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shaping tomorrow with you

BER margin of COM 3dB

Yasuo Hidaka
Fujitsu Laboratories of America, Inc.

September 9, 2015

Abstract

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- I was 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

Statistical Study on COM and BER

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- 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

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- 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

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- 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	
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

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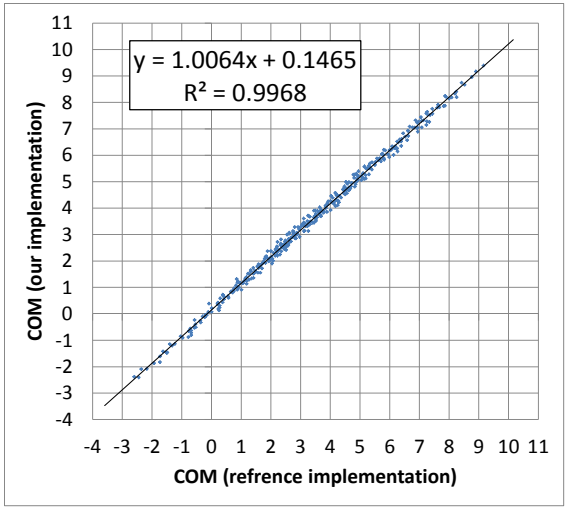
	Factor	Degree of freedom	Variation	Variance	Variance ratio	F test result		Pure Variation	Degree of contribution	Standard deviation
		f	S	V	F0			S'	ρ	σ
A	fp1	1	583.627	583.627	7874.33	100.00%	**	583.5528	12.32%	0.872253
B	case	1	147.7597	147.7597	1993.58	100.00%	**	147.6856	3.12%	0.438805
C	SNRTX	1	48.65585	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%	



- 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)

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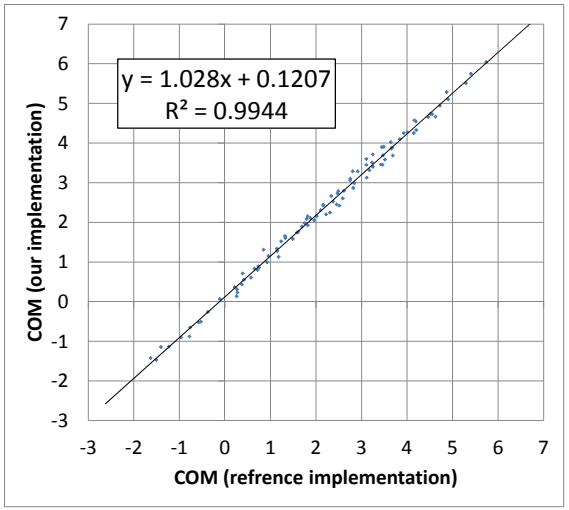
Factor		Degree of freedom	Variation	Variance	Variance ratio	F test result		Pure Variation	Degree of contribution	Standard deviation
		f	S	V	F0			S'	ρ	σ
A	fp1	1	150.4173	150.4173	2046.29	100.00%	**	150.3438	25.48%	0.887209
B	case	1	39.23874	39.23874	533.806	100.00%	**	39.16523	6.64%	0.452828
C	SNRTX	1	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%	



- 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)

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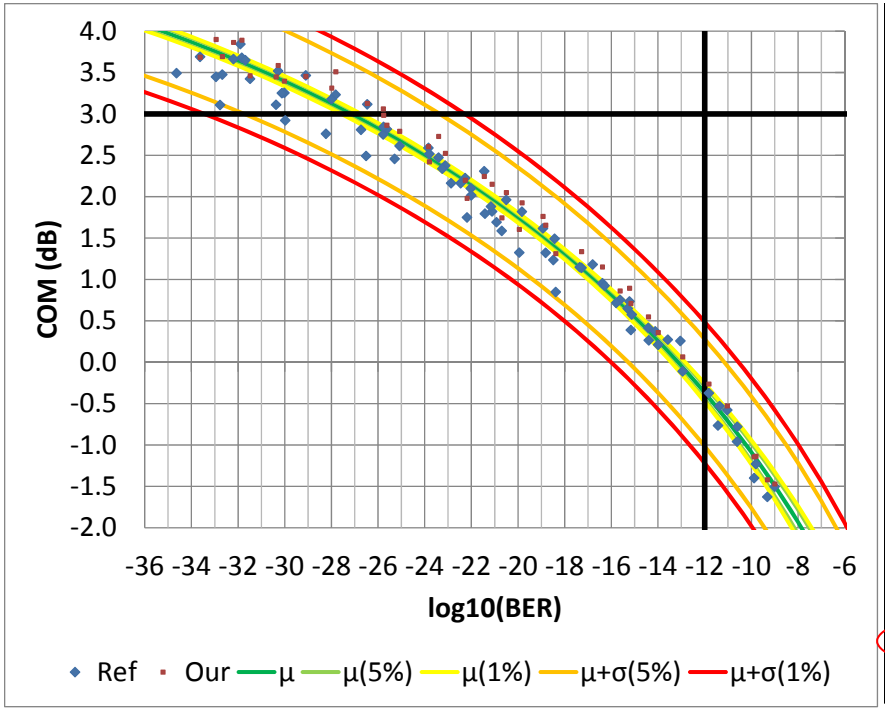

BER	COM (μ)					COM (μ+σ)			
	E	-5%	+5%	-1%	+1%	-5%	+5%	-1%	+1%
1.0E-05	-3.551	-3.786	-3.316	-3.861	-3.241	-4.350	-2.752	-4.606	-2.496
1.0E-08	-1.930	-2.079	-1.781	-2.127	-1.733	-2.643	-1.217	-2.871	-0.989
1.0E-10	-1.086	-1.196	-0.975	-1.232	-0.940	-1.761	-0.411	-1.976	-0.195
1.0E-12	-0.365	-0.448	-0.282	-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

- 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)

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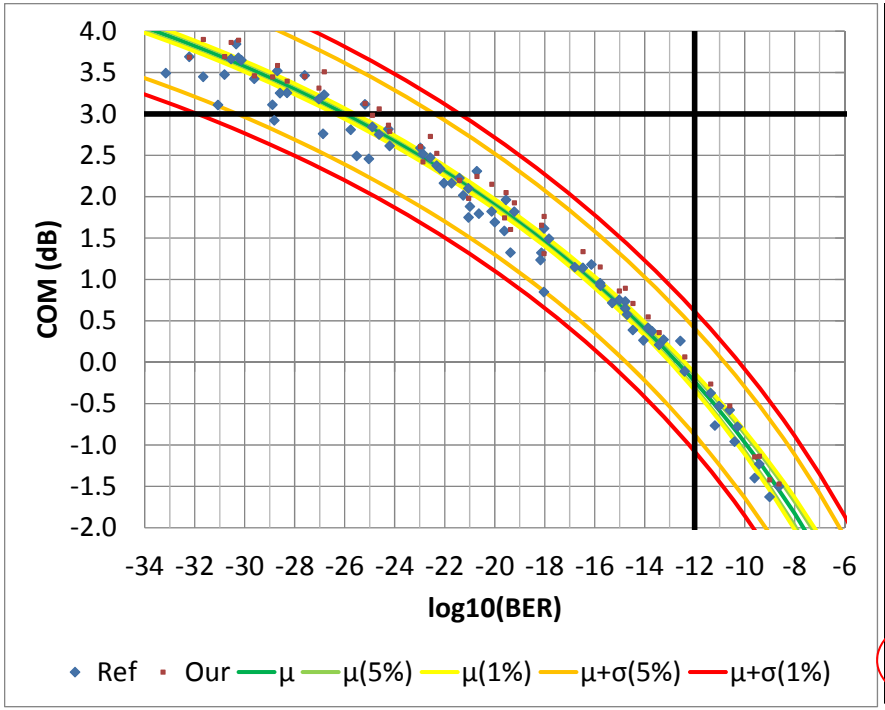

BER	COM (μ)					COM (μ+σ)			
	E	-5%	+5%	-1%	+1%	-5%	+5%	-1%	+1%
1.0E-05	-3.483	-3.719	-3.247	-3.795	-3.171	-4.283	-2.682	-4.539	-2.426
1.0E-08	-1.827	-1.973	-1.680	-2.020	-1.633	-2.538	-1.116	-2.765	-0.888
1.0E-10	-0.966	-1.073	-0.858	-1.107	-0.824	-1.637	-0.294	-1.852	-0.079
1.0E-12	-0.232	-0.311	-0.152	-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

Typical cases

Worst cases

- 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 (J3) vs COM (DER0=1E-12)

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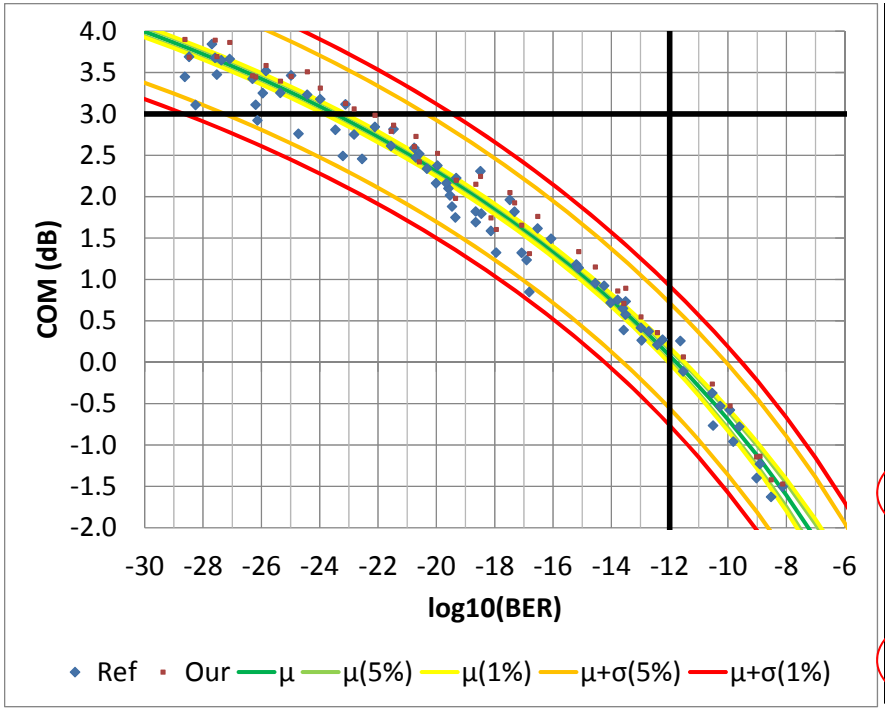

BER	COM (μ)					COM (μ+σ)			
	E	-5%	+5%	-1%	+1%	-5%	+5%	-1%	+1%
1.0E-05	-3.368	-3.616	-3.120	-3.696	-3.041	-4.181	-2.556	-4.440	-2.296
1.0E-08	-1.603	-1.749	-1.458	-1.796	-1.411	-2.314	-0.893	-2.541	-0.666
1.0E-10	-0.692	-0.794	-0.589	-0.827	-0.556	-1.358	-0.025	-1.572	0.189
1.0E-12	0.082	0.008	0.156	-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)

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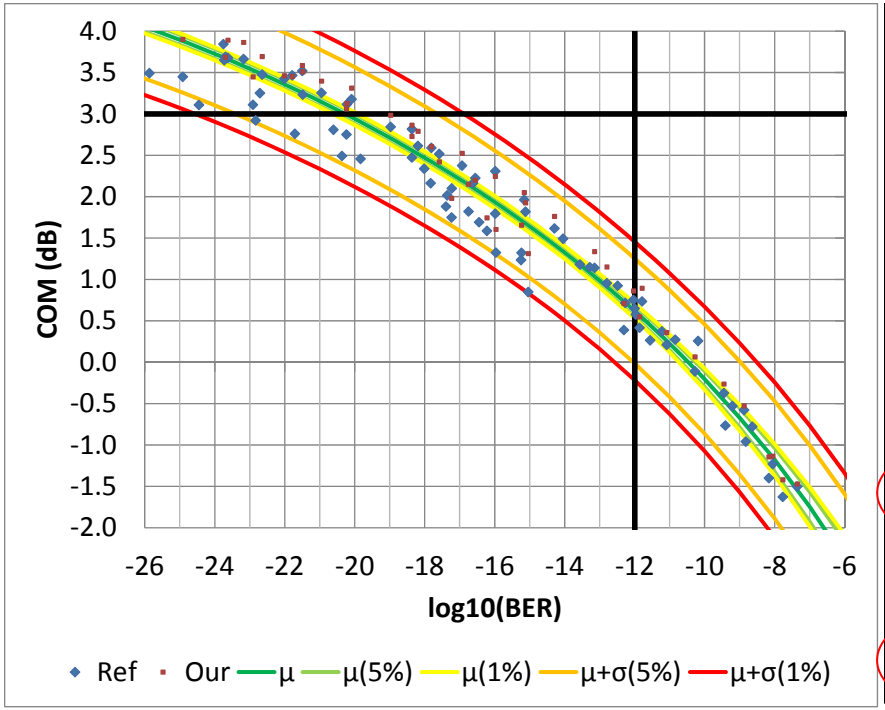

BER	COM (μ)					COM (μ+σ)			
	E	-5%	+5%	-1%	+1%	-5%	+5%	-1%	+1%
1.0E-05	-3.090	-3.360	-2.819	-3.447	-2.732	-3.925	-2.254	-4.192	-1.987
1.0E-08	-1.179	-1.324	-1.034	-1.370	-0.987	-1.888	-0.469	-2.115	-0.243
1.0E-10	-0.201	-0.297	-0.105	-0.328	-0.074	-0.862	0.460	-1.073	0.671
1.0E-12	0.621	0.552	0.690	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								2.500	
3.6E-24						3.000			
1.3E-21						2.500			
5.0E-21	3.000								
7.0E-19	2.500								
2.1E-18							3.000		
1.5E-16							2.500		
1.2E-17									3.000
6.9E-16									2.500

Best cases

Typical cases

Worst cases

- 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

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- 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

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- 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 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 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

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Appendix

Effect of Injected Jitter : RJ

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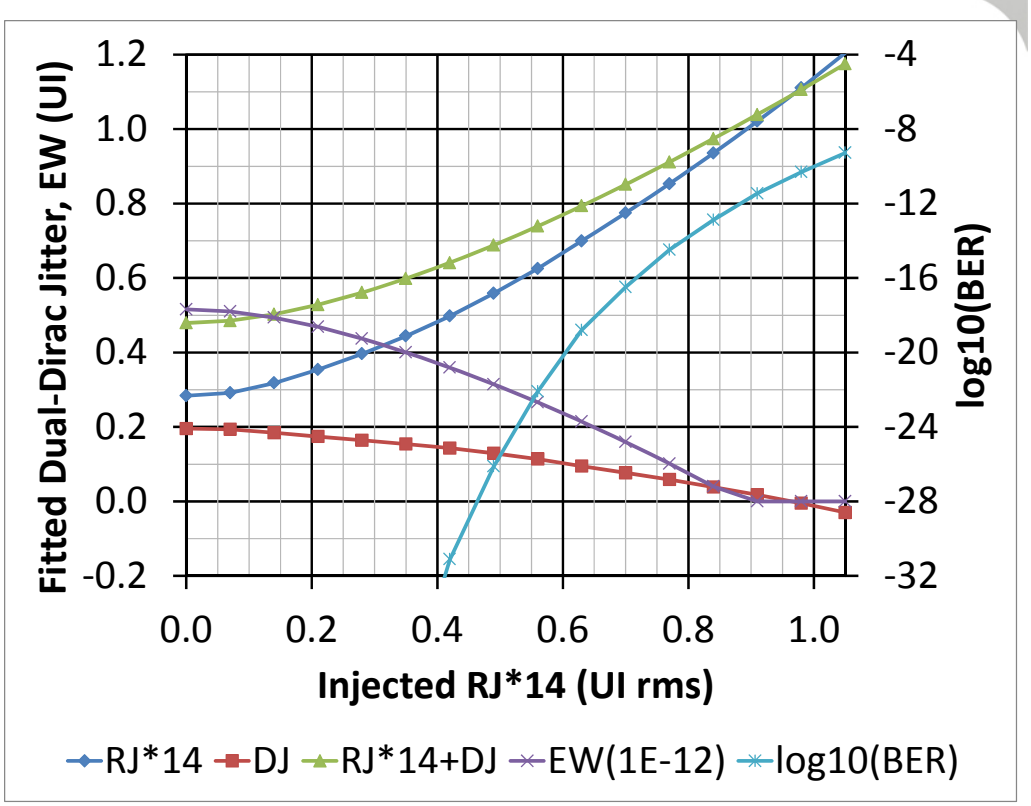
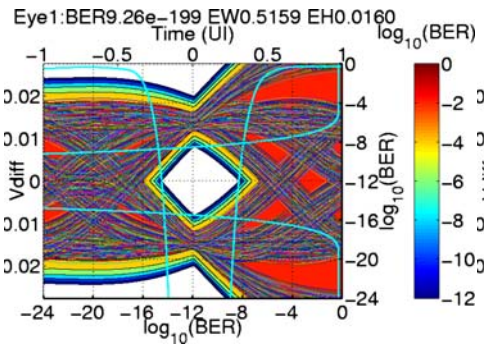
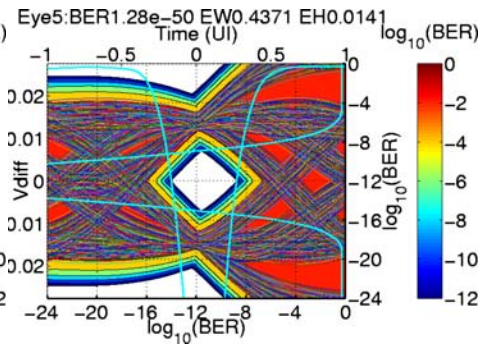
- Conditions
  - Channel and Equalizers
    - Typ 3m G(26QQ) w/o crosstalk
    - 3-tap Tx FIR, 15-tap DFE
    - CTLE (fp1=fb/4)
  - No additional noise
    - SNRTX=∞, η_0 = 0
  - Injected Jitter (Tx Only)
    - RJ = 0 – 0.075 UI rms
      - Step 0.005 UI rms
    - DJ = 0 UI d-d
    - EOJ = 0 UI p-p



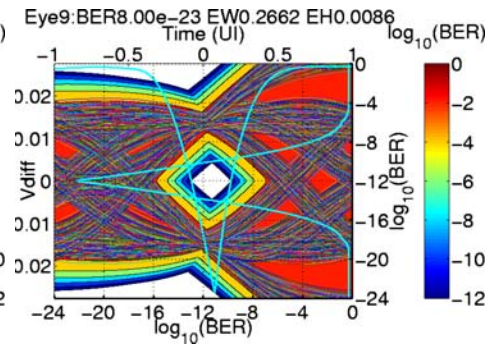
No Jitter Injected



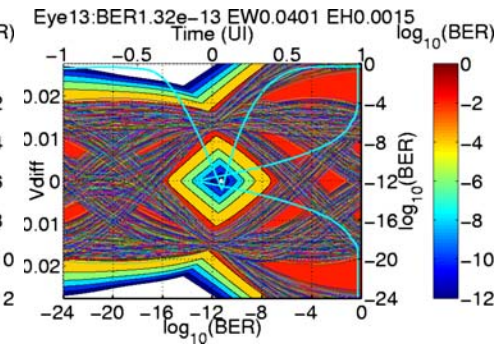
RJ*14 = 0.28 UI rms



RJ*14 = 0.56 UI rms



RJ*14 = 0.84 UI rms



Effect of Injected Jitter : DJ

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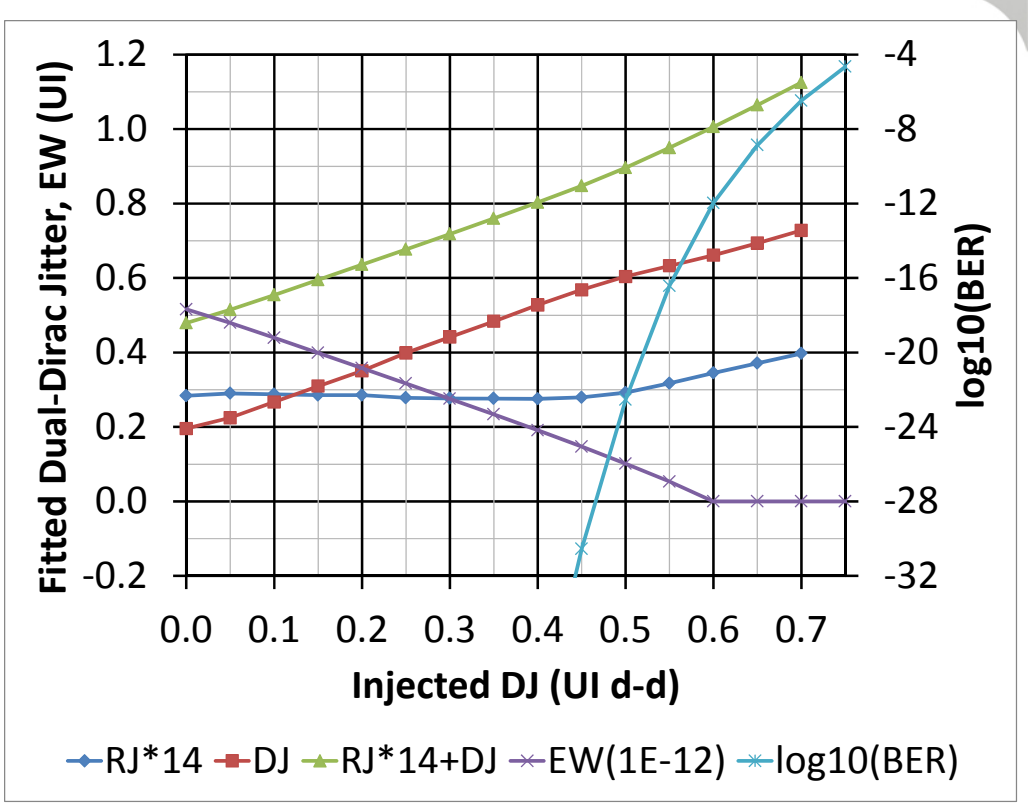
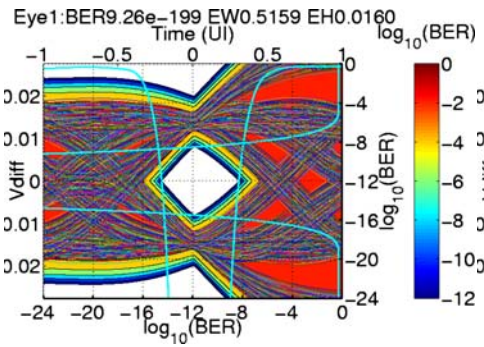
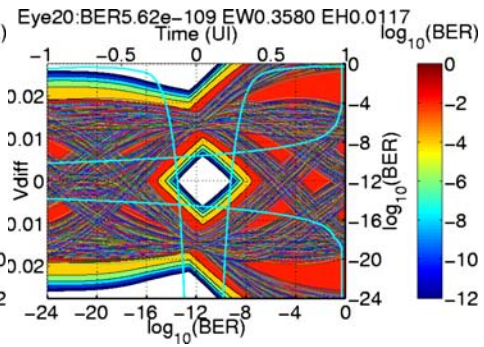
- Conditions
  - Channel and Equalizers
    - Typ 3m G(26QQ) w/o crosstalk
    - 3-tap Tx FIR, 15-tap DFE
    - CTLE (fp1=fb/4)
  - No additional noise
    - SNRTX=∞, η_0 = 0
  - Injected Jitter (Tx Only)
    - RJ = 0 UI rms
    - DJ = 0 – 0.75 UI d-d
      - Step 0.05 UI d-d
    - EOJ = 0 UI p-p



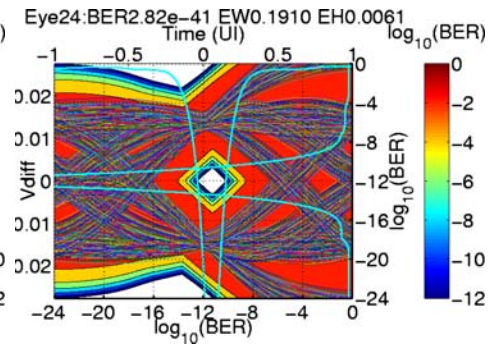
No Jitter Injected



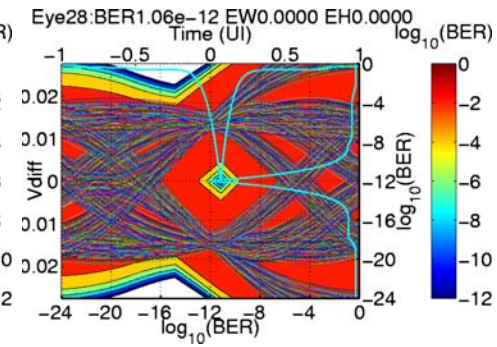
DJ = 0.20 UI d-d



DJ = 0.40 UI d-d



DJ = 0.60 UI d-d



Effect of Injected Jitter : EOJ

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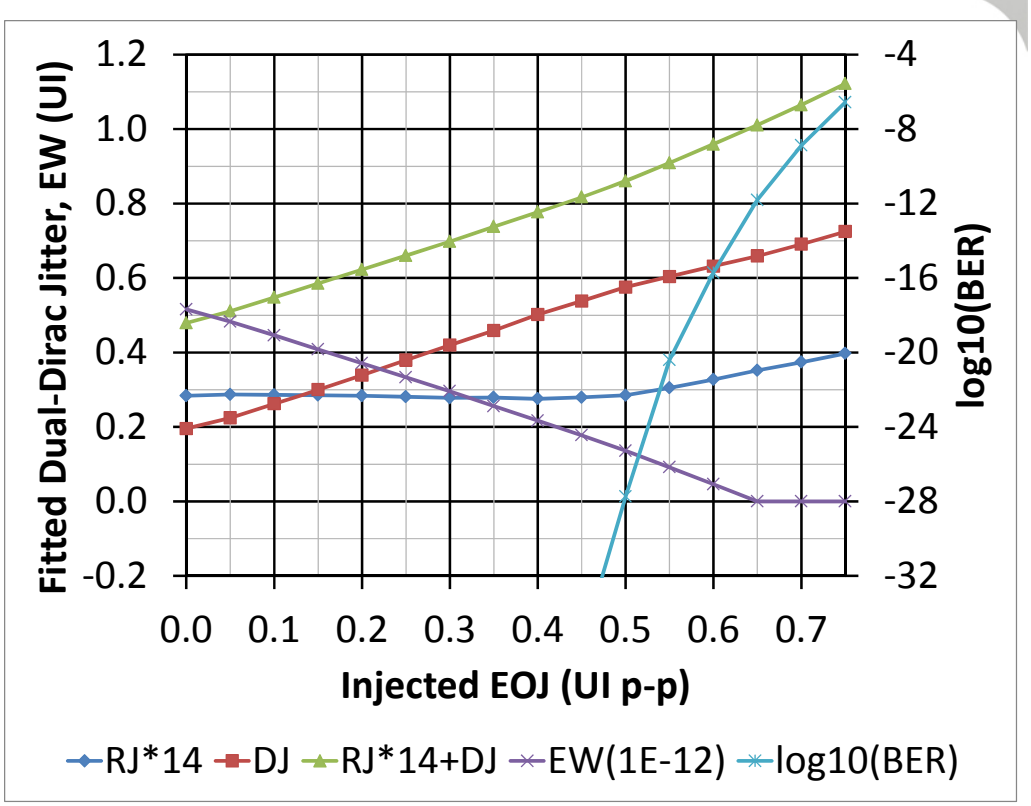
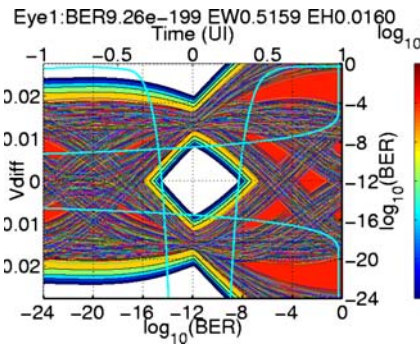
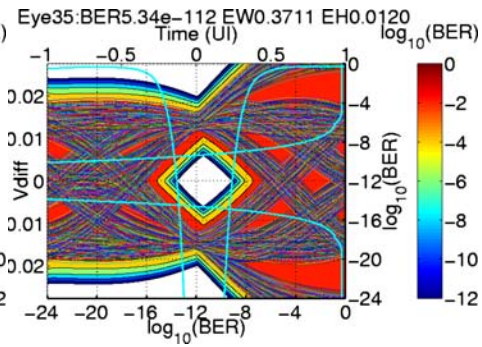
- Conditions
  - Channel and Equalizers
    - Typ 3m G(26QQ) w/o crosstalk
    - 3-tap Tx FIR, 15-tap DFE
    - CTLE (fp1=fb/4)
  - No additional noise
    - SNRTX=∞, η_0 = 0
  - Injected Jitter (Tx Only)
    - RJ = 0 UI rms
    - DJ = 0 UI d-d
    - EOJ = 0 – 0.75 UI p-p
      - Step 0.05 UI p-p



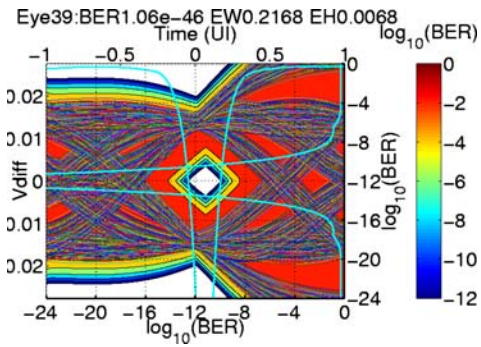
No Jitter Injected



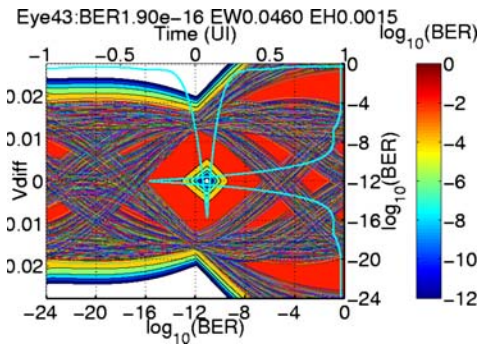
EOJ = 0.20 UI p-p



EOJ = 0.40 UI p-p



EOJ = 0.60 UI p-p



References of Channel Data

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- ~ = 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)

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Thank you