Channel operating margin for PAM4 CDAUI-8 chip-to-chip interfaces

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Introduction

- Channel Operating Margin (COM) is a figure of merit for a passive electrical channel
- If COM exceeds the specified threshold, the channel is expected to interoperate with compliant transmitters and receivers
- Transmitter specifications are converted to parameters of the COM calculation
- Stress channels used to verify receiver performance are calibrated using COM

Words of caution

- A COM value is not a demonstration of feasibility (or lack thereof)
- Transmitters must be able to satisfy the requirements implied by the COM parameters
- Receivers must be able to tolerate the stress implied by the minimum COM
- The reference receiver employed by COM is not an implementation guide
  - Enable innovation so long as the performance requirements are met

A path from CAUI-4 to CDAUI-8

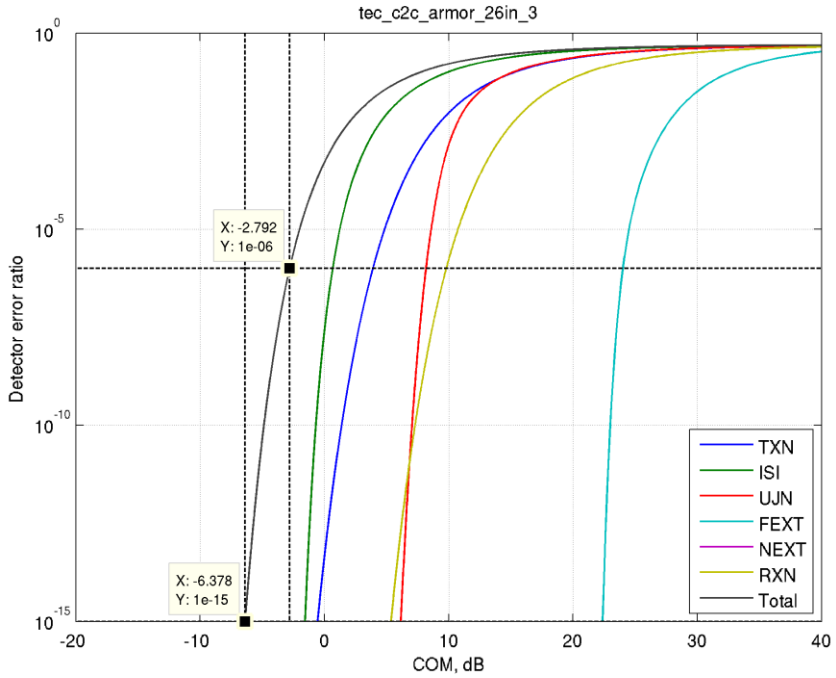
- Results are based on an implementation of Annex 93A that is not ran_com_3bj_3bm_01_1114.zip
- Begin with a set of chip-to-chip channels and the COM parameters specified in Annex 83D
- Test cases 1 through 7 are from mellitz_3bs_01_0714.pdf
- Test case 8 is from shanbhag_02_0914.pdf
- Assume PAM4 and RS(544,514) Forward Error Correction (FEC)
  - Change the number of signal levels, L, to 4
  - Increase the target detector error ratio, DER_0, to 1E−6
  - Increase the signaling rate, f_b, to 26.5625 GBd

Results, first pass

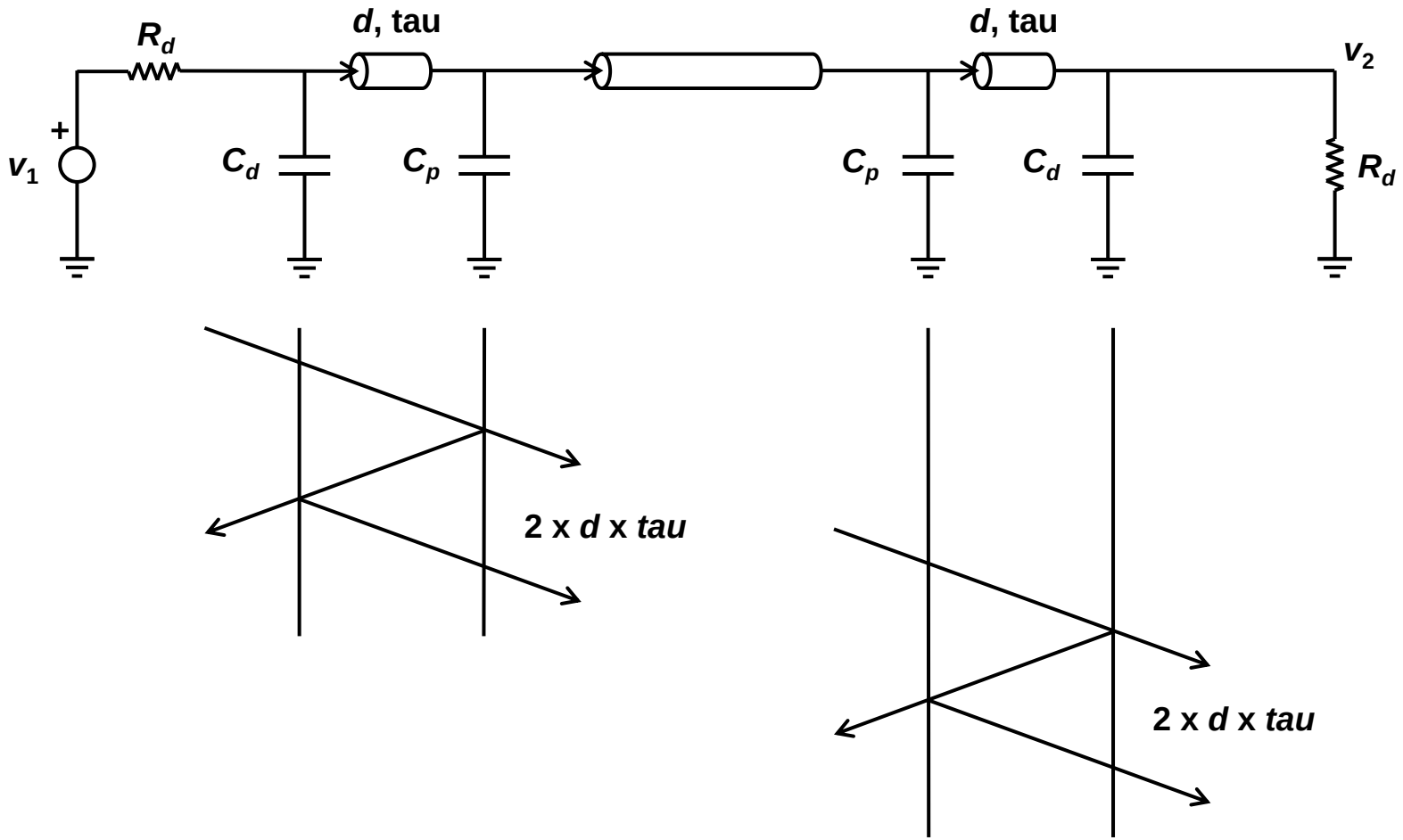
Test case	1	2	3	4	5	6	7	8
mellitz_3bs_01_0714.pdf	2.01	2.78	3.06	2.01	2.18	2.95	3.02	n/a
This implementation, z_p = 12 mm	3.20	3.70	3.24	3.23	3.13	3.73	3.42	4.77
This implementation, z_p = 30 mm	2.00	2.77	3.00	2.03	2.09	2.95	2.86	3.11
Change L to 4, z_p = 30 mm	−6.39	−5.67	−5.33	−6.36	−6.27	−5.45	−5.46	−5.46
Add RS(544,514), z_p = 30 mm	−3.55	−2.91	−2.78	−3.58	−3.24	−2.65	−2.74	−2.79

Top impairments

- Inter-symbol interference (ISI)
- Transmitter noise (TXN)
- Uncorrelated jitter (UJN)



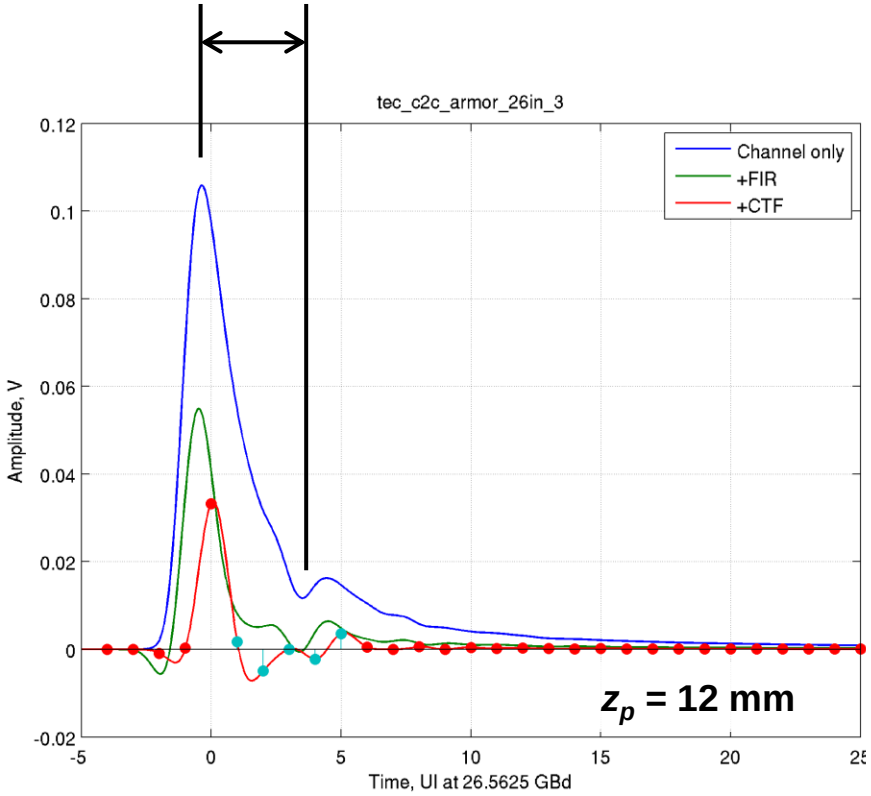
COM device package models



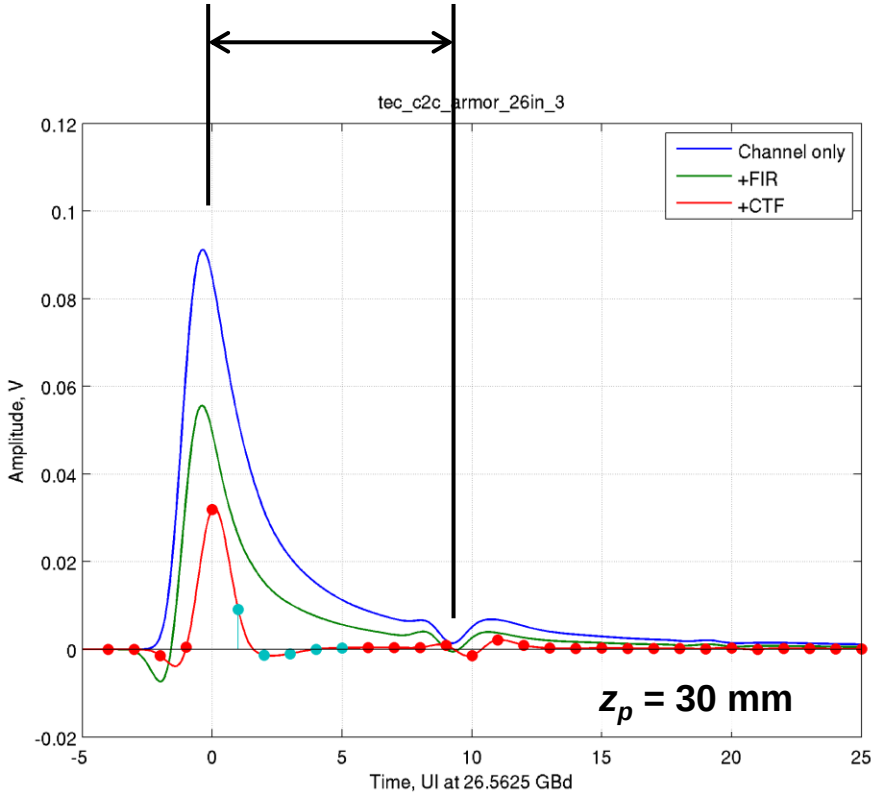
Transmitter and receiver package reflections add constructively!

Influence of COM device package models

2 x (12 mm) x (6.14 ps/mm) ~ 3.9 UI

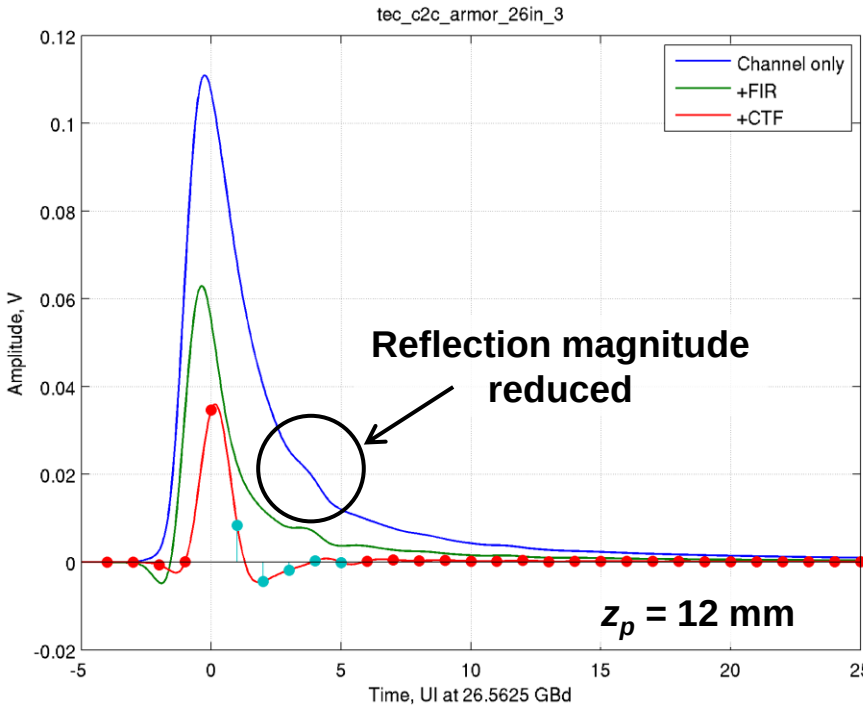


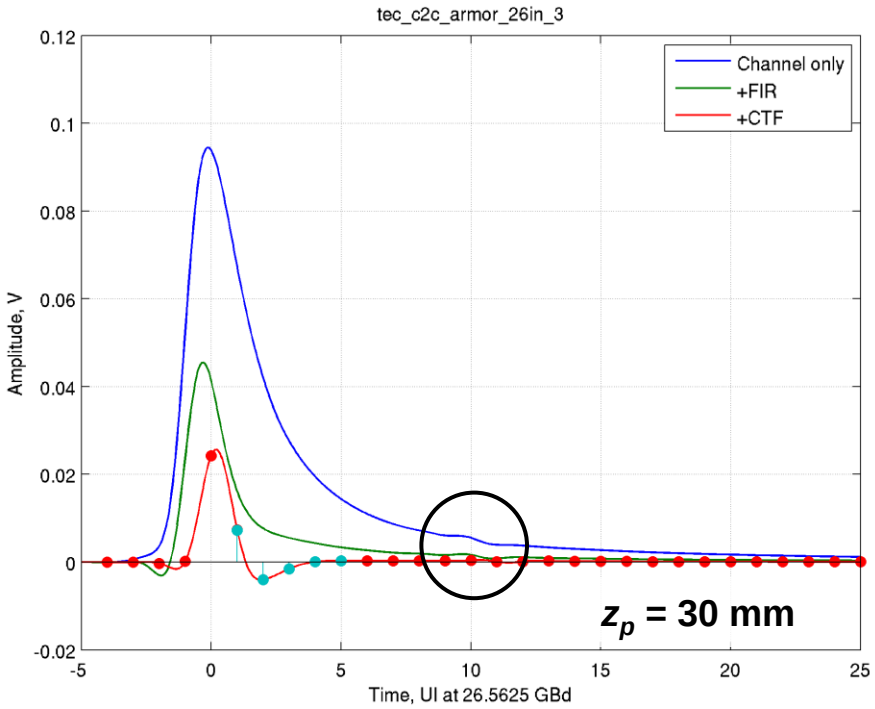
2 x (30 mm) x (6.14 ps/mm) ~ 9.8 UI



Substitute design-based models

Test case	1	2	3	4	5	6	7	8
Add RS(544,514), z_p = 30 mm	−3.55	−2.91	−2.78	−3.58	−3.24	−2.65	−2.74	−2.79
Design-based, z_p = 12 mm	−1.05	−0.15	0.06	−1.14	−1.29	−0.18	−0.14	−0.04
Design-based, z_p = 30 mm	−1.68	−0.65	−0.04	−1.68	−1.73	−0.40	−0.26	−0.78





Device package models have a tremendous influence on COM!

Transmitter noise and jitter

- Reduce peak dual-Dirac jitter, A_{DD}, to 0.02 UI
- Increase transmitter signal-to-noise ratio, SNR_{TX}, to 31 dB
- SNR_{TX} represents the signal-to-noise-and-distortion ratio (SNDR) requirement imposed on the transmitter
- SNDR includes linear fit error (distortion) and uncorrelated noise
- SNR_{TX} defines an additive Gaussian noise source based on the SNDR value
- This could result in a conservative COM value

What is the problem?

- In principle, the transmitter modeled by COM should meet all of the transmitter requirements
  - Balancing on the “edge of compliance” to the largest extent possible

- SNR_{TX} = SNDR can result in a non-compliant transmitter model
  - A component of SNDR is linear fit error which includes residual ISI
  - In this context, “residual” implies ISI outside of an exception window
  - The exception window is typically set to equal the DFE length ($N_p = N_b$)
  - E.g., if $N_p = 5$ then reflections 10 UI from the main cursor degrade SNDR

- The noise is presumably added to the waveform and impacts both sampling and transition times
  - Noise is converted to jitter via the slope of the waveform at the crossing
  - However, the model also defines a timing error based on the worst-case uncorrelated jitter
  - By definition, the jitter measured at the crossing times will then be larger than allowed

Path forward for transmitter noise and jitter

- In general, SNR_{TX} should be greater than or equal to SNDR
- SNR_{TX} should be pro-rated by the residual ISI corresponding to the device package model and specified exception window
- Any correction may be applied to the COM parameters or used as a justification to reduce the transmitter SNDR requirement
- Consider reducing the RMS random jitter parameter, σ_{RJ}, to account for the jitter induced by the SNR_{TX} noise source

Results, third pass

Test case	1	2	3	4	5	6	7	8
Design-based, z_p = 30 mm	−1.68	−0.65	−0.04	−1.68	−1.73	−0.40	−0.26	−0.78
Reduce jitter	−0.61	0.57	1.30	−0.57	−0.62	0.91	1.08	0.53
Increase transmitter SNR	0.51	2.06	3.13	0.58	0.48	2.57	2.80	1.97

Now we are getting somewhere…

Equalization

- Increase de-emphasis range of the continuous time filter by 3 dB
  - g_{DC} from −15 to 0 dB in 1 dB steps
- For CAUI-4, decision feedback equalizer (DFE) coefficients were constrained to limit error propagation
- CDAUI-8 is assumed to leverage RS(544,514) or a similar code
- Adopt the 100GBASE-KP4 coefficient constraints
  - $b_{max}(1) = 1$, otherwise $b_{max}(n) = 0.2$

Results, final pass

Test case	1	2	3	4	5	6	7	8
Increase transmitter SNR	0.51	2.06	3.13	0.58	0.48	2.57	2.80	1.97
Increase g_{DC} range	1.14	2.54	3.13	0.72	0.86	2.76	2.81	2.58
Relax DFE constraints	1.88	2.94	3.13	1.81	1.37	2.76	2.81	2.92
Reduce level separation	1.16	2.22	2.41	1.09	0.65	2.04	2.09	2.20

- Level separation mismatch ratio corresponds to a significant penalty
- E.g., tightening requirement from 0.92 to 0.95 yields COM+0.28 dB
  - However, more data is needed to justify a change

A number of interesting channels show greater than 2 dB margin

Path forward for the COM device package model

- Reduce C_d (currently 250 fF)?
- Reduce C_p (currently 180 fF)?
- Increase Z_c (currently 78.2 Ohms)?
  - This is a parameter of the package transmission line model
- Extend the DFE to cancel the reflections?
- This is a subject for further study

Summary of proposal

Parameter	Symbol	CAUI-4	Proposal	Units
Signaling rate	f_b	25.78125	26.5625	GBd
Device package model				
Single-ended device capacitance	Cd	2.5E−4	TBD	nF
Transmission line length, test 1	z_p	12	12	mm
Transmission line length, test 2	z_p	30	30	mm
Single-ended package capacitance	C_p	1.8E−4	TBD	nF
Single-ended reference resistance	R_0	50	50	Ω
Single-ended termination resistance	R_d	55	TBD	Ω
Receiver 3 dB bandwidth	f_r	0.75 x fb	0.75 x fb	GHz
Transmitter equalizer, minimum cursor coefficient	$c(0)$	0.6	0.6	—
Transmitter equalizer, pre-cursor coefficient	$c(-1)$			
Minimum value		−0.15	−0.15	—
Maximum value		0	0	—
Step size		0.05	0.05	—
Transmitter equalizer, post-cursor coefficient	$c(1)$			
Minimum value		−0.25	−0.25	—
Maximum value		0	0	—
Step size		0.05	0.05	—

Summary of proposal, continued

Parameter	Symbol	CAUI-4	Proposal	Units
Continuous time filter, DC gain	g_{DC}			
Minimum value		−12	−15	dB
Maximum value		0	0	dB
Step size		1	1	dB
Continuous time filter, zero frequency	f_z	f_b / 4	f_b / 4	GHz
Continuous time filter, pole frequencies	f_{p1}	f_b / 4	f_b / 4	GHz
	f_{p2}	f_b	f_b	GHz
Transmitter differential peak output voltage				
Victim	A_v	0.4	0.4	V
Far-end aggressor	A_{fe}	0.4	0.4	V
Near-end aggressor	A_{ne}	0.6	0.6	V
Number of signal levels	L	2	4	—
Level separation mismatch ratio	R_{LM}	1	0.92	—
Transmitter signal-to-noise ratio	SNR_{TX}	27	31	dB
Number of samples per unit interval	M	32	32	—

Summary of proposal, continued

Parameter	Symbol	CAUI-4	Proposal	Units
Decision feedback equalizer (DFE) length	N_b	5	5	UI
Normalized DFE coefficient magnitude limit n = 1 n = 2 to N_b	$b_{max}(n)$	 0.3 0.3	 1.0 0.2	 — —
Random jitter, RMS	σ_{RJ}	0.01	0.01	UI
Dual-Dirac jitter, peak	A_{DD}	0.05	0.02	UI
One-sided noise spectral density	η_0	5.2E−8	5.2E−8	V^2/GHz
Target detector error ratio	DER_0	1E−15	1E−6	—
Channel operating margin, min.	COM	2	2	dB

Key take-aways

- Device package models have a large influence on COM
- Design-based package models yield significantly higher COM values
- Transmitter noise and jitter parameters must be properly calibrated to avoid worse than worst-case modeling and hidden margin
- This proposal yields COM values greater than 2 dB for a multiple chip-to-chip channels given appropriate adjustments to the device package models
- Additional enhancements will be investigated