Comment #241:
BER margin of COM 3dB

Yasuo Hidaka
Fujitsu Laboratories of America, Inc.

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Comment #241

CI **110**   SC **110.10.7**   P **154**   L **2**   # 241

Hidaka, Yasuo   Fujitsu Lab. of Americ

Comment Type   **T**   *Comment Status*   **D**   *Late*

The criteria of COM value to be 3dB reserves too high margin.

Simulation result indicates the following:
When COM is 3dB with DER0=1E-12, BER is < 1E-66.
When COM is 3dB with DER0=1E-6, BER is < 1E-18.
When COM is 3dB with DER0=1E-5, BER is < 1E-13.
When COM is 3dB with DER0=3E-4, BER is < 1E-8.

We should not reserve so high margin for COM.

SuggestedRemedy

Change the COM criteria for the channel as "greater than or equal to 1dB".

Proposed Response   *Response Status*   **O**

Abstract

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- I was optimistic when I submitted comment #241, but I was very curious how much actual margin we have with COM 3dB

- So, I conducted an experiment by simulation to correlate COM and BER values, because our final interest of interoperability is always whether BER is sufficiently low or not

- I also analyzed error variation of COM values which cannot be explained by any factor in the experiment

- As a result, I concluded that COM 3dB has plenty of margin
  - I also derived recommended dB values of COM criteria

IEEE P802.3by 25 Gb/s Ethernet Task Force

Statistical Study on COM and BER

- **Methodology of Study**
  - DoE (Design of Experiment) was done to define simulation conditions
  - ANOVA (Analysis of Variance) was used to analyze variation of COM value
  - RA (Regression Analysis) was used to fit COM value as a function of BER
    - Three terms of log10(BER), sqrt(-log10(BER)), and constant are used in RA
  - Results of RA and ANOVA are added together using t-distribution
- **Simulation conditions: COM 768 conditions, BER 384 conditions**
  - 96 different channel settings
    - 6 different channel data x 16 different COM parameters
  - 8 different only COM settings
    - 4 different DER_0 settings x 2 different COM implementations
  - 4 different only BER settings
    - 4 different jitter levels
- **Equalizer parameters**
  - Always optimized by reference COM implementation
  - Shared with calculation of BER and our COM value

DoE (Design of Experiment) of Sim Conditions

- **Internal factors of DoE**
  - fp1
  - Zp (PKG transmission line length)
  - SNR_{TX}
  - Zc (PCB impedance)
  - Rd (Termination resistance)
- **External factors of DoE**
  - Cable length : 2 levels
    - 3m and 5m
  - Cable quality : 3 levels
    - fair (3m B(30Q4), 5m Q(24QQ))
    - typical (3m G(26QQ), 5m N(26QQ))
    - good (3m H(26Q4), 5m R(24QQ))
- **External factors of DoE for COM**
  - COM implementation : 2 levels
    - reference implementation
    - our implementation
  - DER_0 : 4 levels
    - 1E-12, 1E-8, 1E-5, 1E-15
- **External factor of DoE for BER**
  - Injected jitter : 4 levels (next page)

Orthogonal Array L16(2^{15})

column	1	2	4	7	8
row	fp1	Zp	SNR_{TX}	Zc	Rd
1	fb/4	12mm (test1)	27dB	109.8Ω	55Ω
2					45Ω
3			31dB	91.1Ω	55Ω
4					45Ω
5		30mm (test2)	27dB		55Ω
6					45Ω
7			31dB	109.8Ω	55Ω
8					45Ω
9	fb/15	12mm (test1)	27dB	91.1Ω	55Ω
10					45Ω
11			31dB	109.8Ω	55Ω
12					45Ω
13		30mm (test2)	27dB		55Ω
14					45Ω
15			31dB	91.1Ω	55Ω
16					45Ω

Jitter and Other Simulation Conditions

■ Jitter injected in BER analysis was varied for 4 levels in the following conditions:

Label		J1	J2	J3	J4	Unit
Description		Same jitter as COM	Only Tx Spec (no Rx) jitter	Rx jitter half of Tx Spec	Same Rx jitter as Tx Spec	Unit
TX	RJ	0.01	0.01	0.01	0.01	UI rms
	DJ	0.10	0.10	0.10	0.10	UI δ-δ
	EOJ	0.00	0.035	0.035	0.035	UI p-p
RX	RJ	0.00	0.00	0.005	0.01	UI rms
	DJ	0.00	0.00	0.05	0.10	UI δ-δ
	EOJ	0.00	0.00	0.0175	0.035	UI p-p

■ Other simulation conditions (same as standard COM except bmax)
  ■ bmax = 1.0 (To avoid problems with bmax < 1)
  ■ TX output noise SNR_{TX} = 27 (dB)
  ■ RX input noise η_0 = 5.20E-8 (V^2/GHz)
  ■ Receiver 3dB bandwidth = 0.75 (fb)
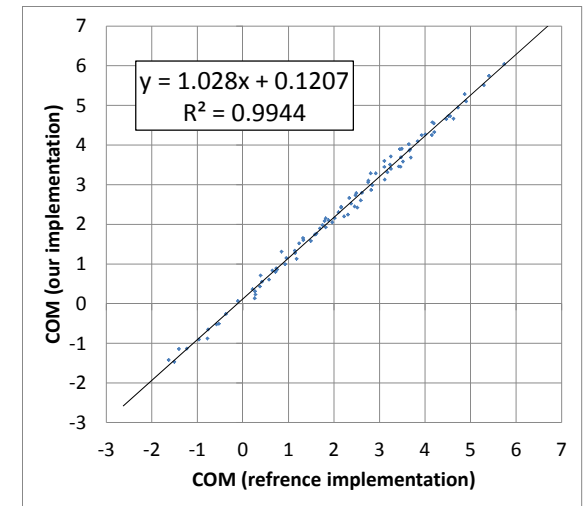
ANOVA (Analysis of Variance) of COM

	Factor	Degree of freedom	Variation	Variance	Variance ratio	F test result	Pure Variation	Degree of contribution	Standard deviation
		f	S	V	F0		S'	ρ	σ
A	fp1	1	583.627	583.627	7874.33	100.00% **	583.5528	12.32%	0.872253
B	case	1	147.7597	147.7597	1993.58	100.00% **	147.6856	3.12%	0.438805
C	SNRTX	1	48.65585	48.65585	656.468	100.00% **	48.58173	1.03%	0.251674
D	Zc	1	15.16591	15.16591	204.619	100.00% **	15.09179	0.32%	0.140273
E	Rd	1	17.80331	17.80331	240.203	100.00% **	17.72919	0.37%	0.152036
F	implementation	1	5.406469	5.406469	72.9444	100.00% **	5.332351	0.11%	0.08338
G	length	1	974.2709	974.2709	13144.9	100.00% **	974.1968	20.57%	1.127005
H3	cable quality (3m)	2	194.9022	97.45112	1314.82	100.00% **	194.754	4.11%	0.503901
H5	cable quality (5m)	2	199.811	99.9055	1347.93	100.00% **	199.6628	4.22%	0.510212
J	DER_0	3	2493.477	831.1589	11214	100.00% **	2493.254	52.64%	1.802958
e	error	753	55.8106	0.074118					
e'	error+insignificant	753	55.8106	0.074118			56.84825	1.20%	0.272246
e*	error+insig.+impl.	754	61.21707	0.08119			62.27254	1.31%	0.284938
T	Total	767	4736.69	6.175606			4736.69	100.00%	

$y = 1.0064x + 0.1465$
$R^2 = 0.9968$

COM (our implementation) vs COM (refrence implementation)

- **Random error of COM was estimated by ANOVA in order to exclude the effects of statistically significant factors**
  - All factors in DoE are significant and are excluded in random error e'
  - Although the effect of implementation is rather small (0.11%, one tenth of random error e), it is significant in statistical sense
    - The effect of implementation is included in random error e*
- **Random error of COM plus the effect of implementation (e*) is estimated as 0.285 dB/σ (f=754)**
  - It is due to effects such as resolution of CTLE gain or Tx FIR coefficients
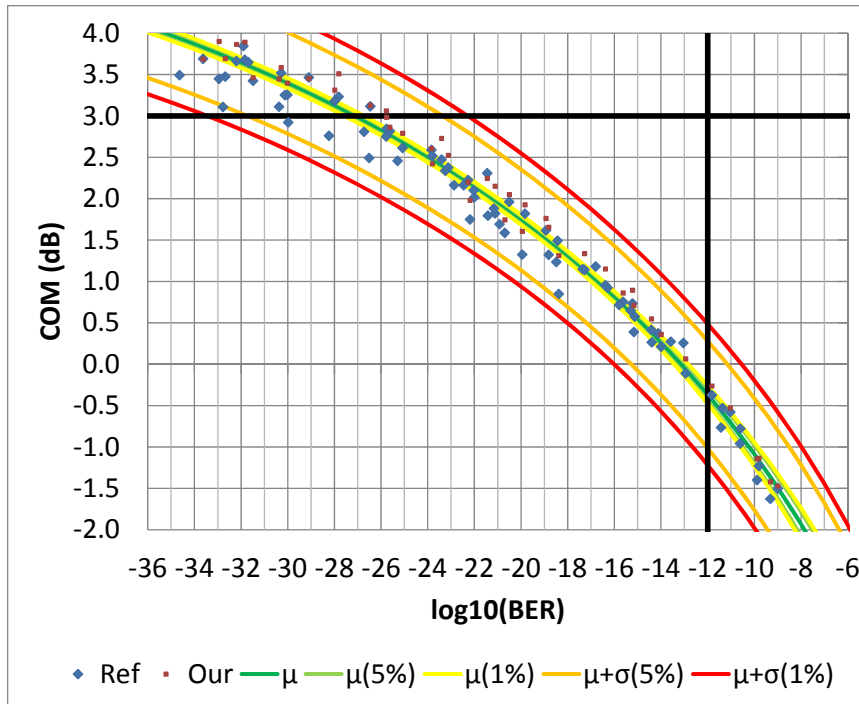
ANOVA of COM (DER0=1E-12)

	Factor	Degree of freedom	Variation	Variance	Variance ratio	F test result	Pure Variation	Degree of contribution	Standard deviation
		f	S	V	F0		S'	ρ	σ
A	fp1	1	150.4173	150.4173	2046.29	100.00% **	150.3438	25.48%	0.887209
B	case	1	39.23874	39.23874	533.806	100.00% **	39.16523	6.64%	0.452828
C	SNRTX	1	13.55506	13.55506	184.404	100.00% **	13.48155	2.29%	0.265677
D	Zc	1	3.952401	3.952401	53.7687	100.00% **	3.878893	0.66%	0.142507
E	Rd	1	4.671961	4.671961	63.5577	100.00% **	4.598453	0.78%	0.155163
F	implementation	1	1.579566	1.579566	21.4885	100.00% **	1.506059	0.26%	0.088798
G	length	1	258.6971	258.6971	3519.33	100.00% **	258.6236	43.84%	1.163637
H3	cable quality (3m)	2	52.5748	26.2874	357.616	100.00% **	52.42779	8.89%	0.523919
H5	cable quality (5m)	2	52.0719	26.03595	354.195	100.00% **	51.92488	8.80%	0.5214
J	DER_0	0							
e	error	180	13.23134	0.073507					
e'	error+insignificant	180	13.23134	0.073507			14.03992	2.38%	0.271123
e*	error+insig.+impl.	181	14.81091	0.081828			15.62919	2.65%	0.286056
T	Total	191	589.9902	3.088954			589.9902	100.00%	

Chart: $y = 1.028x + 0.1207$, $R^2 = 0.9944$
Axes: COM (our implementation) vs COM (refrence implementation)

- **Random error of COM for DER0=1E-12 is estimated by another ANOVA, because DER0 is most significant and our focus is DER0=1E-12**

- **Random error of COM plus the effect of implementation (e*) is estimated as 0.286 dB/σ (f=181)**
  - This is close to the overall random error

BER (J1) vs COM (DER0=1E-12)

BER	COM (μ)					COM (μ+σ)			
	E	-5%	+5%	-1%	+1%	-5%	+5%	-1%	+1%
1.0E-05	-3.551	-3.786	-3.316	-3.861	-3.241	-4.350	-2.752	-4.606	-2.496
1.0E-08	-1.930	-2.079	-1.781	-2.127	-1.733	-2.643	-1.217	-2.871	-0.989
1.0E-10	-1.086	-1.196	-0.975	-1.232	-0.940	-1.761	-0.411	-1.976	-0.195
1.0E-12	-0.365	-0.448	-0.282	-0.475	-0.256	-1.013	0.282	-1.219	0.489
1.0E-15	0.546	0.488	0.603	0.470	0.621	-0.076	1.167	-0.275	1.366
3.3E-34								3.000	
4.4E-30								2.500	
1.7E-32							3.000		
1.2E-28							2.500		
6.8E-28	3.000								
9.6E-25	2.500								
4.1E-24							3.000		
1.8E-21							2.500		
4.9E-23									3.000
1.6E-20									2.500

Best cases — Typical cases — Worst cases

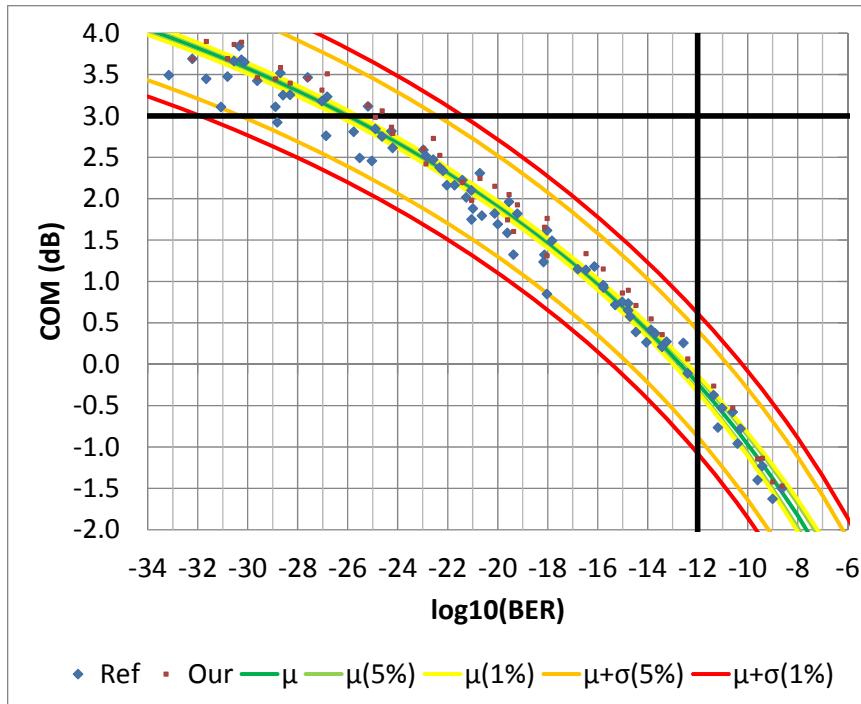◆ Ref · Our —μ —μ(5%) —μ(1%) —μ+σ(5%) —μ+σ(1%)

■ With same jitter as COM (J1)

■ Mean COM for BER=1E-12 is -0.365dB (expected value)

- If COM and BER are consistent, this is supposed to be 0dB
  - The difference is statistically significant; 99% confidence interval is [-0.475, -0.256] dB
- If the inconsistency is resolved, COM for the same BER goes up by ~0.365dB
  - This is regardless of whether COM is fixed or BER is fixed

■ If COM is 3.0dB, worst-case BER is 4.9E-23 (99% confidence limit)
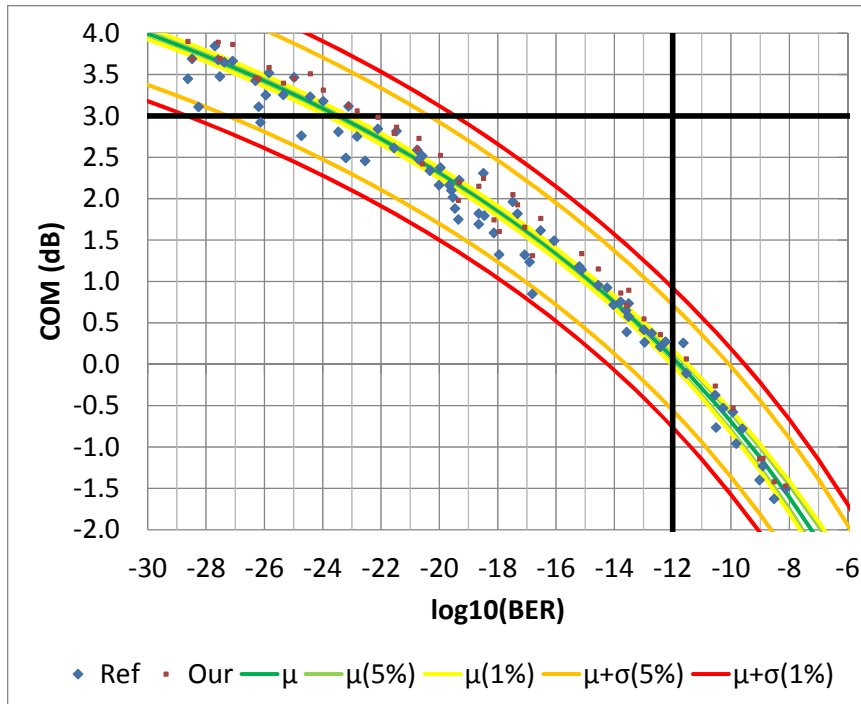
BER (J2) vs COM (DER0=1E-12)

COM (dB) vs log10(BER)

Ref · Our —μ —μ(5%) —μ(1%) —μ+σ(5%) —μ+σ(1%)

BER	COM (μ)					COM (μ+σ)			
	E	-5%	+5%	-1%	+1%	-5%	+5%	-1%	+1%
1.0E-05	-3.483	-3.719	-3.247	-3.795	-3.171	-4.283	-2.682	-4.539	-2.426
1.0E-08	-1.827	-1.973	-1.680	-2.020	-1.633	-2.538	-1.116	-2.765	-0.888
1.0E-10	-0.966	-1.073	-0.858	-1.107	-0.824	-1.637	-0.294	-1.852	-0.079
1.0E-12	-0.232	-0.311	-0.152	-0.337	-0.127	-0.876	0.412	-1.082	0.618
1.0E-15	0.694	0.639	0.750	0.621	0.767	0.075	1.314	-0.123	1.512
1.2E-32								3.000	
8.6E-29								2.500	
4.7E-31							3.000		
1.8E-27							2.500		
9.9E-27	3.000								
9.2E-24	2.500								
3.7E-23						3.000			
1.2E-20						2.500			
3.8E-22									3.000
9.4E-20									2.500

Best cases (1.2E-32 to 1.8E-27)
Typical cases (9.9E-27 to 9.2E-24)
Worst cases (3.7E-23 to 9.4E-20)

■ **With Tx spec (no Rx) jitter (J2)**

  ■ If COM is 3.0dB, worst-case BER is 3.8E-22 (99% confidence)

    • If COM is 2.5dB, worst-case BER is 9.4E-20, degraded by a factor of 247

  ■ In comparison to J1, BER is a little (one order of magnitude) degraded due to additional jitter of TX EOJ = 0.035U
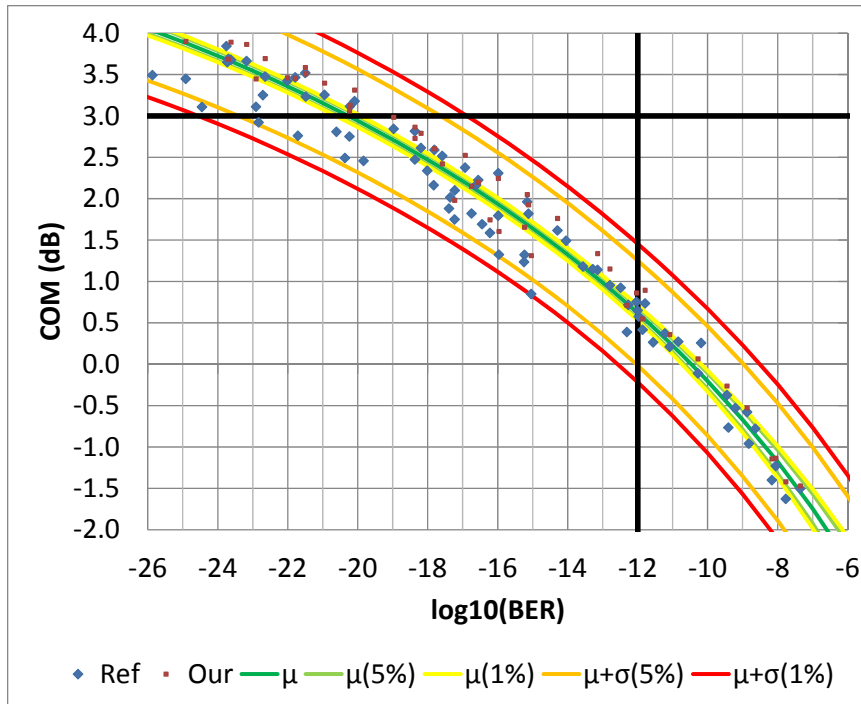
BER	COM (μ)					COM (μ+σ)			
	E	-5%	+5%	-1%	+1%	-5%	+5%	-1%	+1%
1.0E-05	-3.368	-3.616	-3.120	-3.696	-3.041	-4.181	-2.556	-4.440	-2.296
1.0E-08	-1.603	-1.749	-1.458	-1.796	-1.411	-2.314	-0.893	-2.541	-0.666
1.0E-10	-0.692	-0.794	-0.589	-0.827	-0.556	-1.358	-0.025	-1.572	0.189
1.0E-12	0.082	0.008	0.156	-0.016	0.179	-0.557	0.720	-0.761	0.924
1.0E-15	1.052	0.998	1.105	0.981	1.122	0.434	1.669	0.237	1.866
2.1E-29									3.000
4.7E-26									2.500
5.2E-28							3.000		
6.8E-25							2.500		
3.0E-24	3.000								
1.2E-21	2.500								
4.2E-21							3.000		
6.7E-19							2.500		
3.3E-20									3.000
4.1E-18									2.500

Best cases — Typical cases — Worst cases

■ **With Rx jitter half of Tx spec (J3)**

■ If COM is 3.0dB, worst-case BER is 3.3E-20 (99% confidence)
  - If COM is 2.5dB, worst-case BER is 4.1E-18, degraded by a factor of 126
  - Typical-case BER is 3.0E-24 (COM 3.0dB) or 1.2E-21 (COM 2.5dB)

■ Worst-case BER <1E-12 (99% confidence) is satisfied if COM >0.924dB
  - Worst-case BER <1E-15 (99% confidence) is satisfied if COM >1.866dB

BER (J4) vs COM (DER0=1E-12)

BER	COM (μ)					COM (μ+σ)			
	E	-5%	+5%	-1%	+1%	-5%	+5%	-1%	+1%
1.0E-05	-3.090	-3.360	-2.819	-3.447	-2.732	-3.925	-2.254	-4.192	-1.987
1.0E-08	-1.179	-1.324	-1.034	-1.370	-0.987	-1.888	-0.469	-2.115	-0.243
1.0E-10	-0.201	-0.297	-0.105	-0.328	-0.074	-0.862	0.460	-1.073	0.671
1.0E-12	0.621	0.552	0.690	0.530	0.712	-0.013	1.254	-0.215	1.457
1.0E-15	1.641	1.584	1.698	1.566	1.717	1.019	2.263	0.821	2.461
2.5E-25									3.000
1.4E-22					Best cases				2.500
3.6E-24							3.000		
1.3E-21							2.500		
5.0E-21	3.000				Typical cases				
7.0E-19	2.500								
2.1E-18						3.000			
1.5E-16					Worst cases	2.500			
1.2E-17									3.000
6.9E-16									2.500

- Ref · Our —μ —μ(5%) —μ(1%) —μ+σ(5%) —μ+σ(1%)

- **With same Rx jitter as Tx spec (J4)**
  - If COM is 3.0dB, worst-case BER is 1.2E-17 (99% confidence)
    - If COM is 2.5dB, worst-case BER is 6.9E-16, degraded by a factor of 56
    - Typical-case BER is 5.0E-21 (COM 3.0dB) or 7.0E-19 (COM 2.5dB)
  - Worst-case BER <1E-12 (99% confidence) is satisfied if COM >1.457dB
    - Worst-case BER <1E-15 (99% confidence) is satisfied if COM >2.461dB

Rx Internal Performance Factors

- **Rx jitter is usually smaller than Tx jitter**
  - Because Rx does not have to drive transmission line

- **However, Rx jitter of this simulation represents all Rx internal performance factors in actual Rx implementation**
  - Example
    - Rx jitter
    - Resolution of DFE coefficients
    - Resolution of offset cancel
    - Accuracy of adaptive control of equalizer coefficients
    - Actual number of DFE taps
  - All of them are implementer's choice and not included in COM parameter
  - Among them Rx jitter is usually critical, because it is usually possible to improve other factors as much as required by design except Rx jitter

- **Hence, J4 (same Rx jitter as Tx spec) is considered more or less actual condition**

Summary

- **With same Rx jitter as Tx spec (J4)**
  - Worst-case BER is 1E-12 (99% confidence), when COM is 1.457dB
    - Worst-case BER is 1E-15 (99% confidence), when COM is 2.461dB
- **With same Rx jitter as COM (J1)**
  - Typical-case BER is 1E-12, when COM is -0.365dB
    - This is supposed to be 0dB, if COM and BER are consistent
    - If this inconsistency is fixed, COM for the same BER goes up by about 0.365dB, regardless of whether COM is fixed or BER is fixed
- **Assuming the inconsistency is fixed, with same Rx jitter as Tx spec (J4)**
  - Worst-case BER is 1E-12 (99% confidence), when COM is 1.822dB
  - Worst-case BER is 1E-15 (99% confidence), when COM is 2.826dB
- **Revised COM criteria (for no-FEC mode)**
  - Option 1 (change of text in slide 14):
    - Change COM 3dB criteria to 1.83dB to guarantee the worst-case BER < 1E-12
    - Test Rx for BER < 1E-12 without restriction of DFE coefficients
    - Add precoding to meet the MTTFPA requirement
  - Option 2 (change of text in slide 15):
    - Change COM 3dB criteria to 2.83dB to guarantee the worst-case BER < 1E-15
      - Keep DER0 as 1E-12
    - Test Rx for BER < 1E-15 to meet MTTFPA requirement

Change of Text (Comment #147,#241) Option 1

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- **Table 110-10**
  - Change statement before Table 110-10 as follows:
    - COM for any channel within the cable assembly shall be greater than or equal to ~~3dB~~ the value specified in the table for each test.
  - Add a row of COM values

	CA-N	CA-S	CA-L
COM	1.83dB	3dB	3dB

- **Table 110-7**
  - Change the value of COM (max) with 1.83 dB

- **Add precoding in all FEC modes (no FEC, BASE-R FEC, RS FEC modes) as outlined in slide 12 of hidaka_3by_02_0915**

Change of Text (Comment #147,#241) Option 2

- **Table 110-10**
  - Change statement before Table 110-10 as follows:
    - COM for any channel within the cable assembly shall be greater than or equal to ~~3dB~~ the value specified in the table for each test.
  - Add a row of COM values

	CA-N	CA-S	CA-L
COM	2.83dB	3dB	3dB

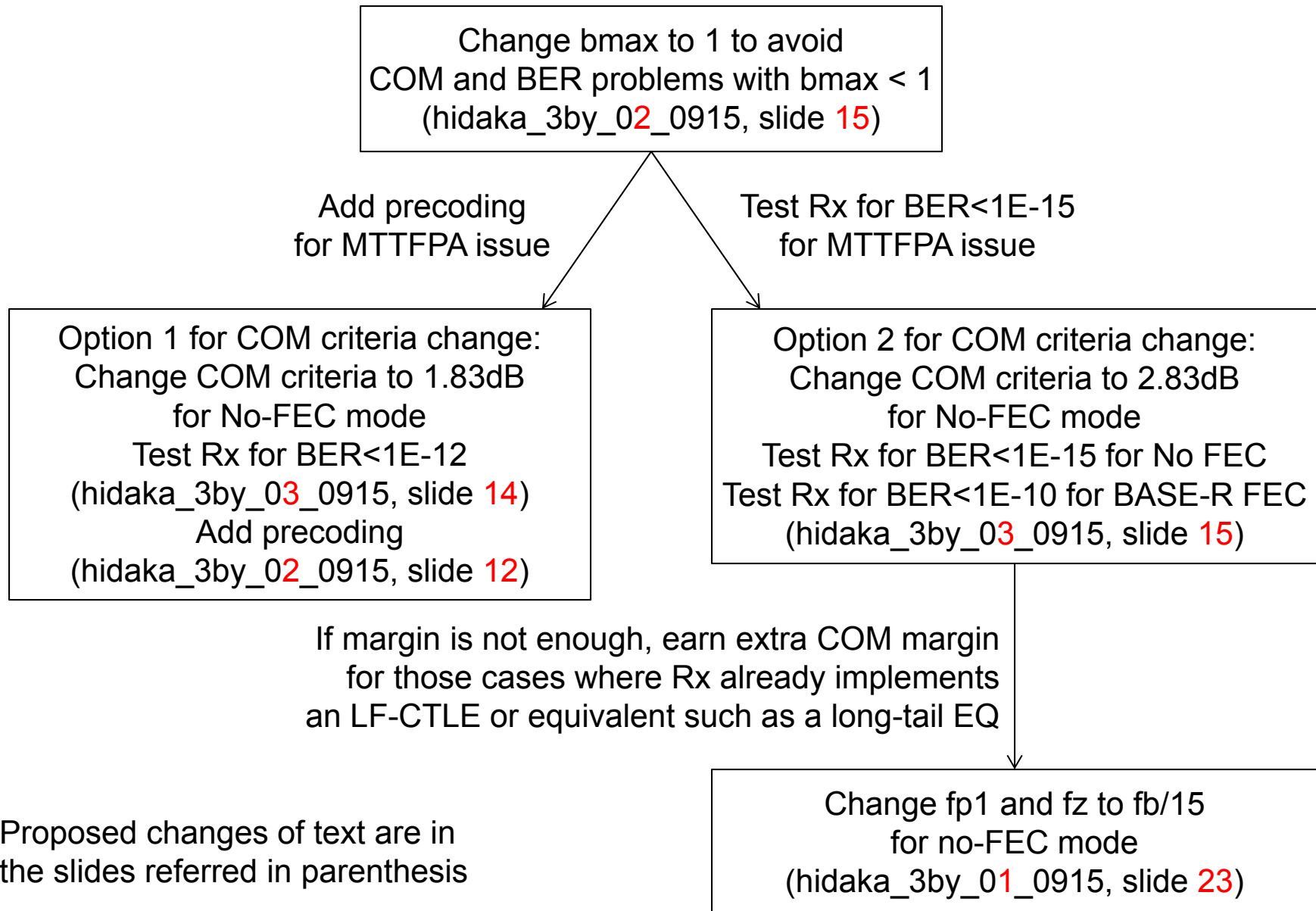 - Keep the values of DER0 same

- **Table 110-7**
  - Change the value of COM (max) with 2.83 dB
  - Change the value of bit error ratio required with $< 10^{-15}$
  - Keep the value of DER0 used in COM calculation as 10^{-12}

- **Table 110-6**
  - Change the value of BASE-R FEC block error ratio required with $< 2.1 \times 10^{-7}$
  - Keep the value of DER0 used in COM calculation as 10^{-8}

Relationship between Proposed Changes

Change bmax to 1 to avoid
COM and BER problems with bmax < 1
(hidaka_3by_02_0915, slide 15)

Add precoding
for MTTFPA issue

Test Rx for BER<1E-15
for MTTFPA issue

Option 1 for COM criteria change:
Change COM criteria to 1.83dB
for No-FEC mode
Test Rx for BER<1E-12
(hidaka_3by_03_0915, slide 14)
Add precoding
(hidaka_3by_02_0915, slide 12)

Option 2 for COM criteria change:
Change COM criteria to 2.83dB
for No-FEC mode
Test Rx for BER<1E-15 for No FEC
Test Rx for BER<1E-10 for BASE-R FEC
(hidaka_3by_03_0915, slide 15)

If margin is not enough, earn extra COM margin
for those cases where Rx already implements
an LF-CTLE or equivalent such as a long-tail EQ

Proposed changes of text are in
the slides referred in parenthesis

Change fp1 and fz to fb/15
for no-FEC mode
(hidaka_3by_01_0915, slide 23)

Appendix

Effect of Injected Jitter : RJ

- **Conditions**
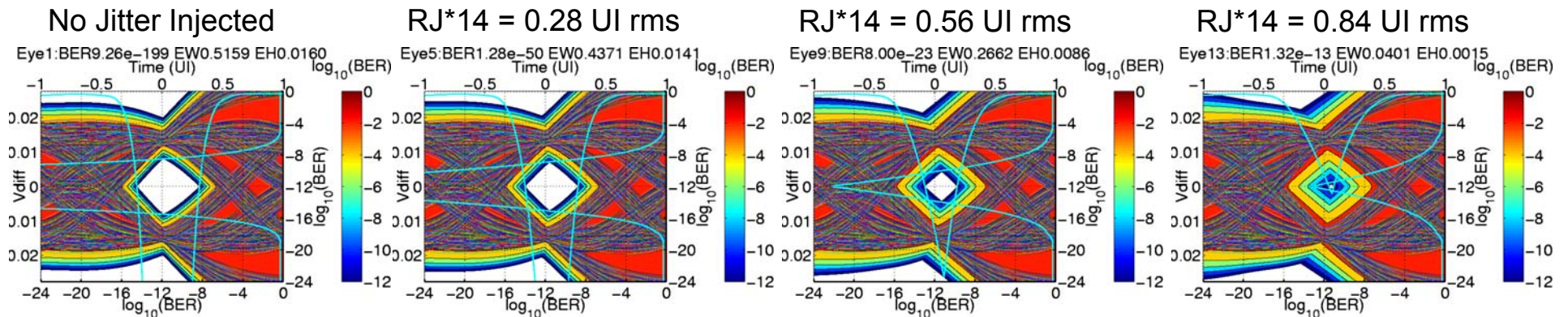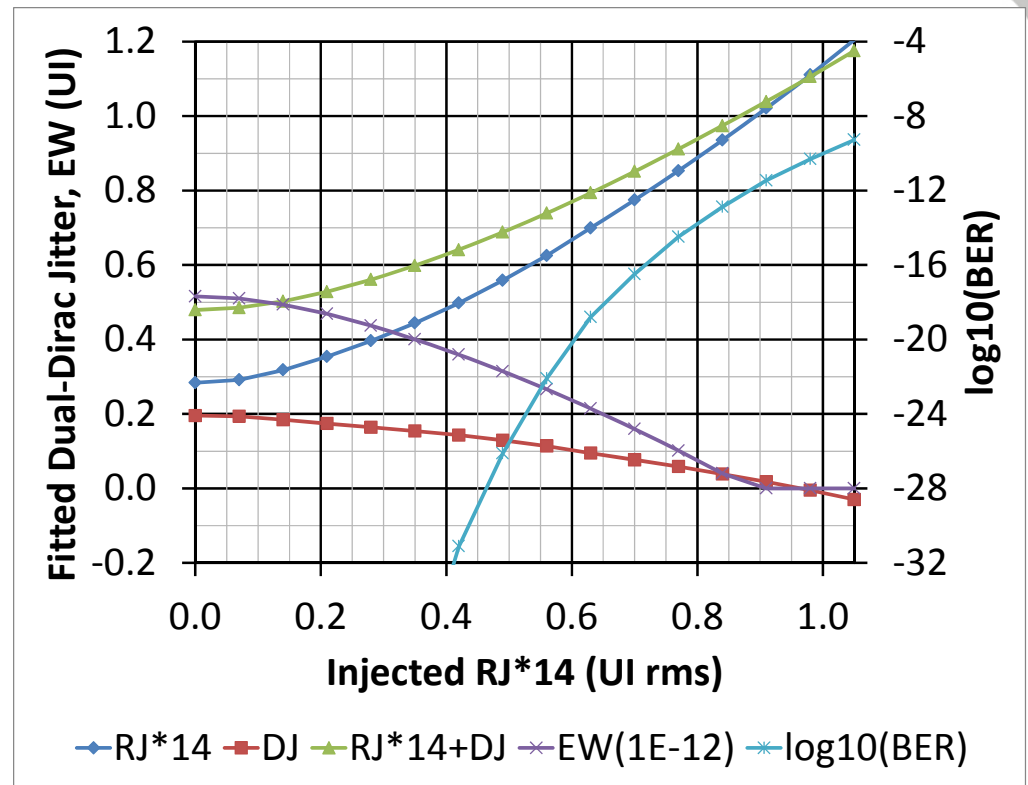 - **Channel and Equalizers**
    - Typ 3m G(26QQ) w/o crosstalk
    - 3-tap Tx FIR, 15-tap DFE
    - CTLE (fp1=fb/4)
  - **No additional noise**
    - SNRTX=∞, η_0 = 0
  - **Injected Jitter (Tx Only)**
    - RJ = 0 – 0.075 UI rms
      - Step 0.005 UI rms
    - DJ = 0 UI d-d
    - EOJ = 0 UI p-p

Plot legend: RJ*14 — DJ — RJ*14+DJ — EW(1E-12) — log10(BER)
Axes: Fitted Dual-Dirac Jitter, EW (UI) / log10(BER) vs Injected RJ*14 (UI rms)

No Jitter Injected — Eye1:BER9.26e–199 EW0.5159 EH0.0160

RJ*14 = 0.28 UI rms — Eye5:BER1.28e–50 EW0.4371 EH0.0141

RJ*14 = 0.56 UI rms — Eye9:BER8.00e–23 EW0.2662 EH0.0086

RJ*14 = 0.84 UI rms — Eye13:BER1.32e–13 EW0.0401 EH0.0015

Effect of Injected Jitter : DJ

- ■ Conditions
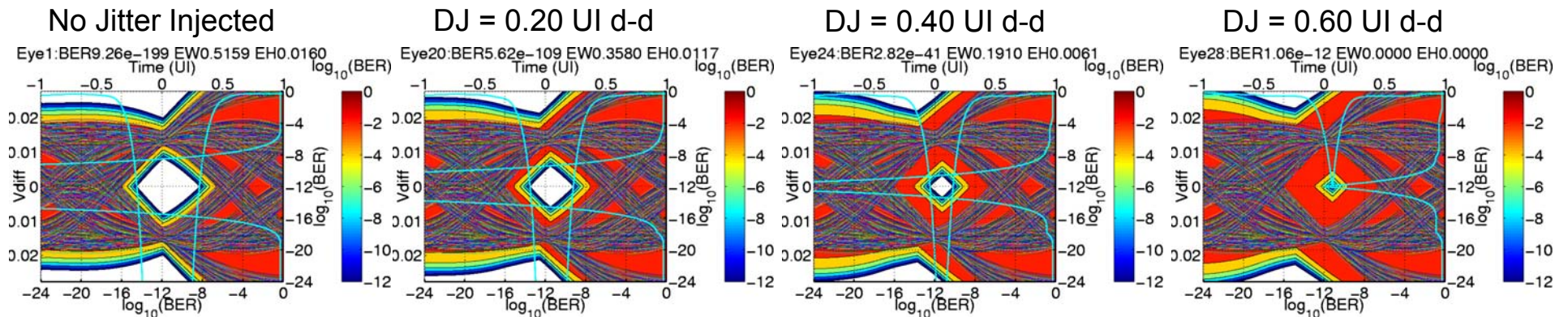 - ■ Channel and Equalizers
    - • Typ 3m G(26QQ) w/o crosstalk
    - • 3-tap Tx FIR, 15-tap DFE
    - • CTLE (fp1=fb/4)
  - ■ No additional noise
    - • SNRTX=∞, η_0 = 0
  - ■ Injected Jitter (Tx Only)
    - • RJ = 0 UI rms
    - • DJ = 0 – 0.75 UI d-d
      - • Step 0.05 UI d-d
    - • EOJ = 0 UI p-p

No Jitter Injected   DJ = 0.20 UI d-d   DJ = 0.40 UI d-d   DJ = 0.60 UI d-d

Eye1:BER9.26e−199 EW0.5159 EH0.0160

Eye20:BER5.62e−109 EW0.3580 EH0.0117

Eye24:BER2.82e−41 EW0.1910 EH0.0061

Eye28:BER1.06e−12 EW0.0000 EH0.0000

Effect of Injected Jitter : EOJ

- **Conditions**
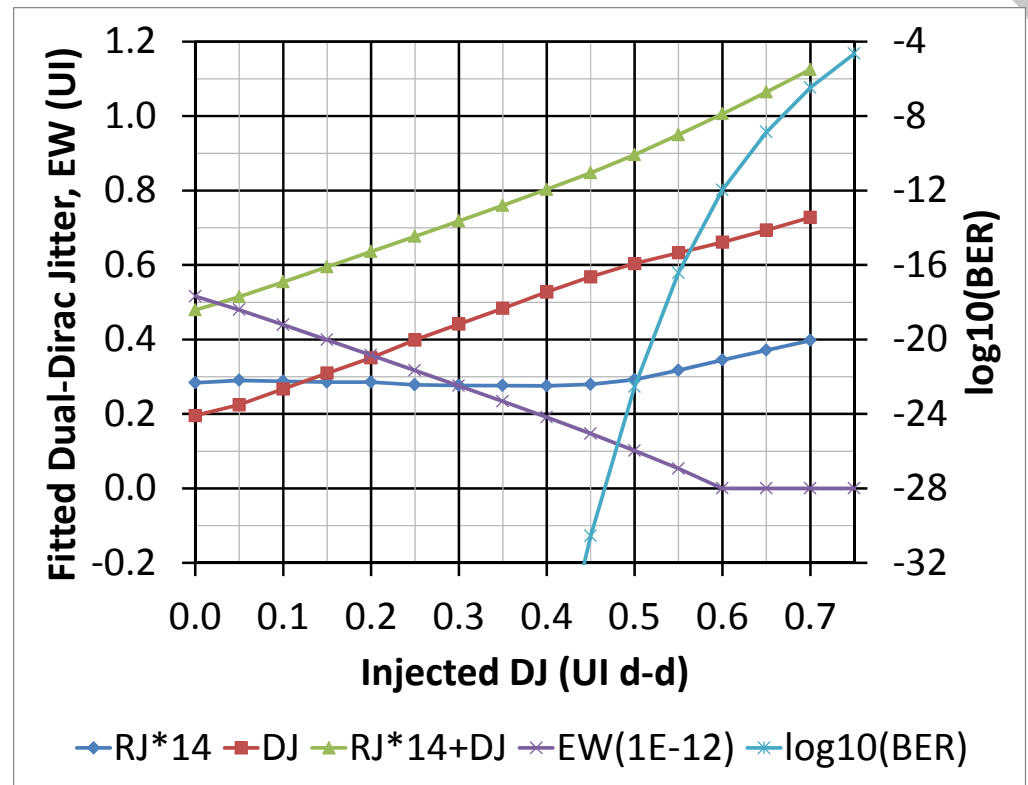 - **Channel and Equalizers**
    - Typ 3m G(26QQ) w/o crosstalk
    - 3-tap Tx FIR, 15-tap DFE
    - CTLE (fp1=fb/4)
  - **No additional noise**
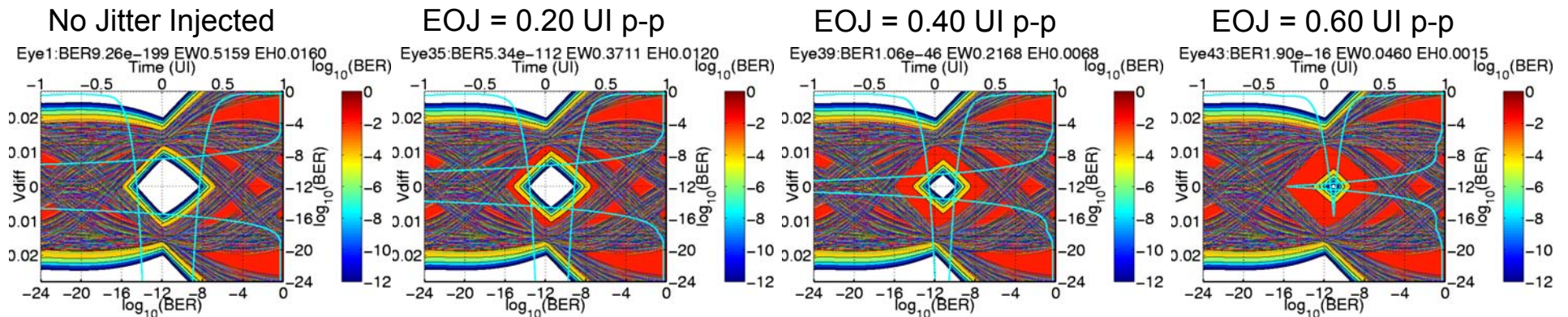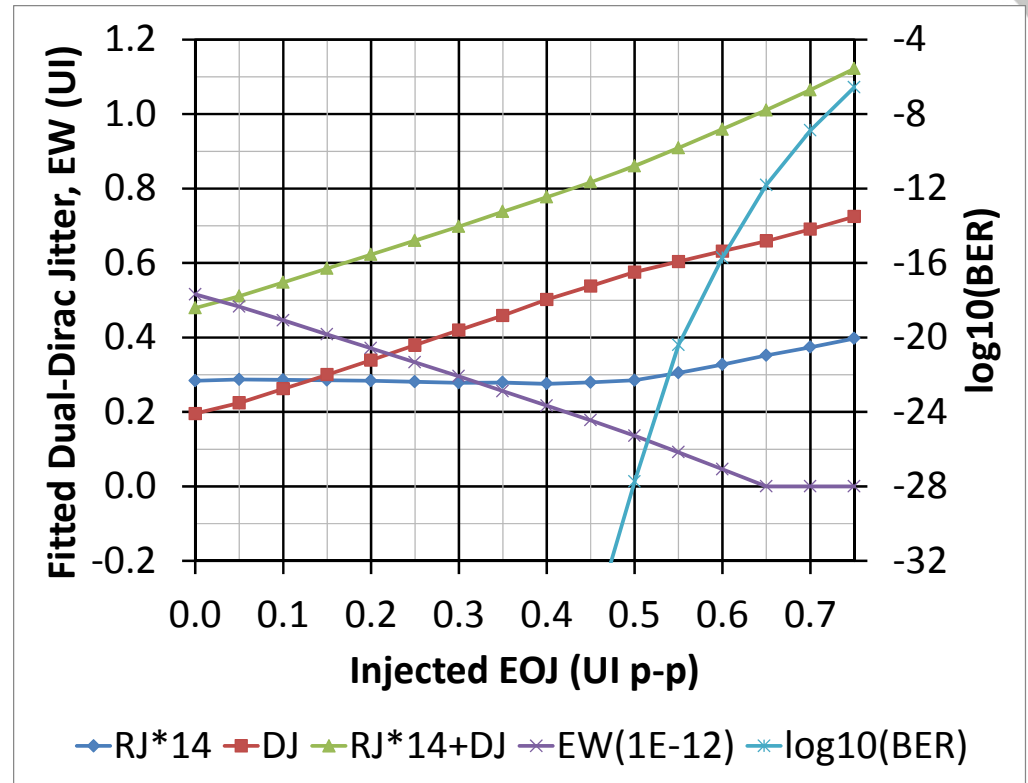   - SNRTX=∞, η_0 = 0
  - **Injected Jitter (Tx Only)**
    - RJ = 0 UI rms
    - DJ = 0 UI d-d
    - EOJ = 0 – 0.75 UI p-p
      - Step 0.05 UI p-p

No Jitter Injected   EOJ = 0.20 UI p-p   EOJ = 0.40 UI p-p   EOJ = 0.60 UI p-p

BER (J1) vs COM (DER0=1E-8)

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BER	COM (μ)					COM (μ+σ)			
	E	-5%	+5%	-1%	+1%	-5%	+5%	-1%	+1%
1.0E-05	-1.696	-1.926	-1.466	-2.000	-1.392	-2.475	-0.917	-2.724	-0.668
1.0E-08	-0.105	-0.251	0.041	-0.298	0.088	-0.800	0.590	-1.022	0.812
1.0E-10	0.721	0.613	0.830	0.578	0.865	0.064	1.379	-0.146	1.589
1.0E-12	1.425	1.344	1.506	1.318	1.532	0.795	2.055	0.594	2.257
1.0E-15	2.313	2.257	2.369	2.239	2.387	1.708	2.918	1.514	3.111
2.4E-22								3.000	
7.9E-20								2.500	
2.4E-21							3.000		
5.8E-19							2.500		
1.5E-18	3.000								
1.8E-16	2.500								
4.5E-16							3.000		
3.0E-14							2.500		
2.4E-15									3.000
1.5E-13									2.500

Best cases · Typical cases · Worst cases

Legend: ◆ Ref · Our ── μ ── μ(5%) ── μ(1%) ── μ+σ(5%) ── μ+σ(1%)
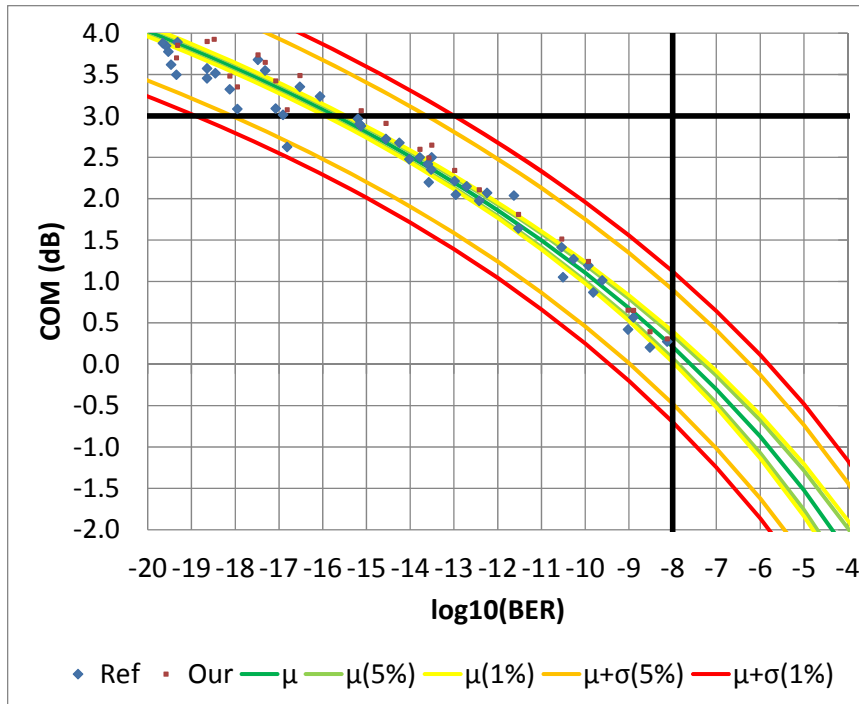
■ With same jitter as COM (J1)

- ■ Mean COM for BER=1E-8 is -0.105dB (expected value)
  - This difference is statistically insignificant, because it is within 95% confidence interval that is [-0.251, 0.041] dB
    - COM and BER are consistent when DER0=1E-8
- ■ If COM is 3.0dB, worst-case BER is 2.4E-15 (99% confidence limit)
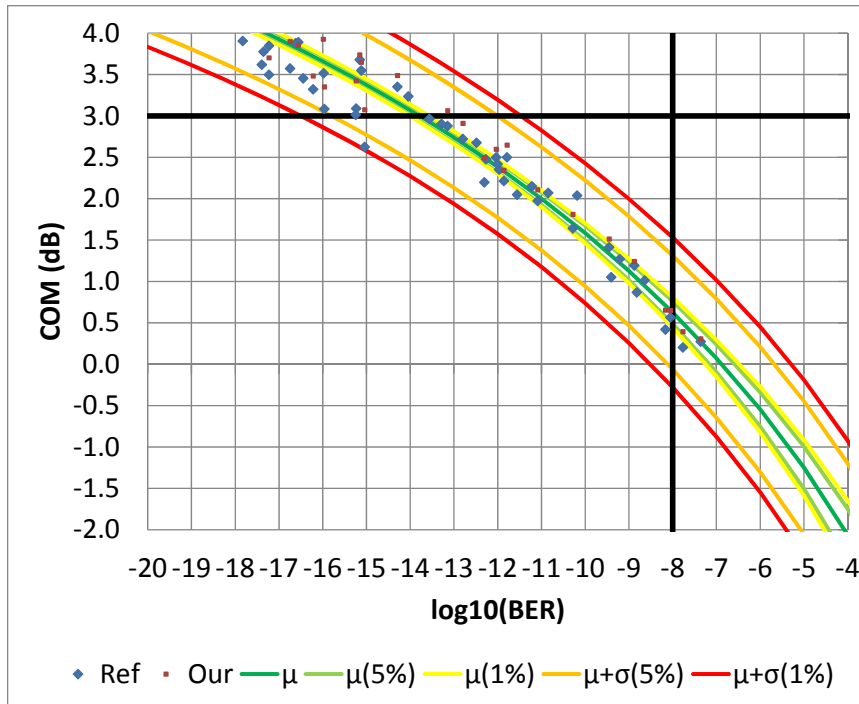
BER (J3) vs COM (DER0=1E-8)

BER	COM (μ)					COM (μ+σ)			
	E	-5%	+5%	-1%	+1%	-5%	+5%	-1%	+1%
1.0E-05	-1.520	-1.757	-1.282	-1.834	-1.206	-2.306	-0.733	-2.558	-0.482
1.0E-08	0.213	0.073	0.353	0.028	0.397	-0.476	0.902	-0.696	1.122
1.0E-10	1.106	1.007	1.204	0.976	1.235	0.458	1.753	0.251	1.960
1.0E-12	1.860	1.790	1.931	1.767	1.954	1.241	2.480	1.042	2.678
1.0E-15	2.804	2.753	2.855	2.737	2.872	2.204	3.404	2.013	3.596
1.2E-19									3.000
1.4E-17									2.500
7.9E-19							3.000		
7.8E-17							2.500		
1.8E-16	3.000								
1.0E-14	2.500								
2.2E-14								3.000	
8.0E-13								2.500	
9.5E-14									3.000
3.0E-12									2.500

Best cases — (1.2E-19, 1.4E-17, 7.9E-19, 7.8E-17)

Typical cases — (1.8E-16, 1.0E-14)

Worst cases — (2.2E-14, 8.0E-13, 9.5E-14, 3.0E-12)

- **With Rx jitter half of Tx spec (J3)**
  - If COM is 3.0dB, worst-case BER is 9.5E-14 (99% confidence)
    - If COM is 2.5dB, worst-case BER is 3.0E-12, degraded by a factor of 32
    - Typical-case BER is 1.8E-16 (COM 3.0dB) or 1.0E-14 (COM 2.5dB)
  - Worst-case BER < 1E-8 (99% confidence) is satisfied if COM > 1.122dB
    - Worst-case BER < 1E-10 (99% confidence) is satisfied if COM > 1.960dB
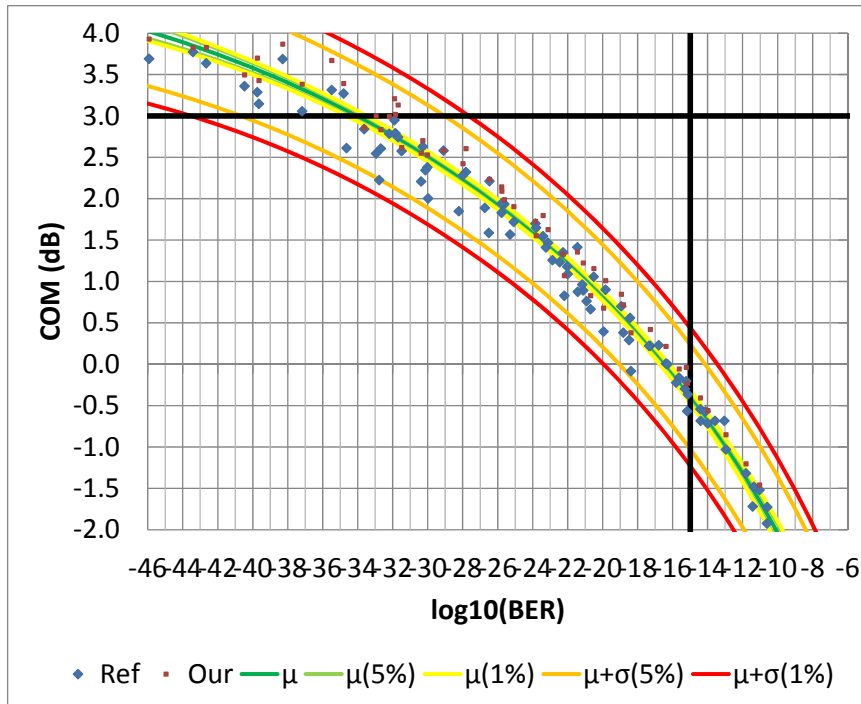 - COM 3dB has plenty of margin

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BER	COM (μ)					COM (μ+σ)			
	E	-5%	+5%	-1%	+1%	-5%	+5%	-1%	+1%
1.0E-05	-1.249	-1.503	-0.994	-1.585	-0.912	-2.052	-0.445	-2.309	-0.188
1.0E-08	0.627	0.491	0.764	0.447	0.807	-0.058	1.313	-0.277	1.532
1.0E-10	1.583	1.493	1.674	1.464	1.703	0.944	2.223	0.739	2.427
1.0E-12	2.385	2.320	2.450	2.299	2.471	1.771	2.999	1.575	3.195
1.0E-15	3.375	3.322	3.429	3.304	3.447	2.773	3.978	2.580	4.171
2.9E-17								3.000	
1.7E-15								2.500	
1.5E-16							3.000		
7.0E-15							2.500		
1.5E-14	3.000								
4.3E-13	2.500								
9.1E-13							3.000		
1.9E-11							2.500		
3.1E-12									3.000
6.0E-11									2.500

Best cases (2.9E-17 – 7.0E-15); Typical cases (1.5E-14 – 4.3E-13); Worst cases (9.1E-13 – 6.0E-11)

- **With Rx jitter same as Tx spec (J4)**
  - ■ If COM is 3.0dB, worst-case BER is 3.1E-12 (99% confidence)
    - If COM is 2.5dB, worst-case BER is 6.0E-11, degraded by a factor of 19.4
    - Typical-case BER is 1.5E-14 (COM 3.0dB) or 4.3E-13 (COM 2.5dB)
  - ■ Worst-case BER < 1E-8 (99% confidence) is satisfied if COM > 1.532dB
    - Worst-case BER < 1E-10 (99% confidence) is satisfied if COM > 2.427dB
  - ■ COM 3dB has plenty of margin

BER (J1) vs COM (DER0=1E-15)

BER	COM (μ)					COM (μ+σ)			
	E	-5%	+5%	-1%	+1%	-5%	+5%	-1%	+1%
1.0E-05	-4.531	-4.768	-4.294	-4.844	-4.218	-5.341	-3.721	-5.600	-3.462
1.0E-08	-2.895	-3.045	-2.745	-3.093	-2.696	-3.618	-2.172	-3.849	-1.940
1.0E-10	-2.041	-2.153	-1.930	-2.189	-1.894	-2.726	-1.357	-2.945	-1.138
1.0E-12	-1.313	-1.396	-1.229	-1.423	-1.202	-1.969	-0.656	-2.179	-0.446
1.0E-15	-0.390	-0.448	-0.332	-0.467	-0.314	-1.021	0.241	-1.223	0.442
2.7E-44								3.000	
5.8E-38		Best cases						2.500	
1.9E-41							3.000		
6.1E-36							2.500		
8.6E-35	3.000	Typical cases							
1.1E-30	2.500								
8.8E-30		Worst cases					3.000		
1.9E-26							2.500		
2.1E-28									3.000
3.0E-25									2.500

- ■ **With same jitter as COM (J1)**
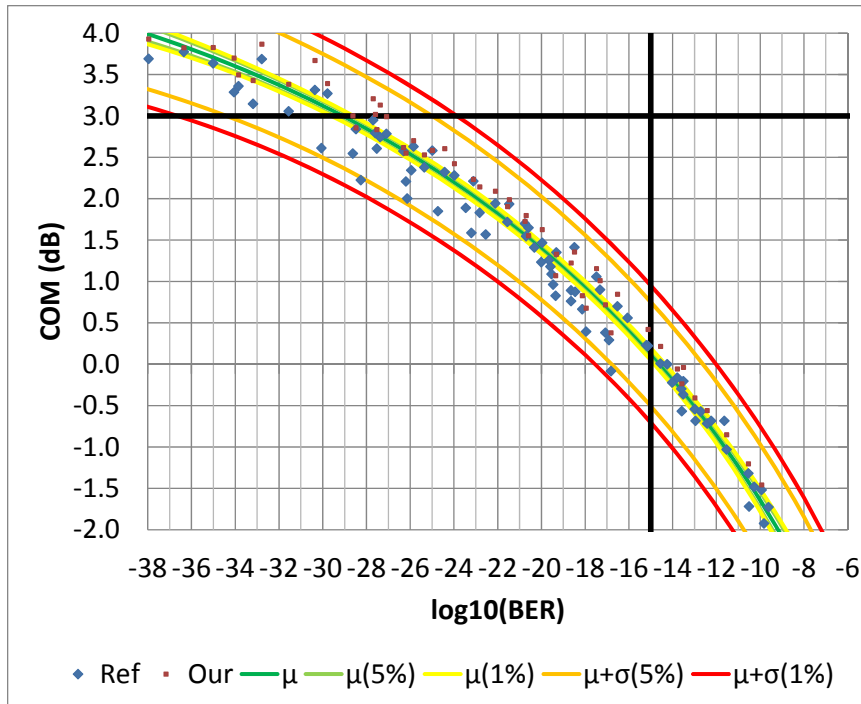
  - ■ Mean COM for BER=1E-15 is -0.390dB (expected value)

    - • If COM and BER are consistent, this is supposed to be 0dB

      - • The difference is statistically significant; 99% confidence interval is [-0.467, -0.314] dB

    - • If the inconsistency is resolved, COM for the same BER goes up by ~0.390dB

  - ■ If COM is 3.0dB, worst-case BER is 2.1E-28 (99% confidence limit)
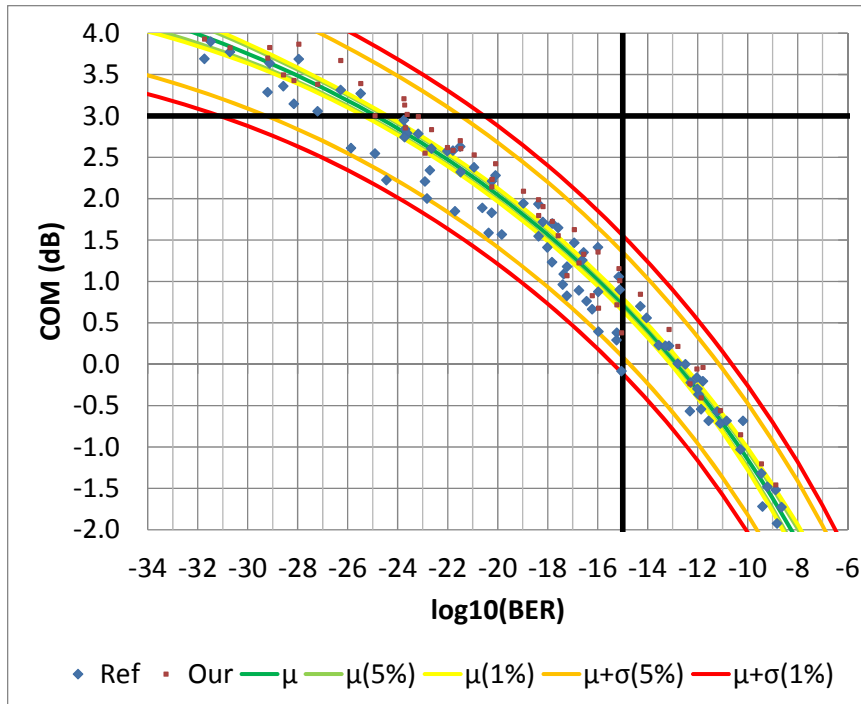
BER (J3) vs COM (DER0=1E-15)

BER	COM (μ)					COM (μ+σ)			
	E	-5%	+5%	-1%	+1%	-5%	+5%	-1%	+1%
1.0E-05	-4.345	-4.599	-4.092	-4.680	-4.010	-5.172	-3.519	-5.436	-3.254
1.0E-08	-2.564	-2.713	-2.415	-2.761	-2.367	-3.286	-1.842	-3.517	-1.611
1.0E-10	-1.642	-1.747	-1.537	-1.781	-1.504	-2.320	-0.964	-2.537	-0.748
1.0E-12	-0.860	-0.935	-0.784	-0.960	-0.760	-1.508	-0.211	-1.716	-0.004
1.0E-15	0.123	0.069	0.178	0.052	0.195	-0.504	0.751	-0.704	0.951
2.1E-37									3.000
2.0E-32		Best cases							2.500
3.7E-35							3.000		
8.7E-31							2.500		
7.7E-30	3.000	Typical cases							
1.6E-26	2.500								
9.2E-26							3.000		
5.0E-23		Worst cases					2.500		
1.3E-24									3.000
4.9E-22									2.500

Ref · Our —μ —μ(5%) —μ(1%) —μ+σ(5%) —μ+σ(1%)

■ **With Rx jitter half of Tx spec (J3)**

  ■ If COM is 3.0dB, worst-case BER is 1.3E-24 (99% confidence)

    • If COM is 2.5dB, worst-case BER is 4.9E-22, degraded by a factor of 387

    • Typical-case BER is 7.7E-30 (COM 3.0dB) or 1.6E-26 (COM 2.5dB)

  ■ Worst-case BER <1E-15 (99% confidence) is satisfied if COM >0.951dB
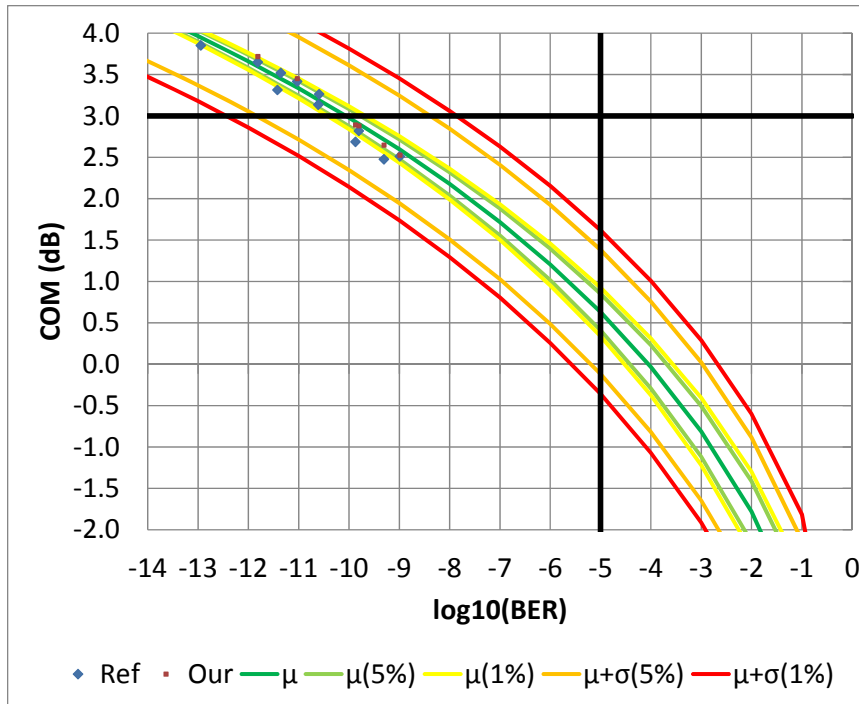
BER (J4) vs COM (DER0=1E-15)

FUJITSU

BER	COM (μ)					COM (μ+σ)			
	E	-5%	+5%	-1%	+1%	-5%	+5%	-1%	+1%
1.0E-05	-4.063	-4.343	-3.783	-4.433	-3.693	-4.916	-3.210	-5.189	-2.937
1.0E-08	-2.134	-2.284	-1.984	-2.332	-1.936	-2.857	-1.411	-3.088	-1.180
1.0E-10	-1.145	-1.245	-1.046	-1.277	-1.014	-1.818	-0.473	-2.033	-0.258
1.0E-12	-0.313	-0.384	-0.242	-0.407	-0.219	-0.957	0.331	-1.163	0.537
1.0E-15	0.722	0.663	0.781	0.644	0.800	0.090	1.354	-0.112	1.556
6.8E-32									3.000
8.3E-28									2.500
5.1E-30							3.000		
1.9E-26							2.500		
1.3E-25	3.000								
6.7E-23	2.500								
3.0E-22							3.000		
5.5E-20							2.500		
2.7E-21									3.000
3.7E-19									2.500

Best cases

Typical cases

Worst cases

Ref · Our —μ —μ(5%) —μ(1%) —μ+σ(5%) —μ+σ(1%)

■ **With same Rx jitter as Tx spec (J4)**

  ■ If COM is 3.0dB, worst-case BER is 2.7E-21 (99% confidence)

   • If COM is 2.5dB, worst-case BER is 3.7E-19, degraded by a factor of 138

   • Typical-case BER is 1.3E-25 (COM 3.0dB) or 6.7E-23 (COM 2.5dB)

  ■ Worst-case BER <1E-15 (99% confidence) is satisfied if COM >1.556dB

BER (J1) vs COM (DER0=1E-5)

BER	COM (μ)					COM (μ+σ)			
	E	-5%	+5%	-1%	+1%	-5%	+5%	-1%	+1%
1.0E-05	0.631	0.409	0.852	0.338	0.923	-0.119	1.381	-0.359	1.621
1.0E-08	2.178	2.038	2.319	1.992	2.364	1.509	2.847	1.295	3.061
1.0E-10	2.979	2.875	3.084	2.842	3.117	2.347	3.612	2.145	3.814
1.0E-12	3.660	3.582	3.739	3.557	3.764	3.054	4.267	2.860	4.461
1.0E-15	4.516	4.462	4.570	4.445	4.588	3.934	5.099	3.748	5.285
3.3E-13								3.000	
1.0E-11								2.500	
1.3E-12							3.000		
3.5E-11							2.500		
8.0E-11	3.000								
1.5E-09	2.500								
3.7E-09							3.000		
5.5E-08							2.500		
1.2E-08									3.000
1.7E-07									2.500

Best cases — Typical cases — Worst cases
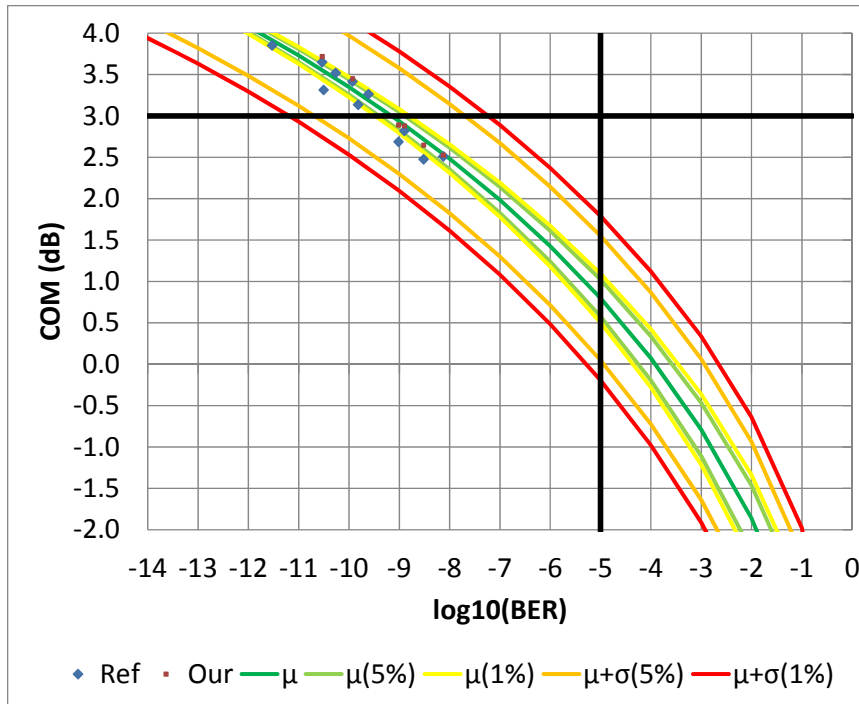
With same jitter as COM (J1)

- Mean COM for BER=1E-5 is 0.631dB (expected value)
  - If COM and BER are consistent, this is supposed to be 0dB
    - The difference is statistically significant; 99% confidence interval is [0.338, 0.923] dB
  - If the inconsistency is resolved, COM for same BER goes down by ~0.631dB
- If COM is 3.0dB, worst-case BER is 1.2E-8 (99% confidence limit)
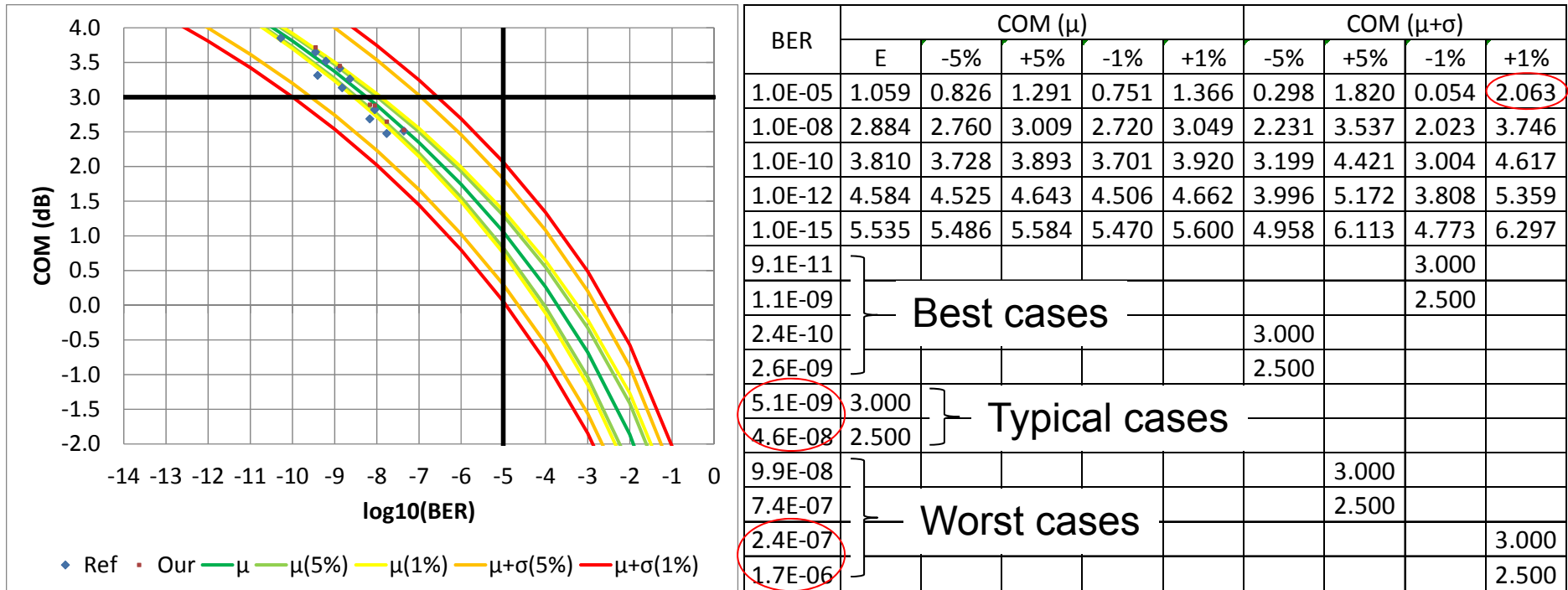
BER (J3) vs COM (DER0=1E-5)

FUJITSU

BER	COM (μ)					COM (μ+σ)			
	E	-5%	+5%	-1%	+1%	-5%	+5%	-1%	+1%
1.0E-05	0.798	0.575	1.021	0.504	1.092	0.047	1.549	-0.193	1.790
1.0E-08	2.484	2.353	2.615	2.311	2.657	1.825	3.144	1.614	3.354
1.0E-10	3.350	3.258	3.442	3.228	3.471	2.729	3.970	2.531	4.169
1.0E-12	4.079	4.013	4.146	3.992	4.167	3.485	4.674	3.295	4.864
1.0E-15	4.988	4.940	5.036	4.925	5.051	4.412	5.564	4.228	5.748
5.8E-12									3.000
1.1E-10									2.500
1.9E-11							3.000		
3.1E-10							2.500		
6.3E-10	3.000								
8.2E-09	2.500								
1.8E-08							3.000		
1.9E-07							2.500		
5.1E-08									3.000
4.9E-07									2.500

Best cases · Typical cases · Worst cases

- **With Rx jitter half of Tx spec (J3)**
  - ■ If COM is 3.0dB, worst-case BER is 5.1E-8 (99% confidence)
    - • If COM is 2.5dB, worst-case BER is 4.9E-6, degraded by a factor of 9.6
    - • Typical-case BER is 6.3E-10 (COM 3.0dB) or 8.2E-9 (COM 2.5dB)
  - ■ Worst-case BER < 1E-5 (99% confidence) is satisfied if COM > 1.790dB

FUJITSU

BER	COM (μ)					COM (μ+σ)			
	E	-5%	+5%	-1%	+1%	-5%	+5%	-1%	+1%
1.0E-05	1.059	0.826	1.291	0.751	1.366	0.298	1.820	0.054	2.063
1.0E-08	2.884	2.760	3.009	2.720	3.049	2.231	3.537	2.023	3.746
1.0E-10	3.810	3.728	3.893	3.701	3.920	3.199	4.421	3.004	4.617
1.0E-12	4.584	4.525	4.643	4.506	4.662	3.996	5.172	3.808	5.359
1.0E-15	5.535	5.486	5.584	5.470	5.600	4.958	6.113	4.773	6.297
9.1E-11									3.000
1.1E-09									2.500
2.4E-10								3.000	
2.6E-09								2.500	
5.1E-09	3.000								
4.6E-08	2.500								
9.9E-08							3.000		
7.4E-07							2.500		
2.4E-07									3.000
1.7E-06									2.500

Best cases (9.1E-11, 1.1E-09, 2.4E-10, 2.6E-09)
Typical cases (5.1E-09, 4.6E-08)
Worst cases (9.9E-08, 7.4E-07, 2.4E-07, 1.7E-06)

■ **With Rx jitter same as Tx spec (J4)**

■ If COM is 3.0dB, worst-case BER is 2.4E-7 (99% confidence)

• If COM is 2.5dB, worst-case BER is 1.7E-6, degraded by a factor of 7.2

• Typical-case BER is 5.1E-9 (COM 3.0dB) or 4.6E-8 (COM 2.5dB)

■ Worst-case BER < 1E-5 (99% confidence) is satisfied if COM > 2.063dB

References of Channel Data

- ~ = http://www.ieee802.3.org/3/
- 3 meter cable assembly
  - B: ~/by/public/channel/TE_QSFP_4SFP_3m_30AWG.zip (TE_3m30AWG_QSFP_4SFP_P1_TX1_P2_RX1_THRU.s4p)
  - G: ~/100GCU/public/ChannelData/Molex_11_0516/bugg_02_0511.zip (3m 26AWG leoni/P1 RX1/TX1.s4p)
  - H: ~/by/public/channel/TE_QSFP_4SFP_3m_26AWG.zip (TE_3m26AWG_QSFP_4SFP_P1_TX1_P2_RX1_THRU.s4p)
- 5 meter cable assembly
  - N: ~/100GCU/public/ChannelData/Molex_11_0516/bugg_02_0511.zip (5m 26AWG Leoni/P1 RX1/TX1.s4p)
  - Q: ~/100GCU/public/ChannelData/Molex_11_0210/5m/5m_all.zip (P1 RX0/TX0.s4p)
  - R: ~/100GCU/public/ChannelData/molex_12_0310/cableb_bugg_03_0312.zip (P1RX1/P2TX1.s4p)

Thank you