “target” signal level) is a free parameter, making it hard to compare EH results
- Dividing the EH (at the desired probability) by the ideal height (signal separation) yields the Normalized Eye Vertical Opening (NEVO), which ranges from 0 to 1
  - An intuitive figure of merit, enabling easy comparison of results
  - Useful for determining allowed implementation penalties: e.g. if a receiver has a signal separation of 400 mV and the NEVO is 25%, then the total noise margin is 400*25%=100 mV

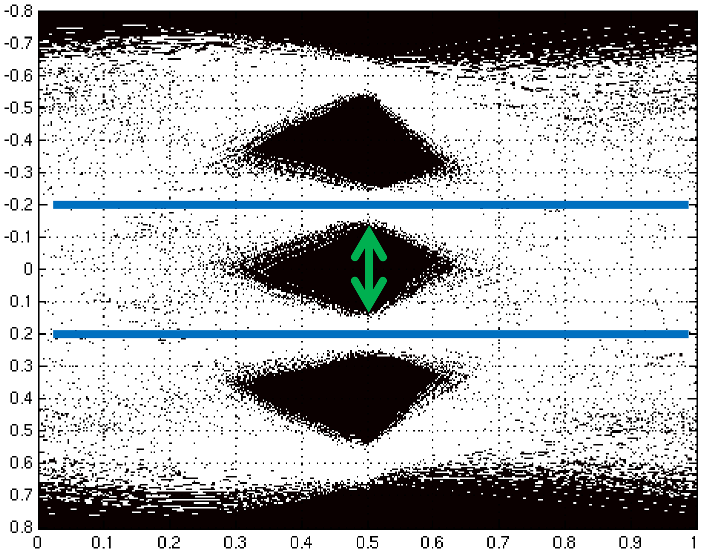
Illustration of NEVO

This is a simulated eye pattern for PAM-4. Sampling instant is at x=0.5 (EH is maximized there by the DFE).

The signal level separation (ideal eye height) is 0.4.

The EH (for the measured period – prob ≈10^{-5}) is ~0.27.

NEVO (@10^{-5}) is 0.27/0.4=68%.



NEVO calculation with statistical analysis

Equalized pulse & aggressors at the channel output

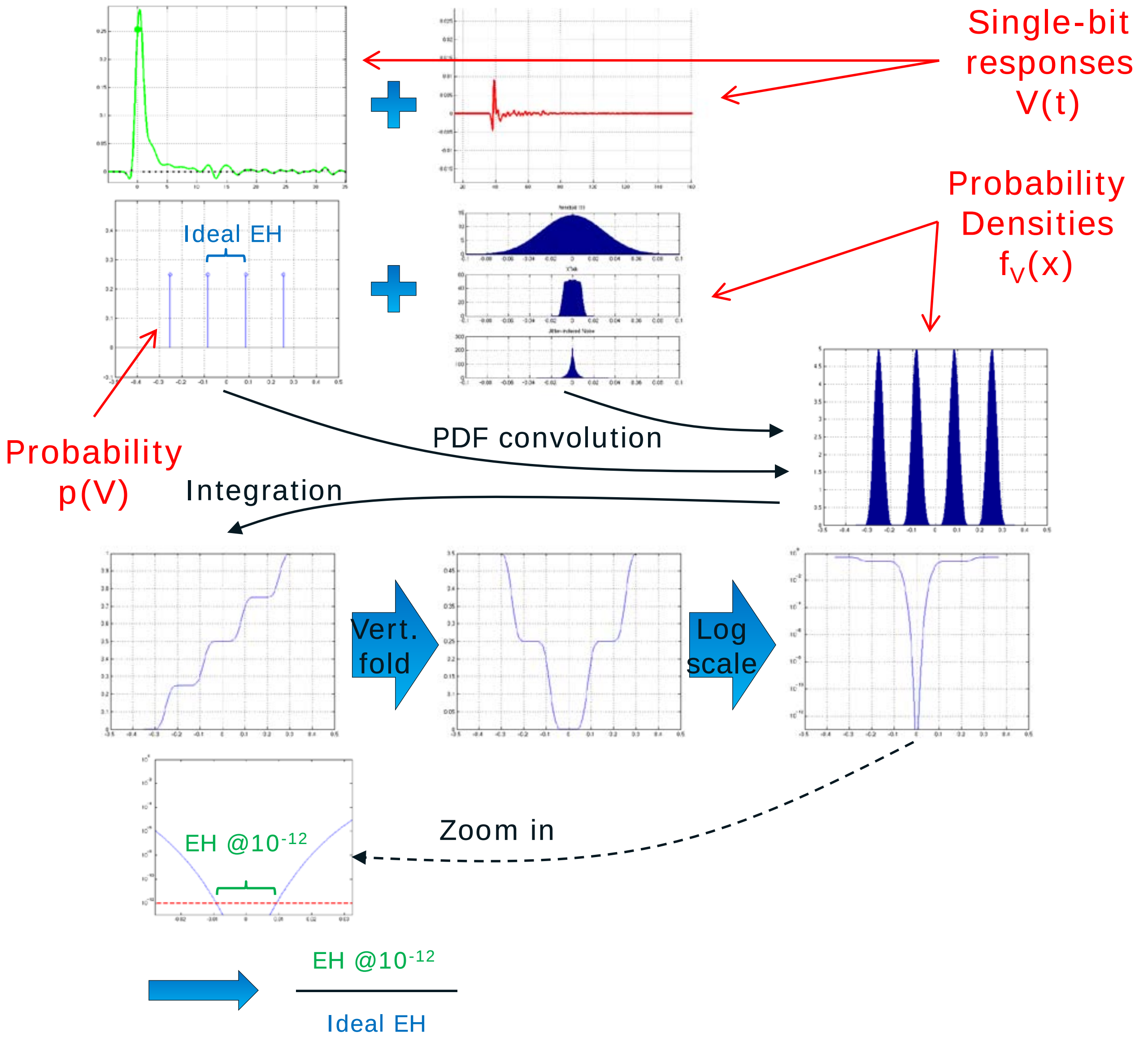
Signal constellation, PDFs of noise sources

Total signal PDF

CDF

Region with prob ½ ± 10^{-12} around decision level

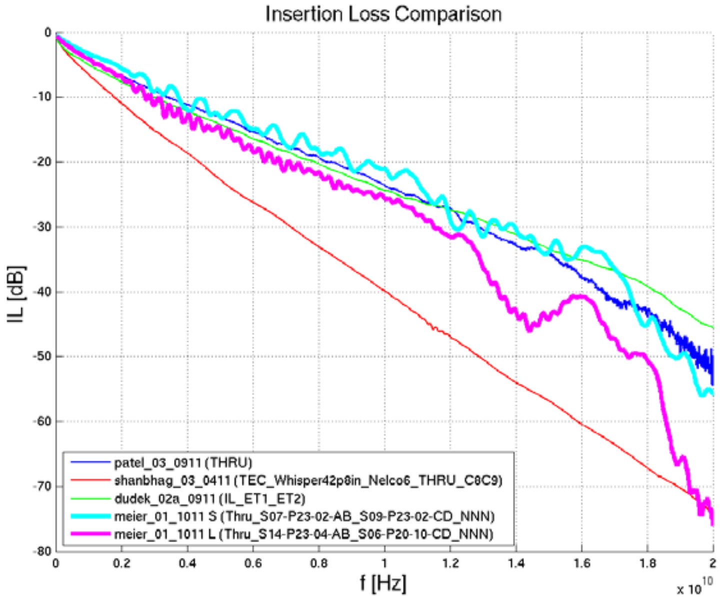
NEVO

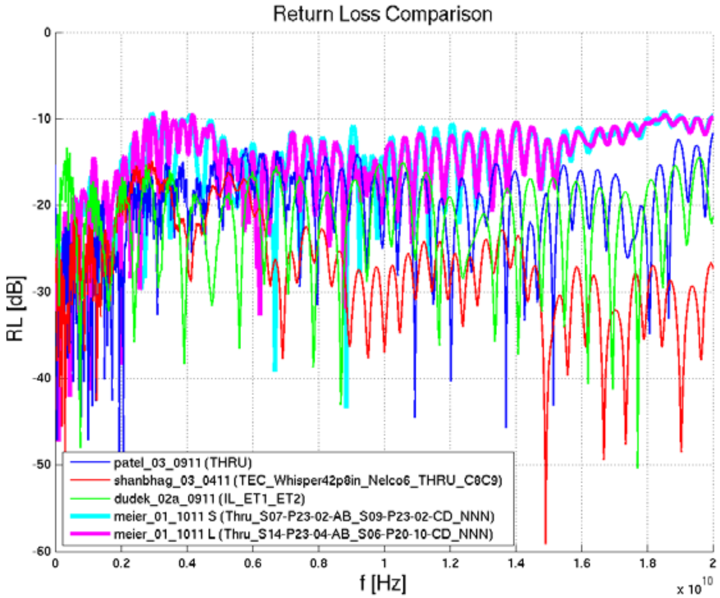


Analysis

Analyzed channels

References: patel_03_0911, shanbhag_03_0411, dudek_02a_0911, meier_01_1011

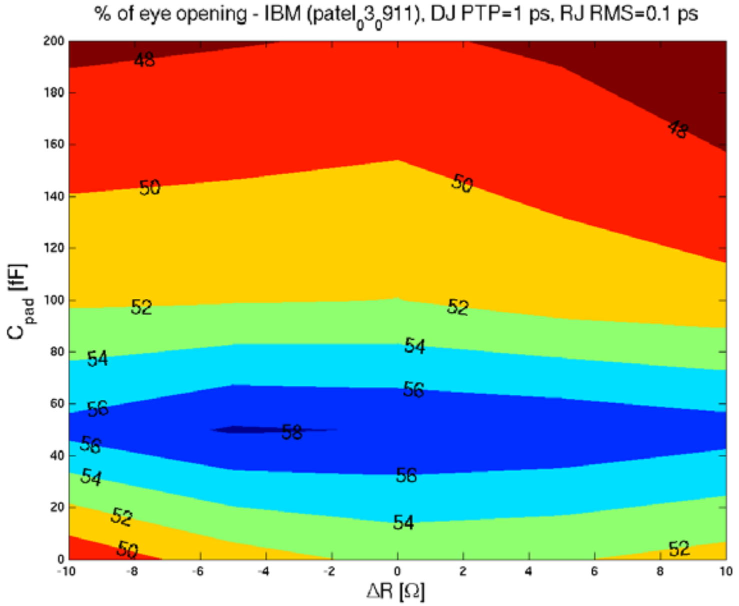




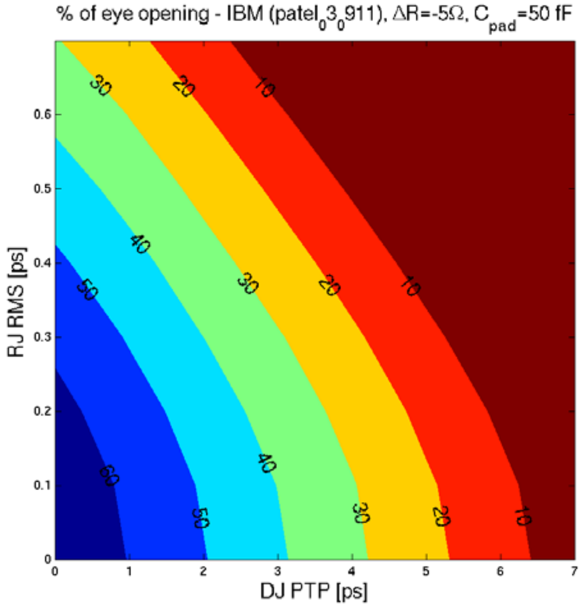
Accompanying crosstalk channels were used for each case – not listed here

NEVO contours – patel_03_0911

Termination tolerance



Jitter tolerance

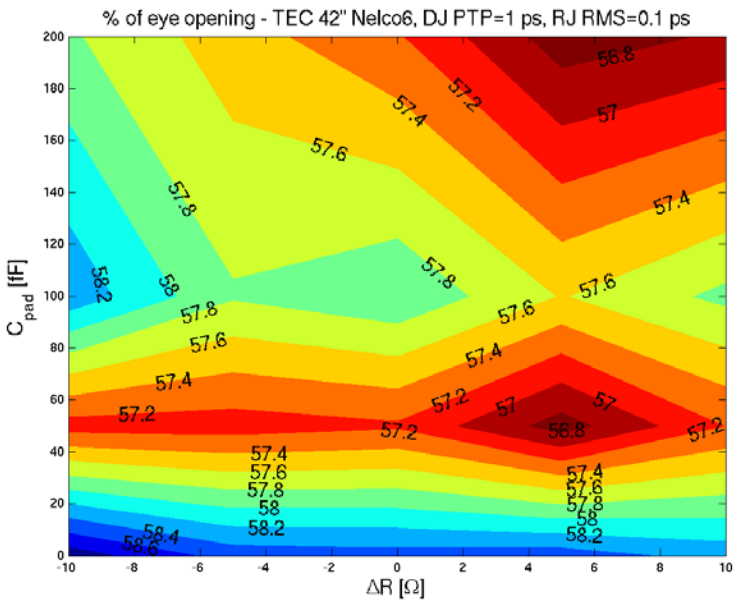


Fair amount of jitter can be tolerated (though not the max KR specs).

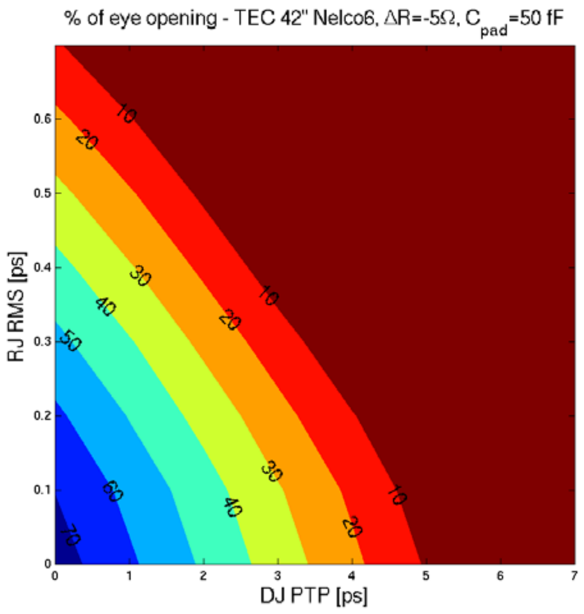
Mismatched termination can cause ~10% degradation – could be related to medium RL levels.

NEVO contours – TEC 42" Nelco6

Termination tolerance



Jitter tolerance



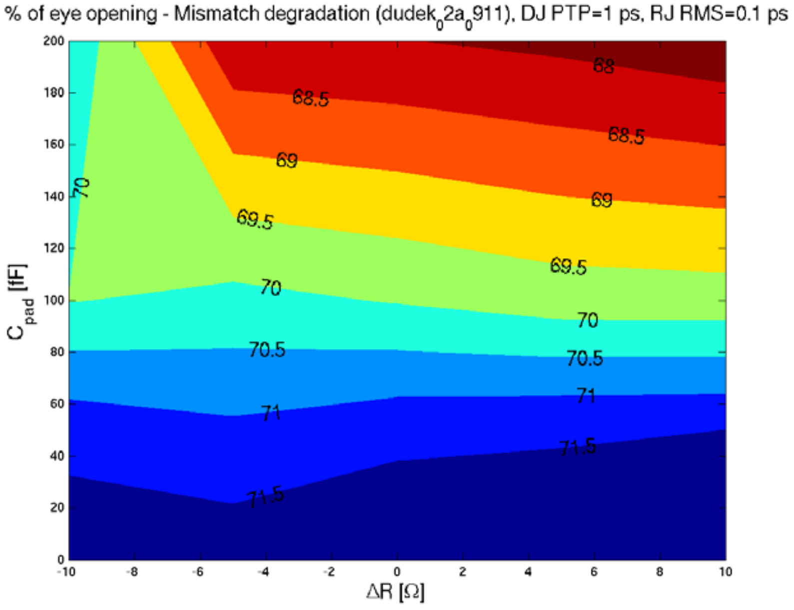
This channel can work well if levels of jitter are kept low.

Termination mismatch has negligible effect (could be related to good RL).

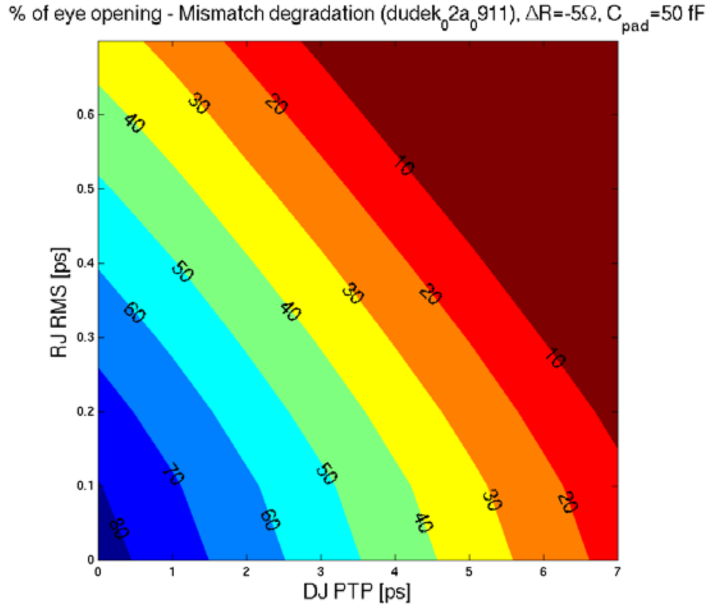
Note that this channel has IL≈50 dB @ 13 GHz, and does not meet the assumed working requirements of PAM-2 @ 26 GBaud (ref. meghelli_01a_0911)

NEVO contours – dudek_02a_0911

Termination tolerance

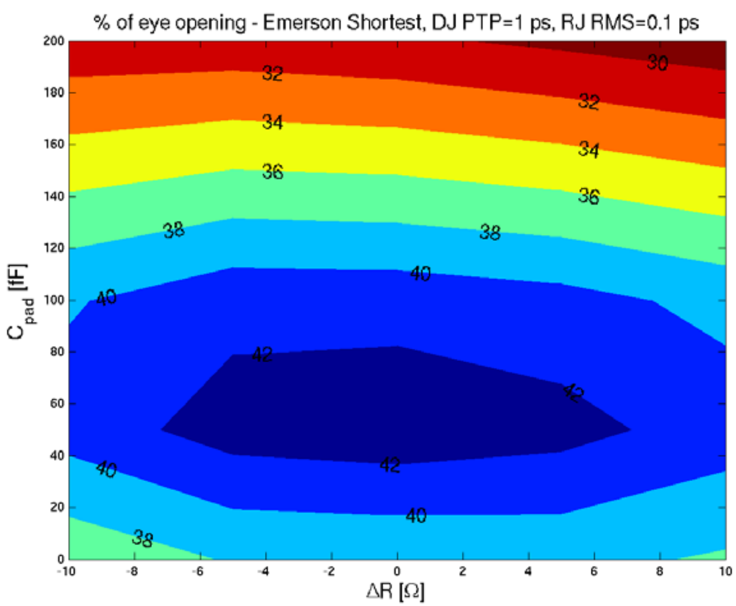


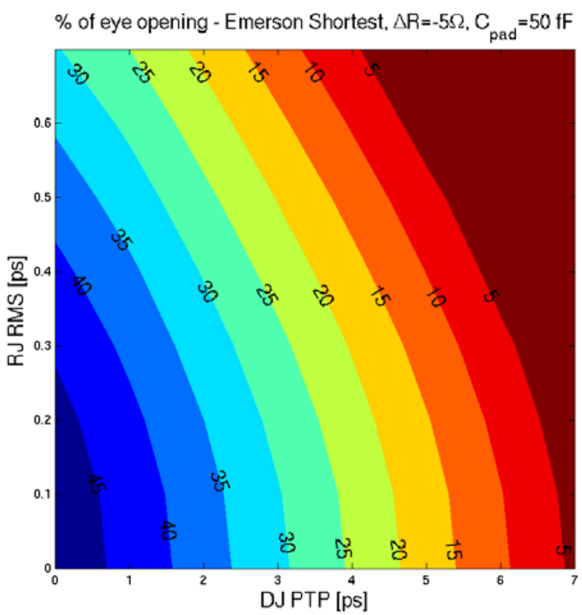
Jitter tolerance



This channel is quite tolerant to jitter.
Termination mismatch has small effect (could be related to good RL).

NEVO contours – meier_01_1011 Short



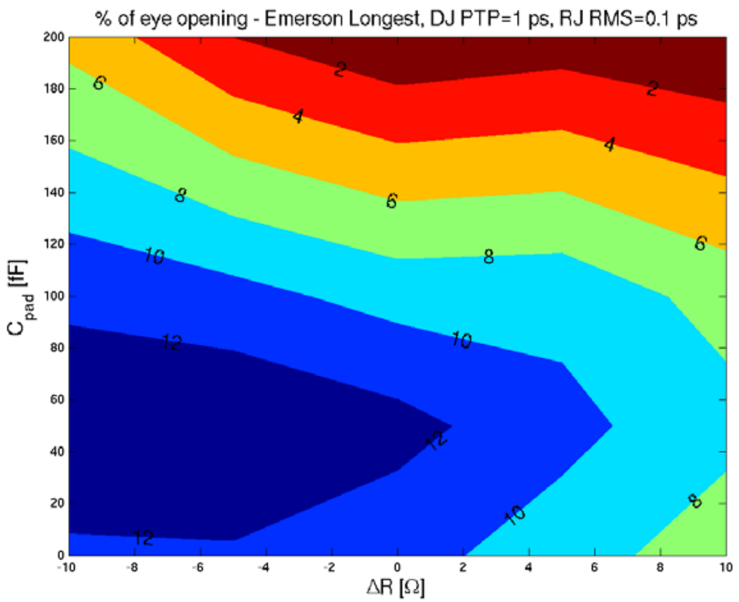


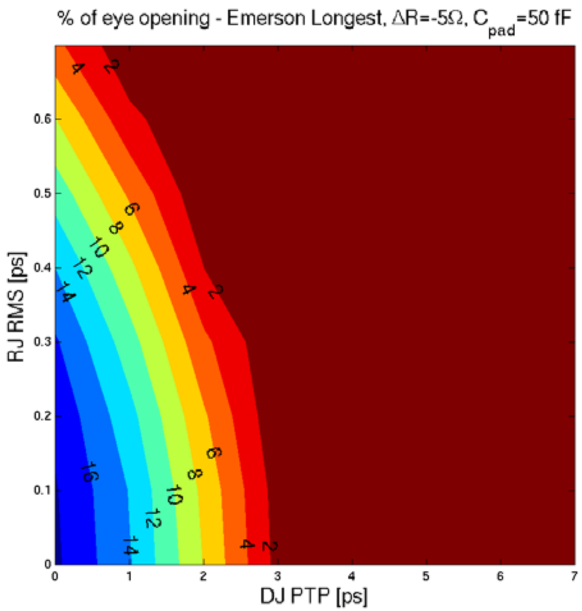
This channel is quite tolerant to jitter despite having a rather closed eye (strong Xtalk…) even without jitter.

Termination mismatch can cause >10% degradation – could be related to not-so-good RL.

Previous analysis (moore_01_0911) suggested that this channel has negative margin for PAM-2 @ 26 Gbaud even with no jitter. (Analysis method is different)

NEVO contours – meier_01_1011 Long





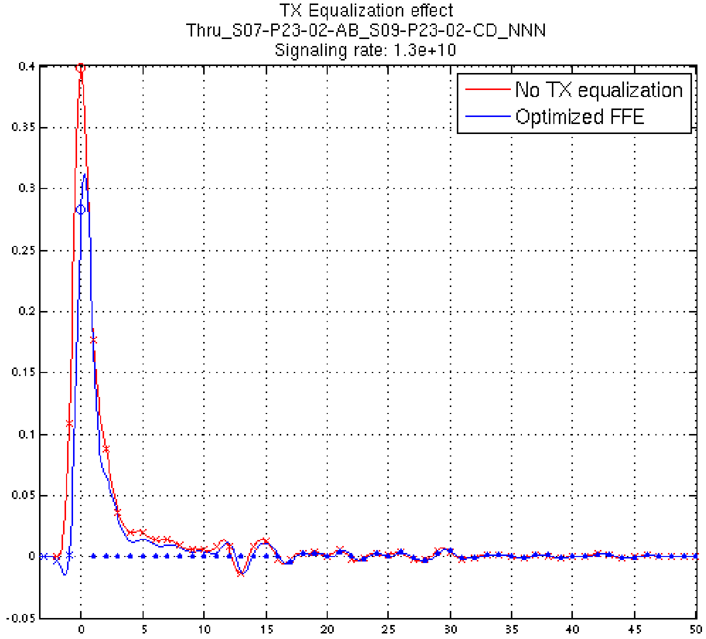
This channel has a small positive margin with the modeled system without jitter. A small amount of jitter or termination mismatch leaves no margin.

Previous analysis ([moore_01_0911]) suggested that this channel has negative margin for PAM-2 @ 26 Gbaud even with no jitter. (Analysis method is different)

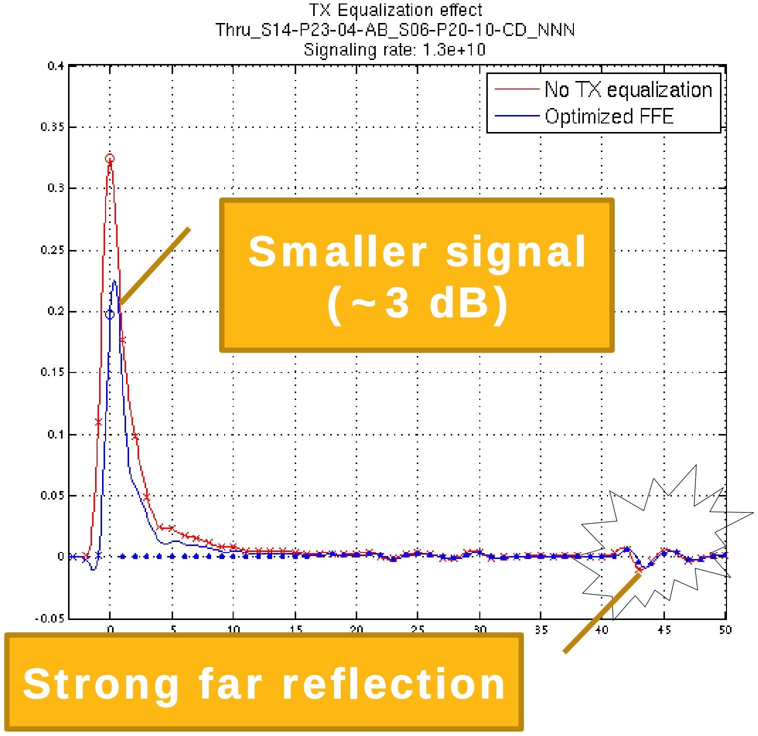
What can be done to improve the margin?

What’s between Short and Long?

Short



Long



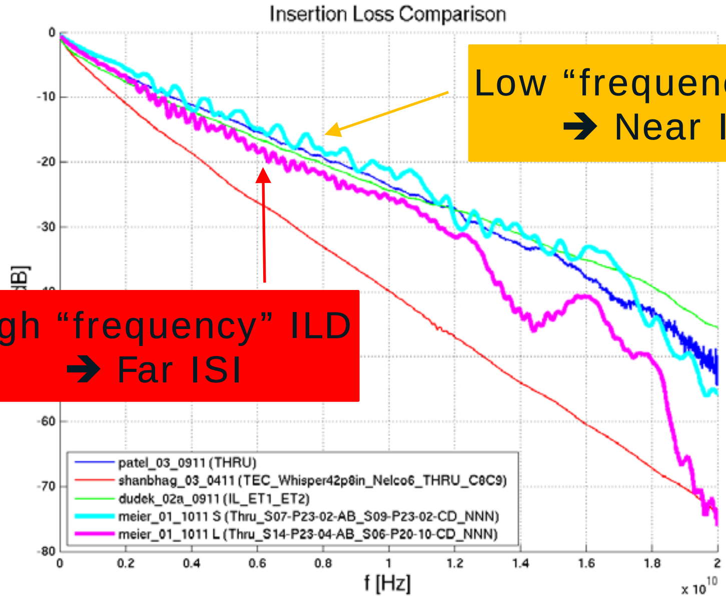
The long channel has a large amount of ISI beyond the current model’s DFE reach.

Performance can be improved by having a longer reach equalizer in the receiver.

Note that the required equalizer reach and number of taps is half that of the equivalent PAM-2 system.

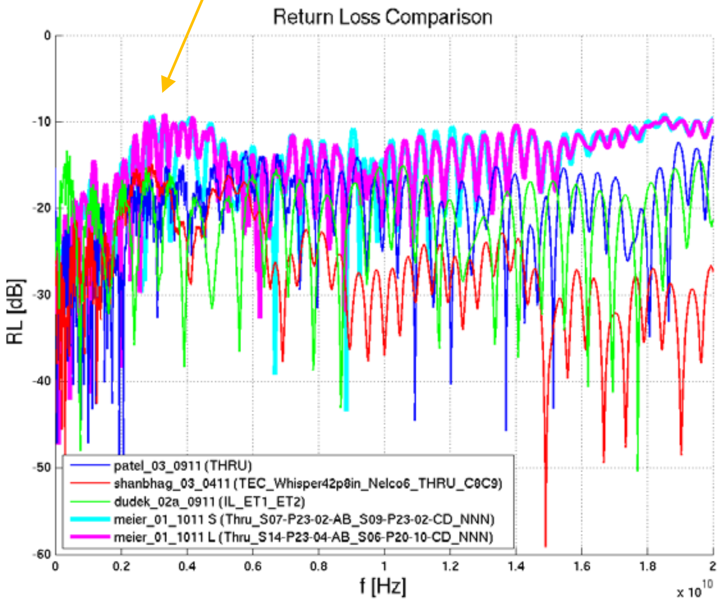
Another look in the frequency domain

High RL values correlate to larger sensitivity to termination



Low “frequency” ILD
➔ Near ISI

High “frequency” ILD
➔ Far ISI



Can we improve ILD check to include ”frequency” of ripple?

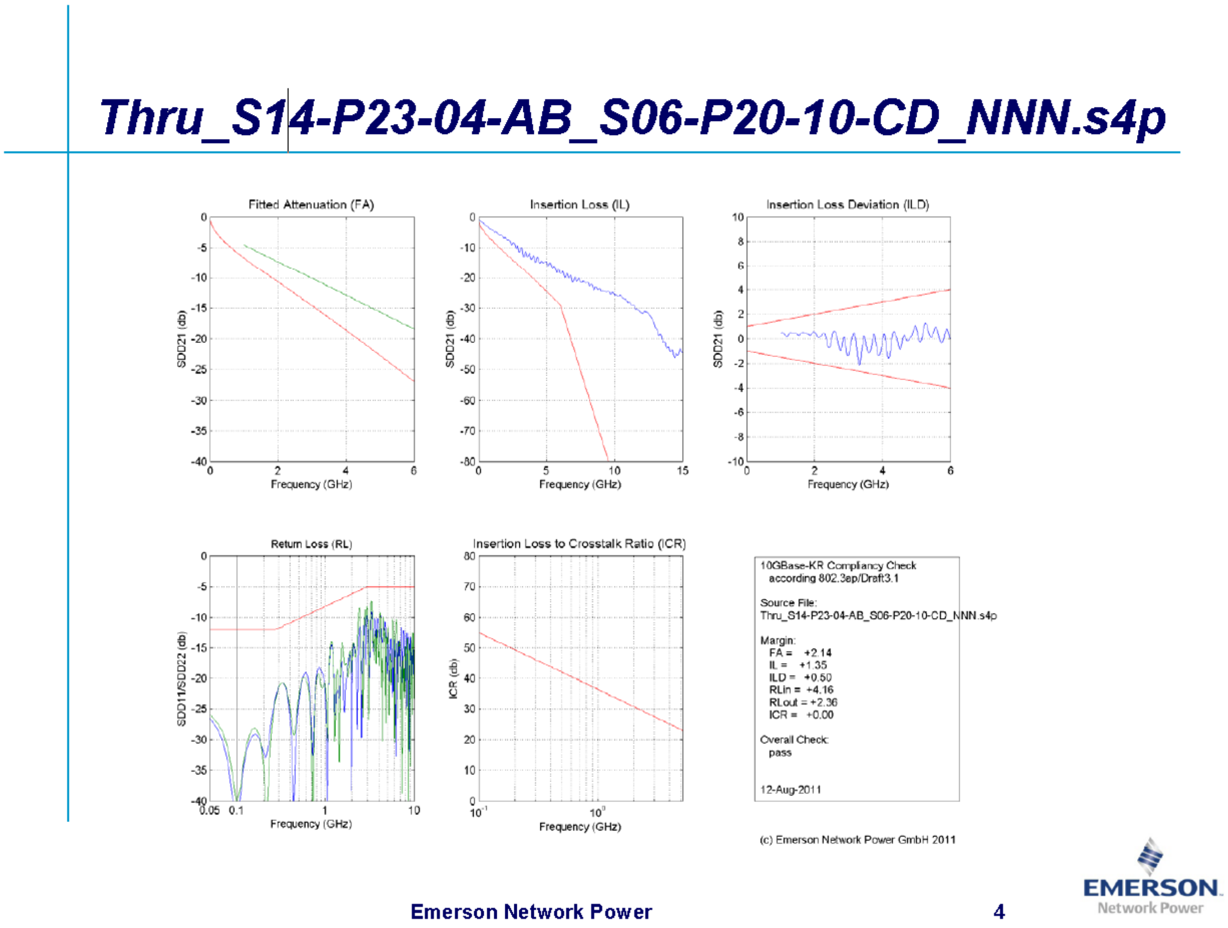
Summary

- A reference TX and RX model for PAM-4 signaling was described.
- Several recently contributed channels can be used with the reference model, providing healthy voltage margin, except one case with large reflection (which can be handled with a longer/sliding DFE).
  - Use of FEC can facilitate even worse channels, or enable simpler PHY implementations.
- Simulated channels have low sensitivity to non-ideal termination, and can tolerate some level of jitter.
  - Termination mismatch effect is shown to have a negligible to low effect with PAM-4.
- Measured channels are more sensitive to jitter and termination. Far reflections can have a large impact.
- Critical parameters for this project:
  - Transmitter Jitter – recommended target is <50% of the KR/CR values (in absolute time units)
  - Transmitter Return Loss (as a measurable test of termination)
    - Specification should be revisited
    - Consider also receiver RL, channel RL
  - Far reflections
    - Can we improve IL-based measures (e.g. ripple “frequency”) to check for that?

Thank You

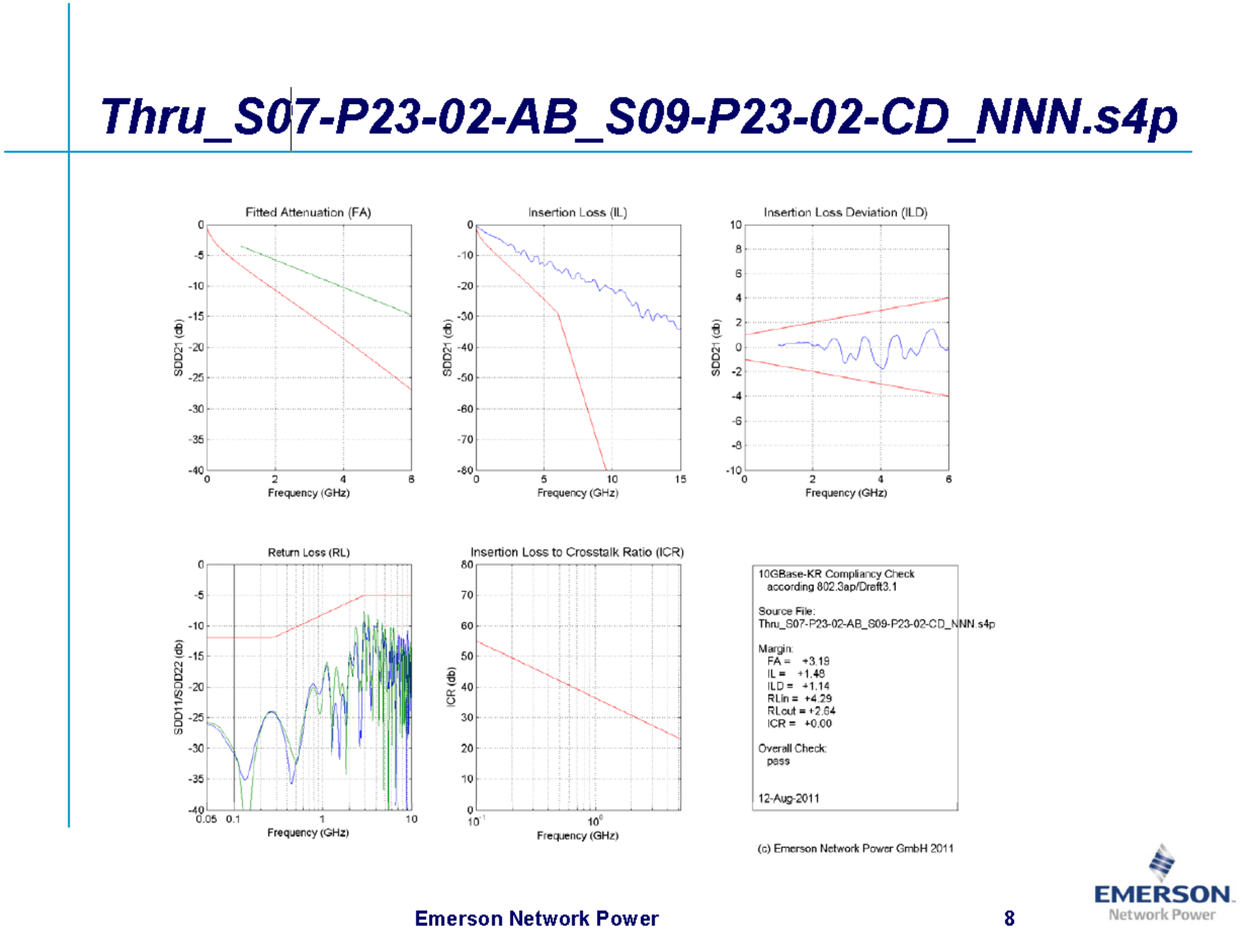
Backup

Emerson long channel



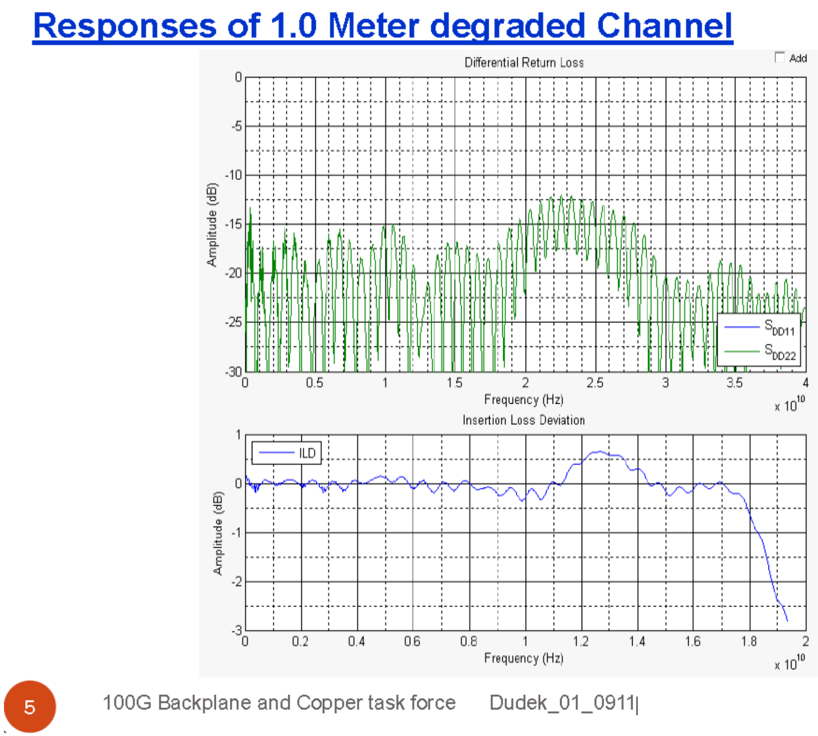
Source: meier_01_1011

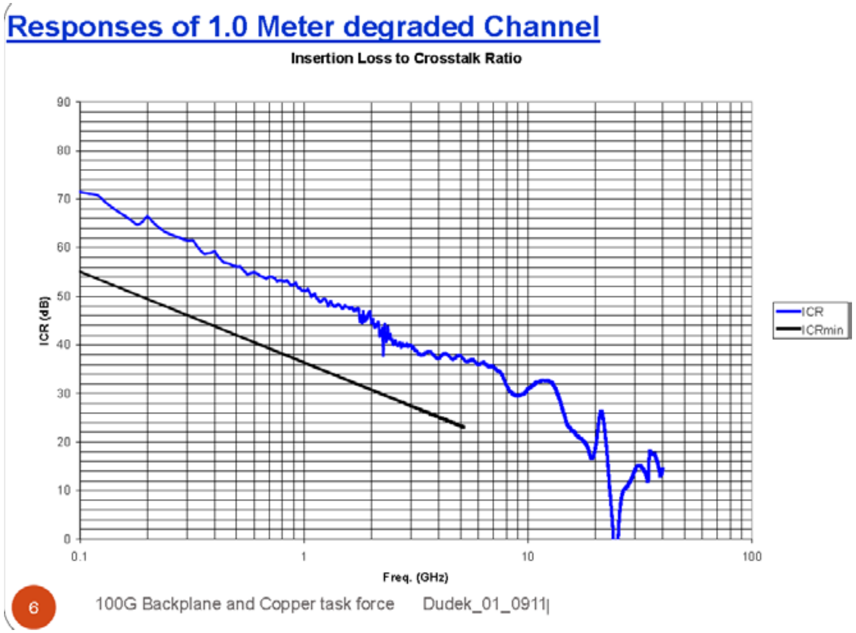
Emerson short channel



Source: meier_01_1011

1.0 m Degraded Channel





source: dudek_01a_0911