400G/lane optical specification challenges

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Overview

1

Link budget

How the 400G/lane power budget is allocated, and what changes from previous generations

2

Receiver requirements

Receiver sensitivity needed to close the budget: responsivity and TIA noise

3

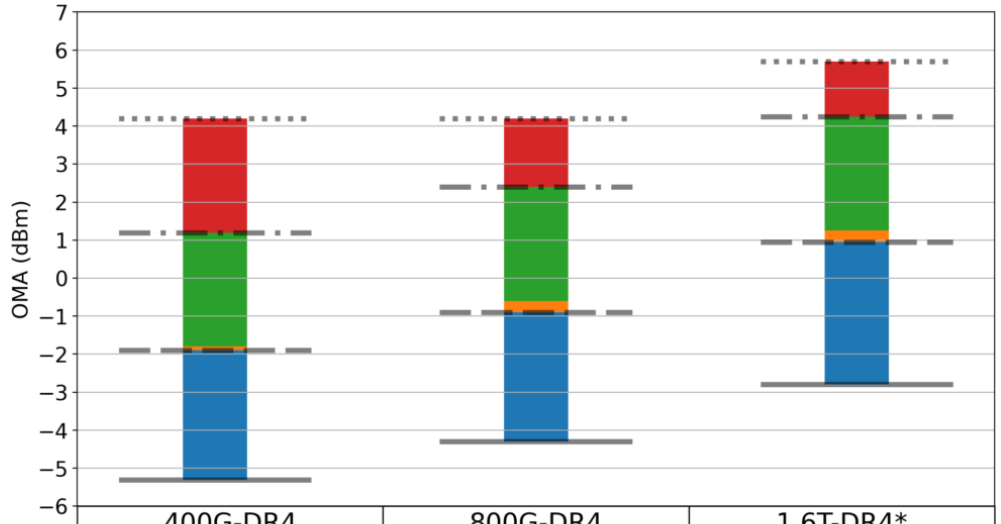
Transmitter dispersion penalty specification

Lessons from 802.3dj on the CD penalty in TDECQ

Link budget

The link budget is built up from the receiver sensitivity predicted to be achievable when modules are shipped.
A baseline specification is proposed in welch_3dw_01_2611

Budget spec have moved up ~1.5 dB per generation, although the real degradation is larger



	400G-DR4	800G-DR4	1.6T-DR4*
BaudRate (GBd)	53.125	106.25	212.5
FEC	FECo	FECo	FECo
Operating distance (m)	500	500	500
TDECQmax (dB)	3.4	3.4	3.75
UnstressedTECQ (dB)	1.4	0.9	0.9
OMAmax (dBm) ·····	4.2	4.2	5.7
OMAmin (dBm) TDECQ<UnstrTECQ OMAmin (dBm) TDECQ>UnstrTECQ	-0.8 -2.2+TDECQ	-0.1 -1.0+TDECQ	1.4 0.5+TDECQ
OMAmin@TDECQmax (dBm) —·—	1.2	2.4	4.25
OMAoverhead (dBm)	3.0	1.8	1.45
SRS (dBm) — —	-1.9	-0.9	0.95
Rx Sens (dBm) TECQ<UnstrTECQ Rx Sens (dBm) TECQ>UnstrTECQ	-3.9 -5.3+TECQ	-3.4 -4.3+TECQ	-1.9 -2.8+TECQ
RSnominal (SECQ=0dB) (dBm) ———	-5.3	-4.3	-2.8
Channel insertion loss (dB)	3.0	3.0	3.0
Additional Penaties (dB)	0.1	0.3	0.3
Allocation for penalties (dB)	3.5	3.7	4.05
Power Budget (dB)	6.5	6.7	7.05

The current proposal assumes:

- The same channel insertion loss
- The same MPI + DGD penalty allocation
- Receivers have margin to absorb the difference

Projected receiver sensitivity

- Each generation, the required Rx OMA rises by ~3 dB (+2.8 dB to 200G, +3.7 dB to 400G), driven by:
  - Higher noise bandwidth (symbol rate)
  - Higher TIA input-referred noise (IRN) density
  - Lower effective responsivity
  - Higher $TECQ_{max}$
- A ~2-3 dB implementation penalty above the theoretical limit is typically required. It covers for nonlinearities and noise enhancement based on Rx bandwidth and equalizer choice
- This projection assumes future receivers with TIA IRN ≤ 20 pA/√Hz and effective responsivity of 0.5 A/W after coupling losses

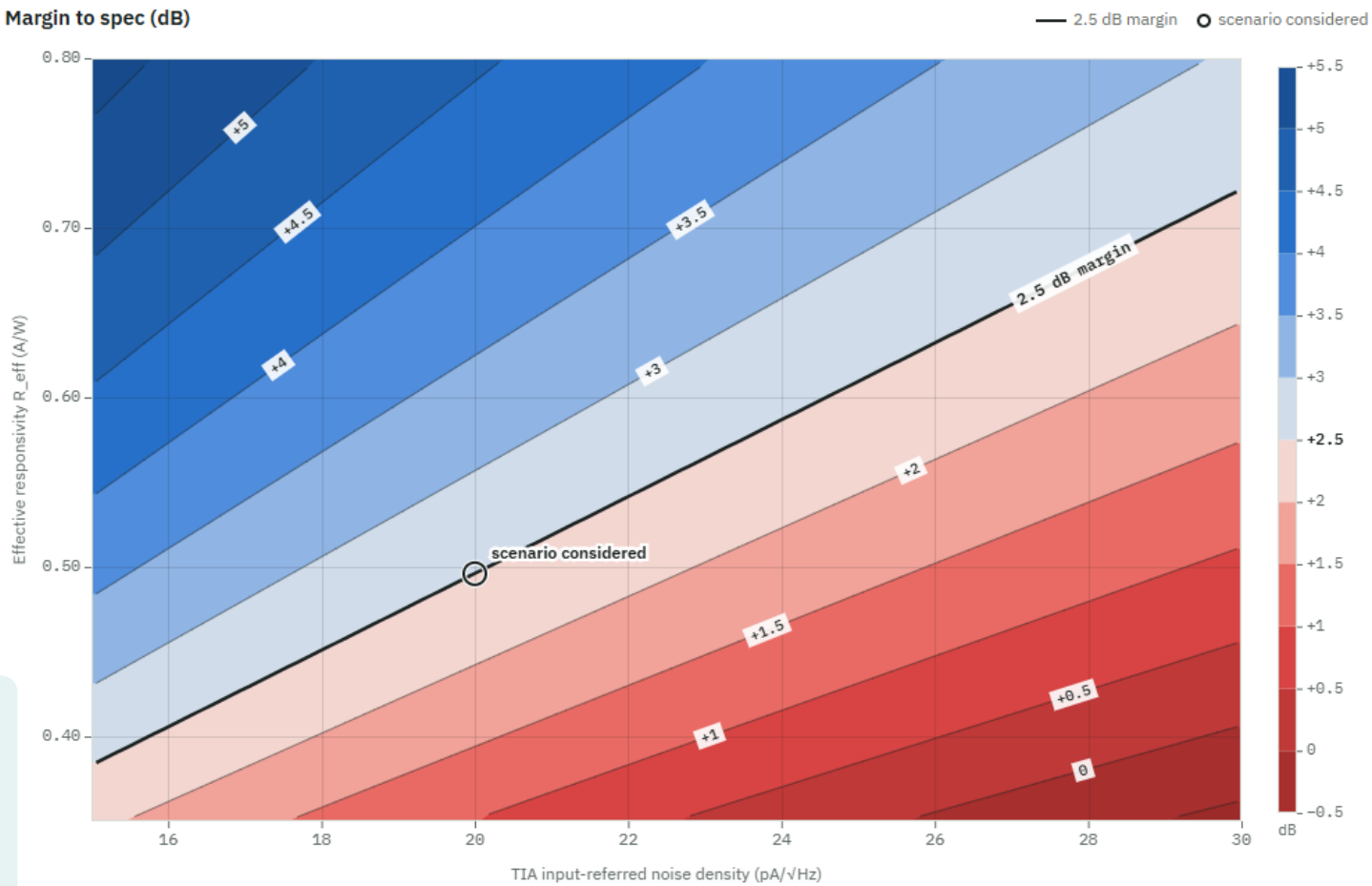
Margin to spec shrinks from +6.2 dB (100G) to +4.4 dB (200G) and +2.5 dB (400G) even with future receiver parameter assumptions



Parameter		100G	200G	400G
Symbol rate	GBd	53.125	106.25	212.5
Configuration		No inner FEC	No inner FEC	No inner FEC
Effective responsivity	A/W	0.61	0.57	0.50
TIA IRN density	pA/√Hz	12.0	15.0	20.0
Max TECQ	dB	3.4	3.4	3.75
IEEE spec at max TECQ	dBm	−1.9	−0.9	+0.95
Required OMA at connector	dBm	−8.07	−5.27	−1.55
Margin to spec	dB	+6.17	+4.37	+2.5
Penalty vs previous case on the line		reference	from 100G	from 200G
Symbol rate (noise bandwidth)	dB	–	+1.5	+1.5
TIA IRN density	dB	–	+1.0	+1.2
Effective responsivity	dB	–	+0.3	+0.6
Max TECQ	dB	–	0.0	+0.4
Shot noise	dB	–	+0.0	+0.0
Total step penalty	dB	–	+2.8	+3.7

400G/lane Rx sensitivity vs. responsivity and TIA noise

- Achievable Rx sensitivity is set by the combination of effective responsivity and TIA input-referred noise (IRN)
- Current receiver specifications do not meet the proposed 400G baseline
- Ongoing Rx technology improvements are required to close the gap



Future receiver characteristics considered:

R_{eff} = 0.5 A/W
TIA IRN = 20 pA/√Hz

Lesson from 802.3dj: CD penalty in TDECQ

Background

- DR and FR PMDs have always shared the same reference Rx/equalizer, because modules use the same DSP
- The same reference Rx/equalizer will therefore likely be reused for future 2 km IMDD PMDs (outside the scope of this project)

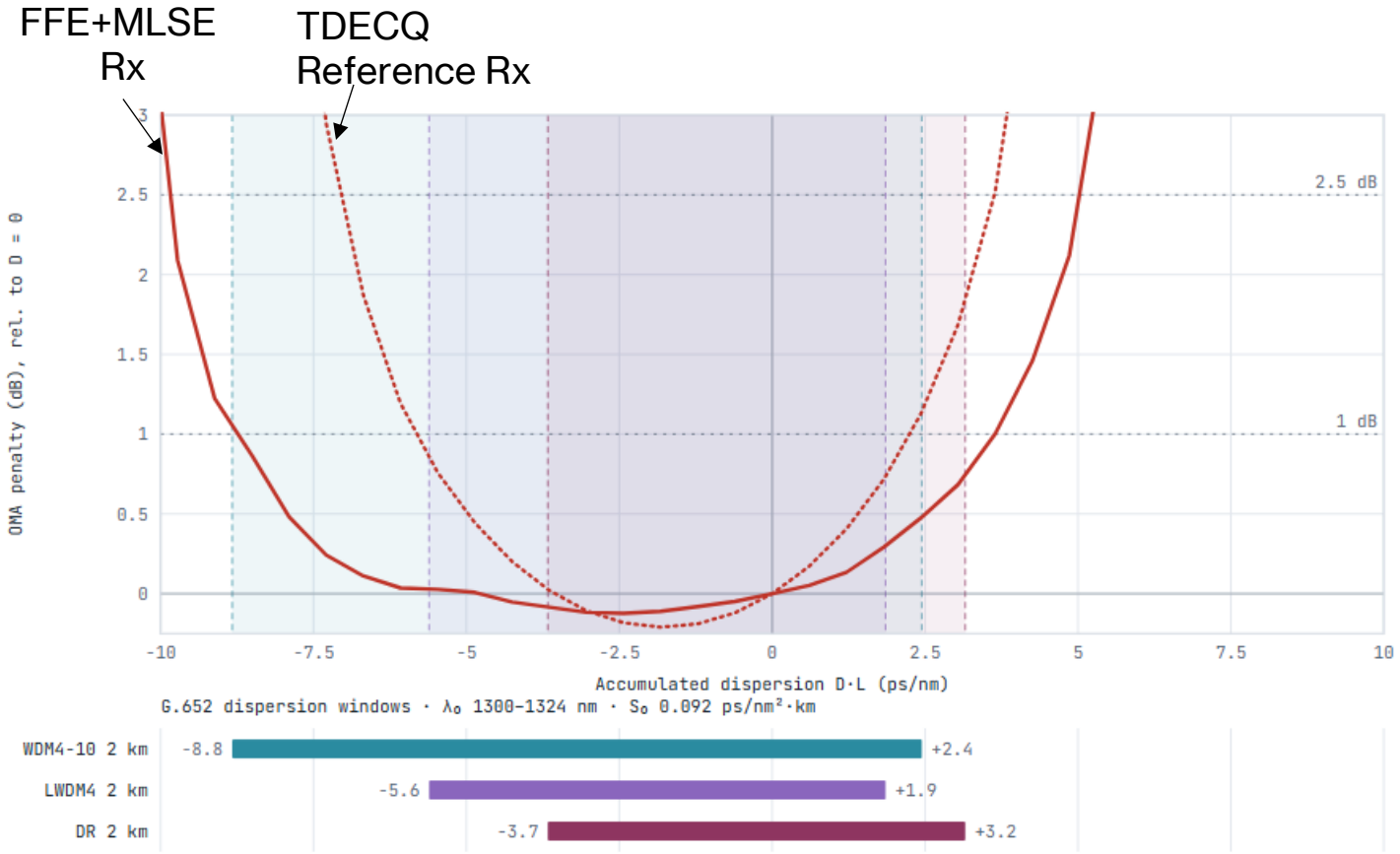
The problem

- TDECQ significantly overestimates the CD penalty
  - Predicted by early simulations [johnson_3df_01a_221011]
  - Confirmed by measured data [he_3dj_01b_2511]
- Proposed fixes [stojanovic_3dj_01_2307; he_3dj_01b_2511] were not adopted in 802.3dj, because the task force focused on short-reach PMDs where CD does not matter
- **Result:** 802.3dj was completed without demonstrating that a Tx can pass the 800G-LR4 TDECQ spec, even though links close with a compliant Rx

Why it matters now

- The stakes are higher at 400G/lane: FR4 and DR4-2km are now affected by CD, and are likely much higher-volume PMDs than LR4
- **We should not repeat the same mistake.**

CD penalty in TDECQ: proposal



OMA penalty vs. accumulated dispersion at 212.5 GBd: FFE + MLSE receiver vs. TDECQ reference equalizer, with 2 km dispersion windows, chirp = 0.5

Proposal: reconsider the CD penalty

Option A

Improve the reference Rx equalizer: add MLSE and remove the window spacing

Option B

Base the CD penalty on functional Rx BLER penalty

Alternative

If CD is not relevant to this task force:

- Drop TDECQ from the spec and keep TECQ
- Define the CD penalty in a future task force covering 2 km PMDs

Conclusions

1

Link budget

The 400G/lane proposal shifts up receiver spec by 1.5 dB compared to 200G/lane, while keeps the same channel loss and MPI + DGD allocation. Extra degradation on receiver sensitivity must be absorbed by the receiver margin

2

Receiver requirements

Closing the budget needs future receivers with $R_{eff} \geq 0.5$ A/W and TIA IRN ≤ 20 pA/√Hz; not met today, but expected with ongoing Rx improvements

3

Transmitter dispersion penalty

TDECQ overestimates the CD penalty and 802.3dj left this unresolved; with FR4 and DR4-2km now affected, it should be addressed in this project or explicitly deferred