Budgeting for receiver noise in Channel Operating Margin (COM)

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Philosophy

- IEEE 802.3 standards avoid the definition of implementations and instead define externally observable behaviors
- Such behaviors are constrained in a way to foster interoperability between different implementations
- It is often the case that a reference model needs to be defined in order to describe the observable behaviors
- Reference models may have aspects that resemble implementations
- However, it is a non-goal for the reference model to be a detailed model of any specific implementation

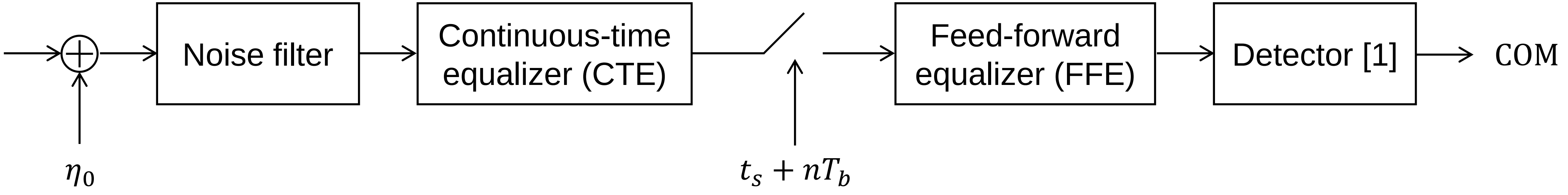
Role of a reference receiver

- A reference receiver is a model that describes the externally observable behaviors of a receiver
- It is used to describe the ability of a receiver to equalize an input signal
- It allows for impairments that limit the performance of practical receiver implementations
- It does not need to include a detailed model for each impairment
- However, it should provide an impairment budget that is large enough to accommodate a realistic level of impairments
- A reference receiver should set a lower bound on receiver performance that enables interoperability with compliant transmitters and channels

The reference receiver “trap”

- It is easy to interpret features of the reference receiver to be requirements on implementations
- It is only the externally observable behavior that matters regardless of how an implementation achieves that behavior
- The more the reference receiver resembles a detailed receiver model, the easier it becomes to fall into this “trap”
- A reference receiver should not include details beyond what is necessary to achieve the goals of the standard

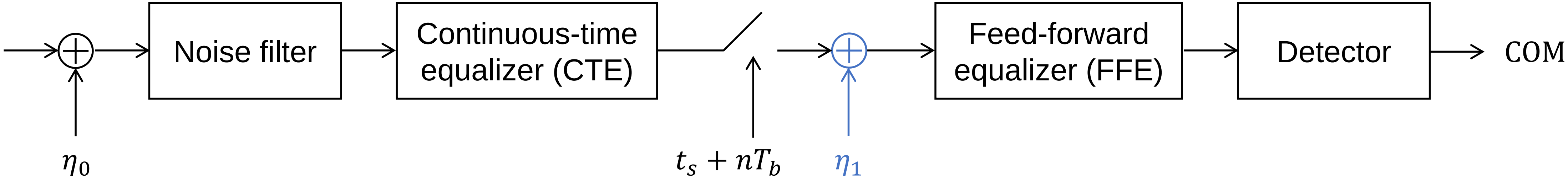
Reference receiver noise budget



- The calculation of Channel Operating Margin (COM) includes two terms that can be used to allocate a budget for receiver noise (impairments)
- Input-referred noise spectral density η_0 has a channel-dependent impact on COM
- The η_0 term is often assumed to correspond to sources of noise external to the receiver (but it can include internal noise sources)
- Minimum COM provides a channel-independent allocation for additional noise (impairments)

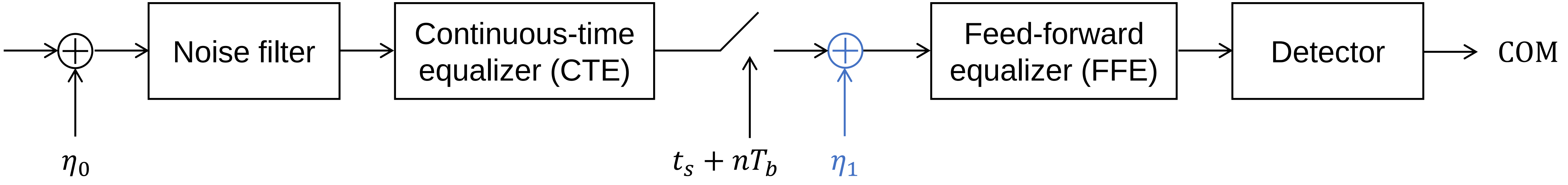
[1] Symbol-by-symbol detector (SBSD) with decision feedback equalizer (DFE) or maximum likelihood sequence detector (MLSD)

Augmenting the receiver noise budget

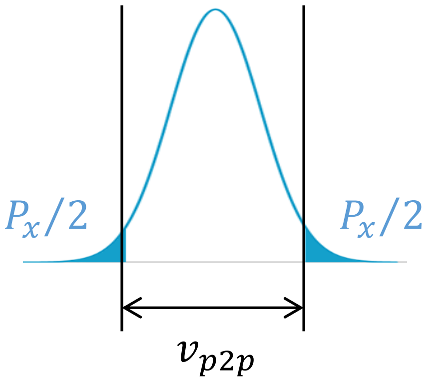


- It has been suggested that an additional noise term η_1 is needed for the receiver noise budget
- It is intended to represent analog-to-digital converter (ADC) quantization noise
- It could also be used to model additional sources of noise internal to the receiver
- The distinguishing characteristic is that it is only "enhanced" by the FFE (where η_0 is also "enhanced" by the CTE)

Simplified model for quantization noise



Distribution of signal and noise amplitude at the sampler output



$v_{lsb} = v_{p2p} 2^{-\mathrm{ENOB}}$ ADC quantization step

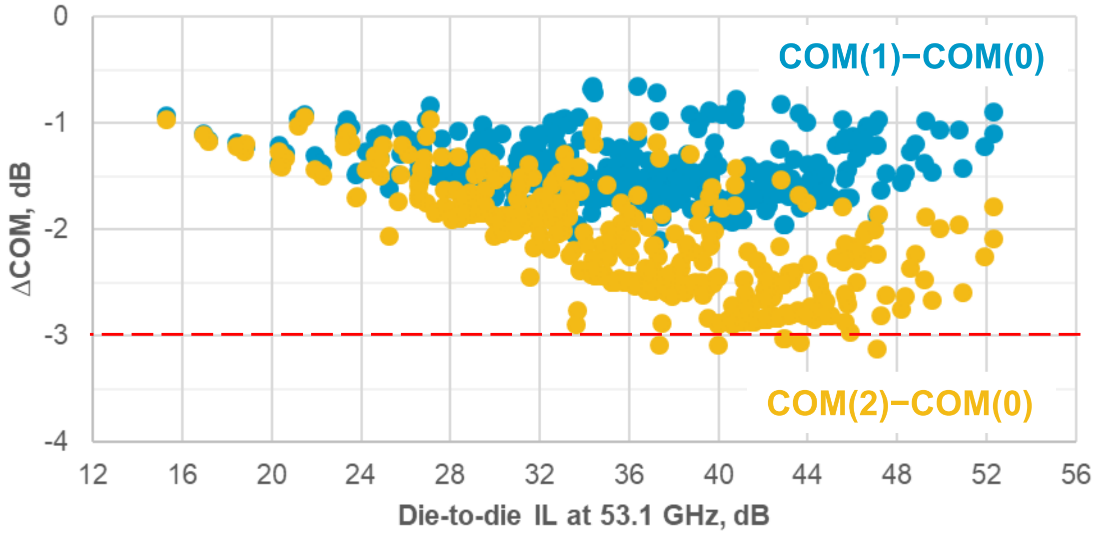
$\sigma_{qn}^2 = \dfrac{v_{lsb}^2}{12}$ Quantization noise variance (uniform distribution)

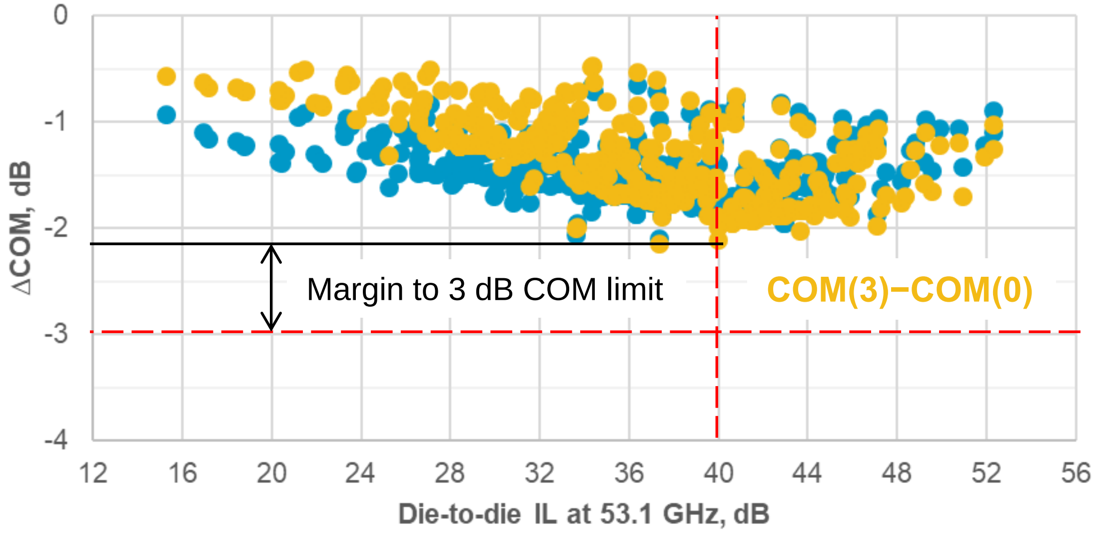
$S_{qn}(\theta) = \dfrac{\eta_1}{2} = \dfrac{\sigma_{qn}^2}{f_b}$ $\theta = [-\pi, \pi)$ Power spectral density at sampler output (f_b is the signaling rate, π is $f_b/2$)

P_x is the probability that the signal exceeds v_{p2p}. It is set to $3\mathrm{DER}_0/4$ (which is the probability of an initial PAM-4 symbol error corresponding to DER_0) for now. This choice is a subject for discussion.

- This is a starting point for an η_1 model that can be used for analysis

Impact of quantization noise

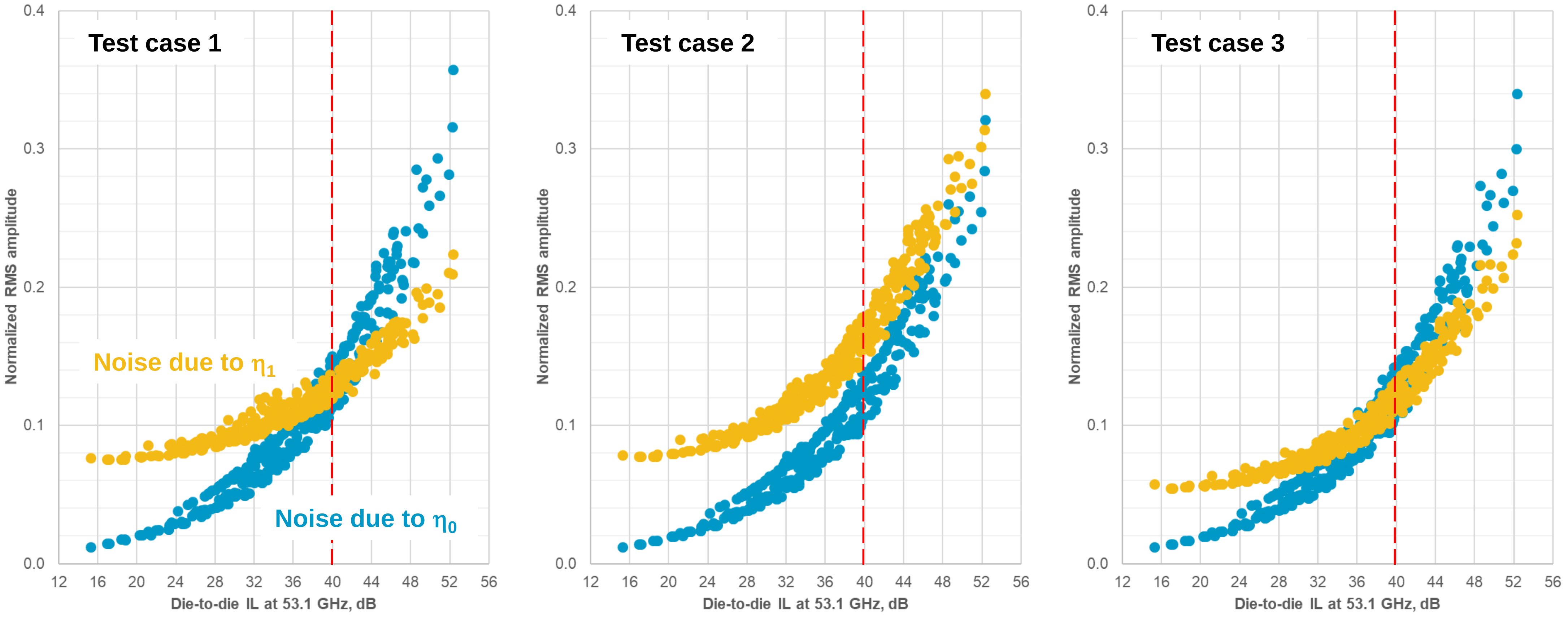




- Refer to Appendix A for details on test cases and COM configuration
- COM reduction due to quantization noise is a function of ENOB and CTE capability
- Consumes the majority of the traditional 3 dB fixed noise allocation
- Various combinations of ENOB and CTE yield similar worst-case performance

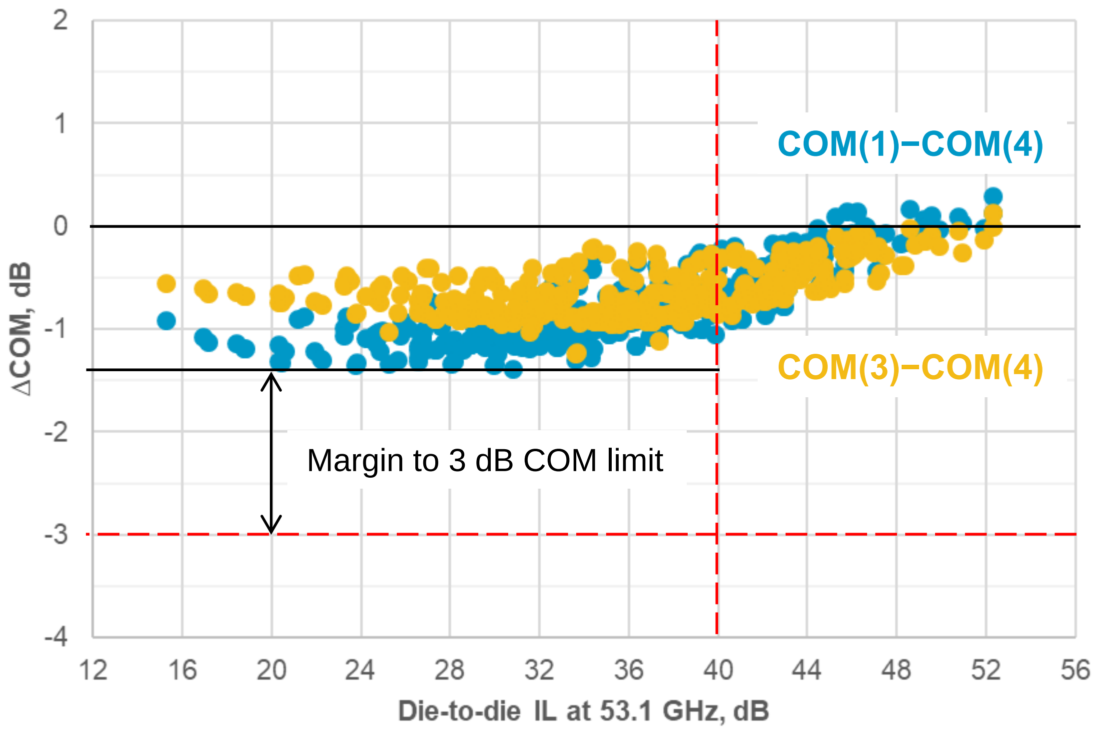
Test case	CTE	ENOB
0 (baseline)	Scaled CR/KR with g_{DC} = 0	Infinite
1	Scaled CR/KR	5.5
2	Scaled C2M	5.5
3	Scaled C2M	6

Composition of noise at the FFE output



- Noise at the FFE output due to η_1 increases with channel loss
- Low-loss asymptote related to choice of ENOB value

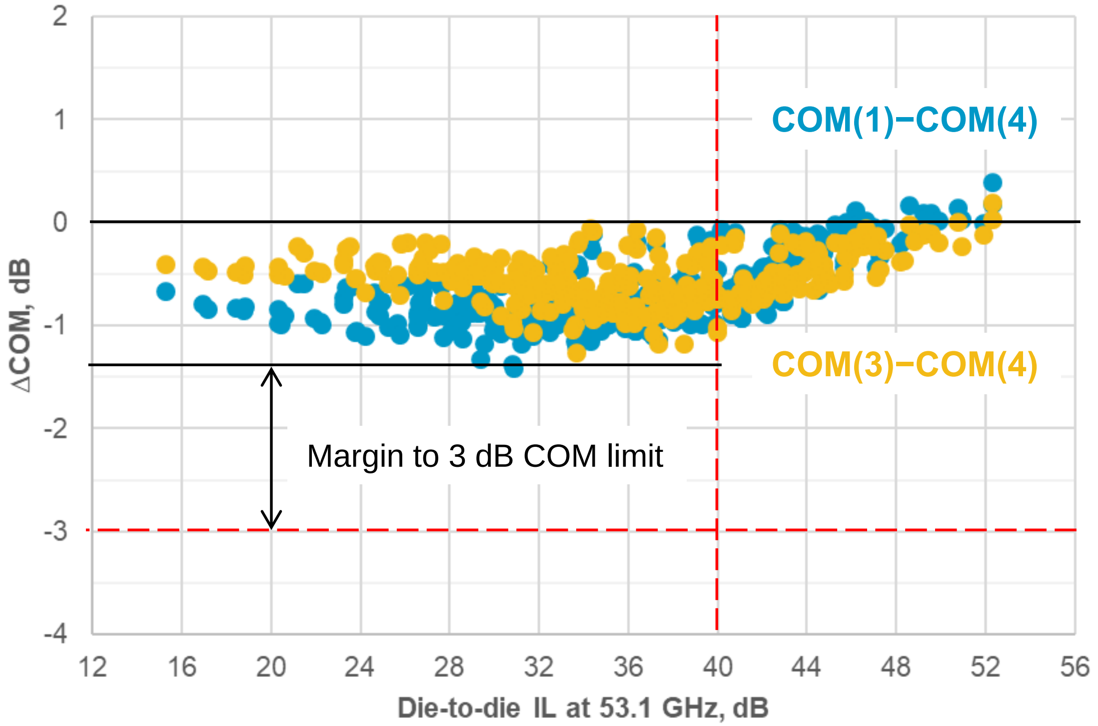
Is an additional noise term needed?



- Signature of quantization noise at FFE output suggests two components to its impact
- Channel-dependent or loss-dependent impact
- Channel-independent impact
- Components can be mapped into the original noise budget parameters
- Example comparing results with increased η_0 to results including η_1 is shown
- ΔCOM < 0 suggests that a portion of the fixed (channel-independent) budget is being used

Test case	CTE	η_0, V^2/GHz	ENOB
1	Scaled CR/KR	6e−9	5.5
3	Scaled C2M	6e−9	6
4	Scaled CR/KR with g_{DC} = 0	10e−9	Infinite

Impact on the prediction of MLSD performance



- Results updated using equation set U1.c from shakiba_3dj_01b_2401
- Similar trends observed
- Suggests original noise budget methodology could be applied here as well

Test case	CTE	η_0, V²/GHz	ENOB
1	Scaled CR/KR	6e−9	5.5
3	Scaled C2M	6e−9	6
4	Scaled CR/KR with g_{DC} = 0	10e−9	Infinite

One way to account for quantization noise

- COM includes two parameters that can be used to allocate a noise budget for compliant receiver implementations
- It has been shown that ADC quantization noise can consume an outsized portion of the budget for channels approaching the 40 dB loss limit
- As a result, the values for these noise budget parameters must be chosen carefully
- An increase in the value of η_0 is warranted to mimic the dependence of the quantization noise penalty on channel loss
- There is also a penalty “floor” that needs to be considered in the minimum COM limit
- High-frequency equalization can be removed from the CTE (and done by the FFE) reducing COM calculation complexity and time

Another way to account for quantization noise

- It has been suggested that a new parameter be added to the noise budget to account for the impact of quantization noise
- This would create a specific “signature” for the penalty due to quantization noise based on the values chosen for CTE parameters, ENOB, etc.
- Implementations may not exhibit this specific signature
- The result could still be used as a lower bound on performance
- The additional noise source will require a search loop to optimize the CTE high-frequency equalization adding to the COM calculation time
- Parameters of the CTE high-frequency equalization capability will need to be discussed and agreed upon

The bottom line...

- Impact of quantization noise should be addressed in the COM calculation
- Either approach to this problem could be used
- COM can represent a specific signature for the quantization noise penalty at the expense of computation complexity and time
- Keep in mind that the goal for COM should be to provide a lower bound on performance that is applicable to multiple implementations
- It is necessary to decide which approach to take in order achieve closure on the COM calculation and COM parameter values

Appendix A

COM test cases and configuration

Test case definition (133 x 3 = 399 test cases)

KR channel source files	Number of cases
shanbhag_3dj_02_2305	4
weaver_3dj_02_2305	36
weaver_3dj_elec_01_230622	4
mellitz_3dj_02_elec_230504	27
mellitz_3dj_03_elec_230504	25
akinwale_3dj_01_2310	7
Total	103

CR channel source files	Number of cases
shanbhag_3dj_01_2305	6
kocsis_3dj_02_2305	5
lim_3dj_03_230629	1
lim_3dj_04_230629	1
lim_3dj_07_2309	1
akinwale_3dj_02_2311	4
weaver_3dj_02_2311	12
Total	30

Parameter	Model A1	Model A2	Model B	Units	Information
package_tl_gamma0_a1_a2	[5e−4, 8.9e−4, 2e−4]		[5e−4, 6.5e−4, 3e−4]	var.	
package_tl_tau	6.141e−3		6.141e−3	ns/mm	
package_Z_c	[87.5, 87.5; 92.5, 92.5]		[92, 92; 70, 70; 80, 80 ; 100, 100]	Ohm	[TX, RX]
z_p (TX)	[13; 1.8]	[34; 1.8]	[46; 1; 1; 0.05]	mm	
z_p (NEXT)	[13; 1.8]	[34; 1.8]	[46; 1; 1; 0.05]	mm	
z_p (FEXT)	[13; 1.8]	[34; 1.8]	[46; 1; 1; 0.05]	mm	
z_p (RX)	[11; 1.8]	[32; 1.8]	[44; 1; 1; 0.05]	mm	
C_p	[40e−6, 40e−6]			nF	[TX, RX]

COM configuration used for testing (not a proposal)

Parameter	Setting	Units	Information
L	4		
f_b	106.25	GBd	
M	32		
A_v	0.413	V	
A_fe	0.413	V	
A_ne	0.45	V	
T_r	0.004	ns	
R_0	50	Ohm	
R_d	[50, 50]	Ohm	[TX, RX]
C_d	[40e−6, 90e−6, 110e−6; 40e−6, 90e−6, 110e−6]	nF	[TX; RX]
L_s	[0.13, 0.15, 0.14; 0.13, 0.15, 0.14]	nH	[TX; RX]
C_b	[30e−6, 30e−6]	nF	[TX, RX]
SNR_TX	33	dB	
A_DD	0.02	UI	
sigma_RJ	0.01	UI	
eta_0	6e−9	V^2/GHz	
DER_0	2e−4		

- COM 4.50beta3 augmented to include...
- Quantization noise model
- Corrected implementation of equation U1.c from shakiba_3dj_01b_2401

COM configuration used for testing, continued

Parameter	Setting	Information
c(0)	1	
c(−1)	0	
c(−2)	0	
c(−3)	0	
c(−4)	0	
c(1)	0	
c(0)	1	

No TX FFE for now...

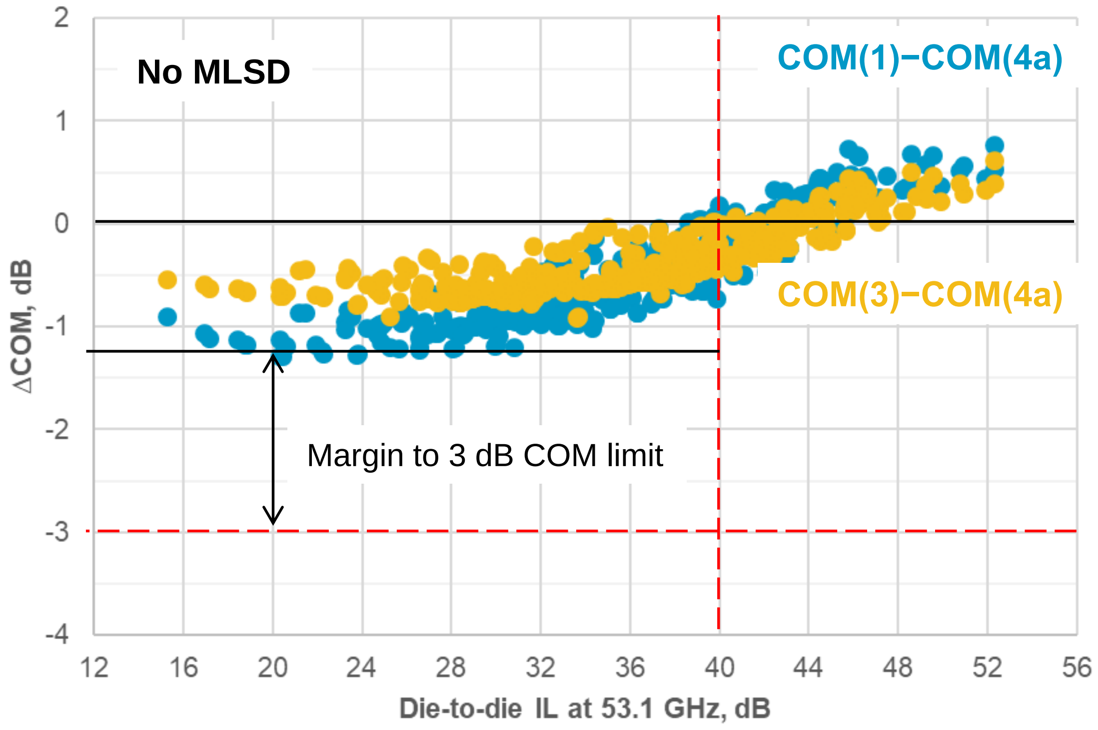
Parameter	Scaled CR/KR	Scaled C2M	Units	Information
f_r	0.58		*f_b	
g_DC	[−20:1:0]	[−11:1:0]	dB	[min:step:max]
f_z	42.5	25.16	GHz	
f_p1	42.5	40	GHz	
f_p2	106.25	56	GHz	
g_DC_HP	[−6:1:0]	[−3:0.5:0]	dB	[min:step:max]
f_HP_PZ	1.328125	2.65625	GHz	

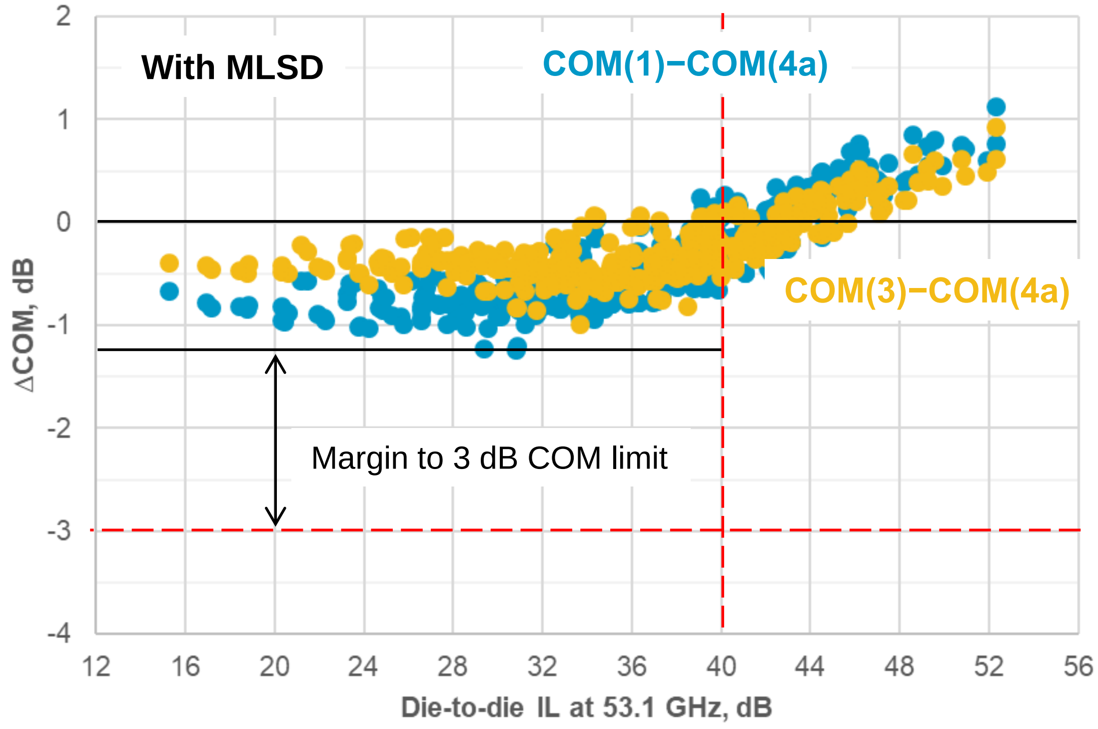
Parameter	Setting	Information
TS_SRCH_MODE	full-sweep	
ts_anchor	1	
sample_adjustment	[-32, 16]	
ffe_pre_tap_len	5	
ffe_post_tap_len	10	
ffe_pre_tap1_max	1	
ffe_post_tap1_max	1	
ffe_tapn_max	1	
N_g	1	Number of floating tap groups
N_f	4	Taps per group
N_max	60	Maximum floating tap index
N_tail_start	11	Earliest floating tap position
N_b	1	
b_max(1)	0.85	
b_min(1)	0	
MLSE	0 or 3	No MLSE or Equation U1.c

Appendix B

Additional simulation results

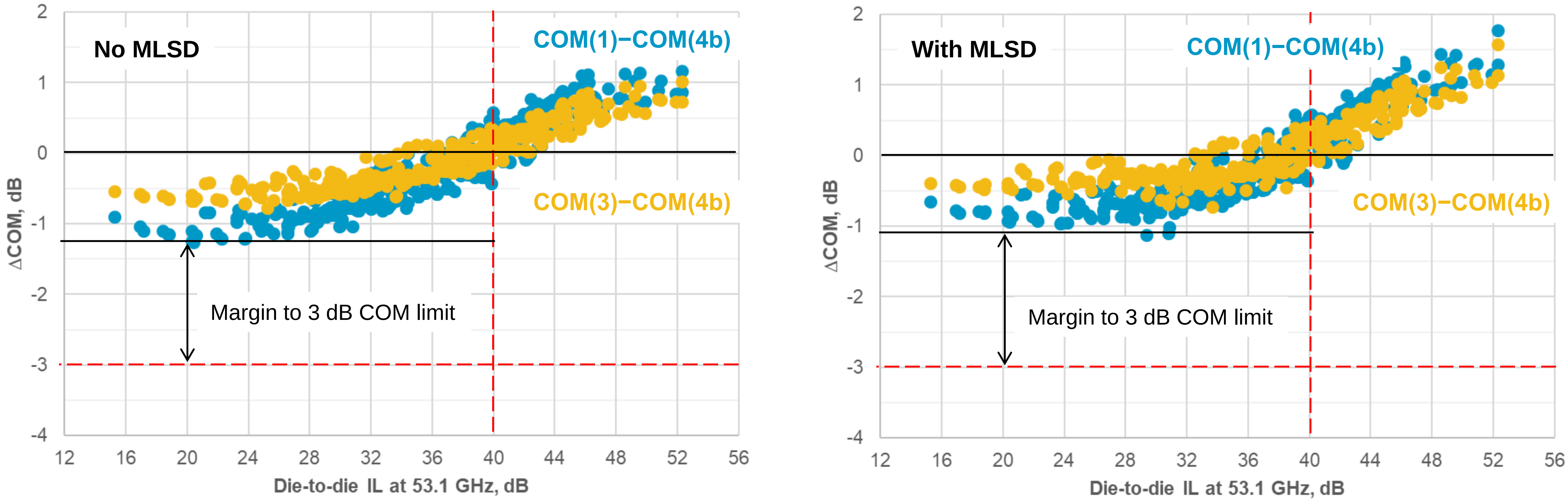
Compare η_0 = 12e−9 V^2/GHz to models including η_1





Test case	CTE	η_0, V^2/GHz	ENOB
1	Scaled CR/KR	6e−9	5.5
3	Scaled C2M	6e−9	6
4a	Scaled CR/KR with g_{DC} = 0	12e−9	Infinite

Compare η_0 = 14e−9 V²/GHz to models including η_1



Test case	CTE	η_0, V²/GHz	ENOB
1	Scaled CR/KR	6e−9	5.5
3	Scaled C2M	6e−9	6
4b	Scaled CR/KR with g_{DC} = 0	14e−9	Infinite