Even-Odd Jitter (EOJ) Test Method
IEEE 802.3ck Electrical ad-hoc
(Comment resolution edition)

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Appendix: New comment resolution proposal
Starting on page 16

Background / Goals

- Review current EOJ measurement methodology
- The Unexpected Problem Impacting EOJ Measurements
- Review EOJ measurement results performed with different CR loop bandwidths
- Recommendations to consider in anticipation of comments to be submitted against draft 1.3

APPENDIX: Supplemental EOJ Measurement Data

Output Jitter: IEEE 802.3ck

Table 162-10 – Summary of transmitter specifications at TP2
Even-odd jitter (max 19 mUI) references Subclause 162.9.3.3.

162.9.3.3 Output jitter

Output jitter is characterized by three parameters, J3u, J_{RMS}, and even-odd jitter. These parameters are calculated from measurements with a single transmit equalizer setting to compensate for the loss of the transmitter package and host channel. The equalizer setting is chosen to minimize any or all of the jitter parameters.

J3u and J_{RMS} are calculated using the measurement method specified in 120D.3.1.8.1. J3u is defined as the time interval that includes all but 10^{-3} of $f_J(t)$, from the 0.05th to the 99.95th percentile of $f_J(t)$.

Even-odd jitter is calculated using the measurement method specified in 120D.3.1.8.2.

Table 120F-1 – Transmitter electrical characteristics at TP0v
Even-odd jitter (max 19 mUI) references 120F.3.1.3

120F.3.1.3 Output jitter

Output jitter is characterized by three parameters: J4u, J_{RMS}, and even-odd jitter. These parameters are calculated from measurements with a single transmit equalizer setting to compensate for the loss of the transmitter package and test fixture. The equalizer setting is chosen to minimize any or all of the jitter parameters.

J4u and J_{RMS} are calculated using the jitter measurement method specified in 120D.3.1.8.1.

Even-odd jitter is calculated using the jitter measurement method specified in 120D.3.1.8.2.

Both EOJ measurements in IEEE 802.3ck reference EOJ measurement method outlined in IEEE 802.3-2018 Annex 120D.3.1.8.2
(see next slide)

Even-Odd Jitter (EOJ) Measurement defined in 120D.3.1.8.2

REFERENCE: IEEE 802.3-2018

IEEE Std 802.3-2018, IEEE Standard for Ethernet
SECTION EIGHT

120D.3.1.8.2 Even-odd Jitter

For one of the 12 specific transitions in PRBS13Q in Table 120D–4:

a) Trigger once in 3 repeats of the PRBS13Q test pattern
   1) Obtain the mean time (*T3*) for this transition in the first PRBS13Q.
   2) Obtain the mean time (*T4*) for the same transition in the second PRBS13Q.

b) The difference between the two means (*T4* – *T3*), is the estimated period of the repeating pattern

For each of the 12 specific transitions in PRBS13Q in Table 120D–4:

a1) Trigger once in 2 repeats of the PRBS13Q test pattern.
   1) Obtain the mean time (*T1*) for the specific transition in the first PRBS13Q.
   2) Obtain the mean time (*T2*) for the same transition in the second PRBS13Q.

b1) Calculate even-odd jitter for this transition as $|(T2 - T1) - (T4 - T3)|$

Even-odd jitter EOJ is the maximum of the 12 measurements.

NOTE 1—Both of (*T2* – *T1*) and (*T4* – *T3*) are about 8191 UI, which is much larger than the EOJ value. Hence, each of *T1* through *T4* should have high precision.

NOTE 2—Even-odd jitter has been referred to as *duty cycle distortion* by other Physical Layer specifications for operation over electrical backplane or twinaxial copper cable assemblies (see 72.7.1.9). The term *even-odd jitter* is used here to distinguish it from the duty cycle distortion referred to by Physical Layer specifications for operation over fiber optic cabling.

Annex 120D.3.1.8.2: EOJ is measured with a PRBS13Q pattern using a Clock Recovery Unit (CRU) with loop BW 4 MHz and slope 20 dB/dec.

IEEE Std 802.3-2018, IEEE Standard for Ethernet
SECTION EIGHT

Table 120D–4—PRBS13Q pattern symbols used for jitter measurement

Label	Description	Gray coded PAM4 symbols	Index of first symbol	Index transition begins	Index transition ends	Index of last symbol	Threshold level
REF	Reference for symbol index	3333333	1	—	—	7	—
R03	0 to 3 rise	10000 330	1830	1834	1835	1837	$(V_0+V_3)/2$
F30	3 to 0 fall	23333 001	1269	1273	1274	1276	
R12	1 to 2 rise	0111111 2222221	3638	3644	3645	3651	$(V_1+V_2)/2$
F21	2 to 1 fall	022222 113	1198	1203	1204	1206	
R01	0 to 1 rise	100000 113	6835	6840	6841	6843	$(V_0+V_1)/2$
F10	1 to 0 fall	21111 003	2992	2996	2997	2999	
R23	2 to 3 rise	32222 330	6824	6828	6829	6831	$(V_2+V_3)/2$
F32	3 to 2 fall	033333 2222223	7734	7739	7740	7746	
R02	0 to 2 rise	10000 223	3266	3270	3271	3273	$(V_0+V_2)/2$
F20	2 to 0 fall	122222 0000002	7282	7287	7288	7294	
R13	1 to 3 rise	011111 331	133	138	139	141	$(V_1+V_3)/2$
F31	3 to 1 fall	23333 112	7905	7909	7910	7912	

The jitter is measured with a clock recovery unit (CRU) with a corner frequency of 4 MHz and a slope of 20 dB/decade. Jitter measurements are performed with transmitters on all lanes enabled and using identical transmitter equalizer settings. Transmitters on lanes not under test transmit PRBS31Q, or a valid 200GBASE-R or 400GBASE-R signal. PRBS31Q is described in 120.5.11.2.2.

The J4u, J_{RMS}, and Even-odd jitter specifications shall be met regardless of the transmit equalization setting.

Even-Odd Jitter (EOJ) Max Specs

REFERENCE: IEEE 802.3-2018 VS IEEE 802.3 DRAFT 1.3

IEEE 802.3bs/cd (IEEE 802.3-2018)

- Baud Rate: 26.5625 GBd
- EOJ Max: 19 mUI = **715 fs**

IEEE 802.3ck Draft 1.3

- Baud Rate: 53.125 GBd
- EOJ Max: 19 mUI = **358 fs**

# of mUI is the same, but absolute time is reduced by 50%.

- Has root cause for EOJ on new 53 GBd transmitter designs been able to scale accordingly?
- Was measurement repeatability considered when selecting EOJ max spec of 358 fs? More on this later…

- Bottom Line: EOJ has extremely low margins in 802.3ck Draft 1.3.

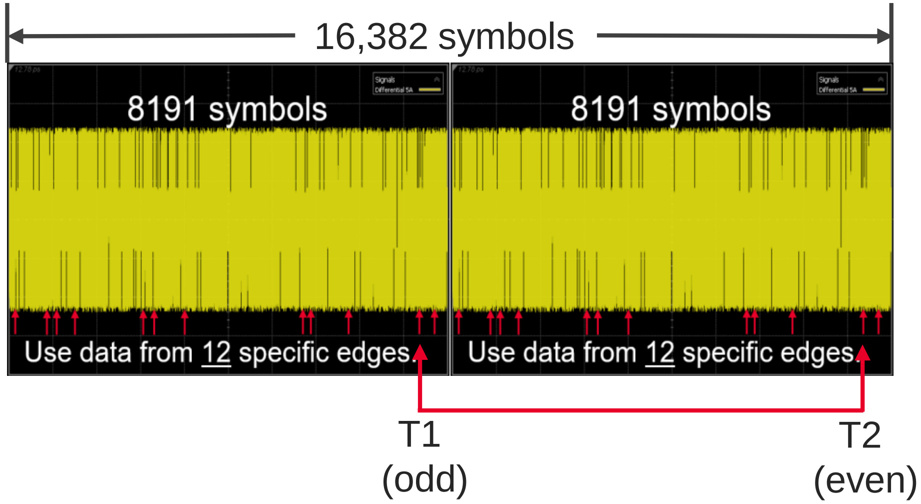
Even-Odd Jitter

SUB-HARMONICS INTRODUCED BASED ON F_BAUD AND PATTERN REPETITION RATE

Identifies jitter impairments due to ½ rate clock systems (rising or falling clock edge), including impairments from Tx designs that generate PAM4 signals from two independent NRZ signals (-> need to characterize all 12 combinations of PAM4 transitions).

The Standard intended to measure the **timing differences between “even” and “odd” versions of the same edge.**

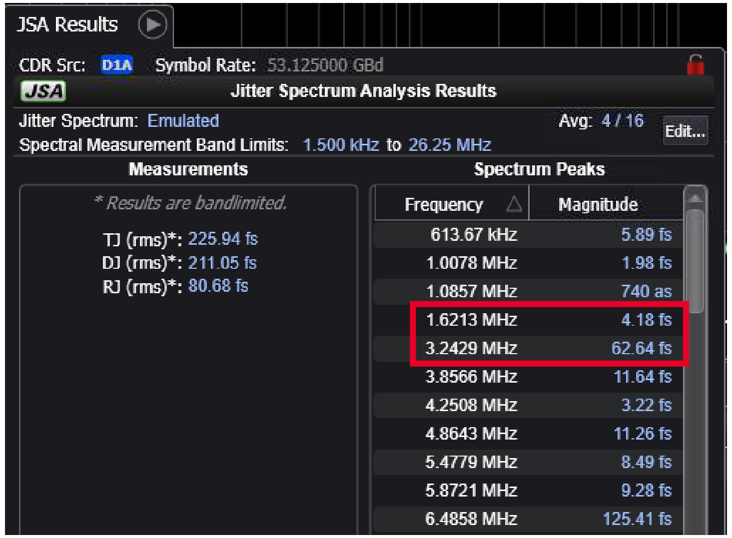
Note - When using a PRBS13Q pattern to characterize EOJ, this places the “even” and “odd” **transitions being compared 8191 symbols apart.**



8191 symbols

Sub-Harmonics of EOJ are created based on Fbaud and Pattern Length:

- Baud Rate: 53.125 Gbd
- PRBS13Q Pattern Length: 8191 Symbols
- Spectral Component = Fbaud / (2*PatternLength) = 3.24 MHz (in-band)

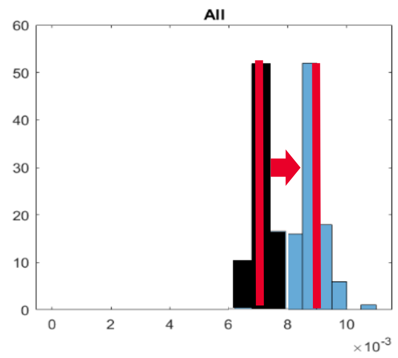


Unexpected Problem Impacting EOJ Measurements

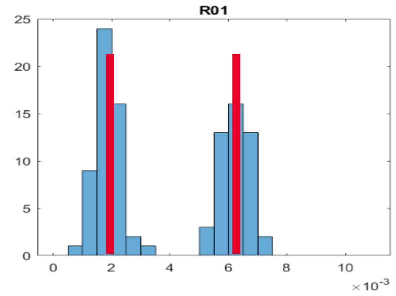
COMBINATION OF FBAUD, PATTERN LENGTH, CRU LOOP BW

In practice, the EOJ result is impacted by the CDR loop BW and the selected pattern length.

1. **EOJ from DUT:** CDR responds to the EOJ in the signal, is filtered by the Jitter Transfer Function (JTF) low-pass response, and moves the phase of the clock.
   - Spectral Component = Fbaud / (2*PatternLength) = 53.125 GBd/16,382 symbols = 3.24 MHz (in-band)
   - Normal distribution, increases/decreases the amplitude of the EOJ component based on phase relationship.
   - But EOJ algorithm always records the maximum of the of the 12 edges (worst case result), so EOJ result will always be increased due to the component (sub-harmonic) of EOJ that falls within the loop BW of the CDR.



2. **EOJ from CDR:** If ½ rate hardware CR does not have exactly 50% duty cycle, it introduces its own F/2 jitter.
   - Spectral Component = Fbaud / (2*PatternLength) = 53.125 GBd/16,382 symbols = 3.24 MHz (in-band) .
   - #2 can "interact" with #1 and create bi-modal EOJ on top of #1 (increased EOJ).



➢ Neither of these interactions are what the EOJ measurement is trying to characterize. Efforts should be taken to minimize the impact CR on the measurement.

What can be done?

Since "Real" systems don't have repetitive patterns that create this type of issue, it is our belief that any impairment of EOJ due to this relationship is <u>unintended by the standard</u>.

Is this understanding true? That is, CR loop BW of 4 MHz and test pattern length were chosen independently with no intent to create this interaction.

If our understanding is correct, the "interaction" effect can be mitigated **<u>if EOJ is measured with</u>**:

1. **A lower CR Loop BW.**
   - Allow CR loop BW to be lowered from 4 MHz to x MHz (Example: ~ 100 kHz).=> Simple
   - **See data that follows.**

2. **A "clean" reference clock (no CDR)**
   - Not readily available in many systems. **=> Not practical.**

3. **A shorter pattern such as PRBS9Q**
   - Not defined in the Standard…a pretty big change. **=> Not practical.**
   - Fbaud / (2*PatternLength) = 53.125 GBd / (2*511) = 52 MHz >> 4 MHz CR loop BW

EOJ Experiment: Evaluate Impact of CR Loop BW

3 DUTs characterized. Tx Source configured for 53.125 GBd, PAM4, PRBS13Q:

1. M8040A JBERT Pattern Generator
2. DUT#2 (53.125 GBd PAM4)
3. 106G PHY (53.125 GBd PAM4)

Measure EOJ with two CR loop BW settings (100 measurements each) on the same oscilloscope setup (N1000A DCA-X +N1060A):

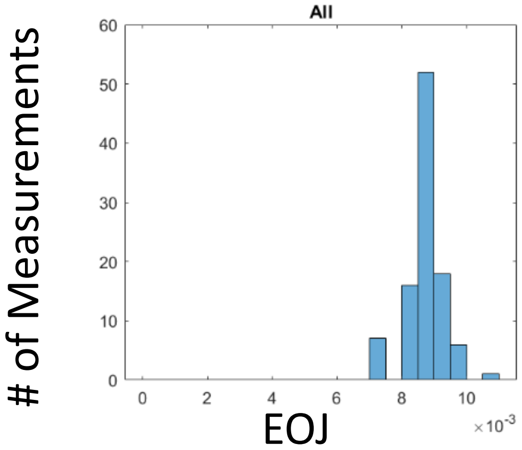
1. 4 MHz (currently specified by IEEE 802.3ck)
2. 106 kHz or 1 MHz

Evaluate impact of CR Loop BW on EOJ results:

1. EOJ Result
2. EOJ Distribution
3. EOJ Repeatability

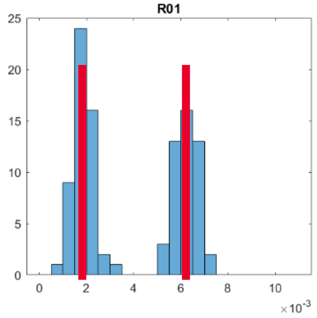
DUT 1: M8040A JBERT Pattern Generator

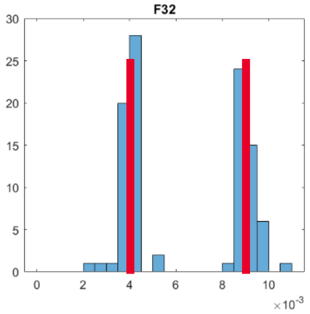
CR Loop BW: 4 MHz (current spec)



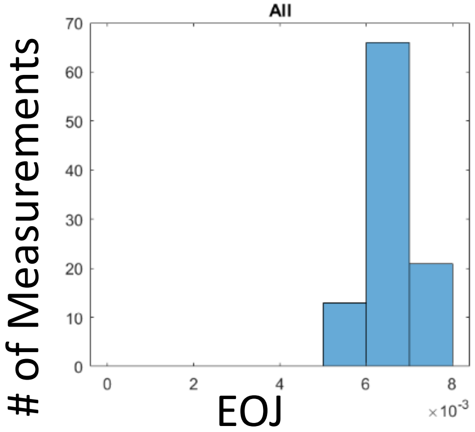
- EOJ Mean: 8.75mUI
- EOJ Min-Max: 7.5mUI - 10.5mUI (3 mUI)

“ALL” result looks “Normal” (above), but individual edges are bi-modal (below).



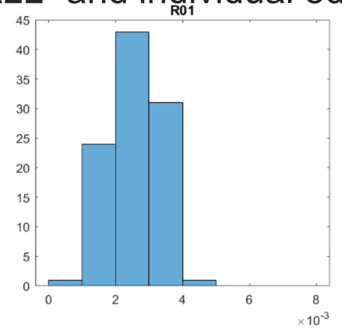


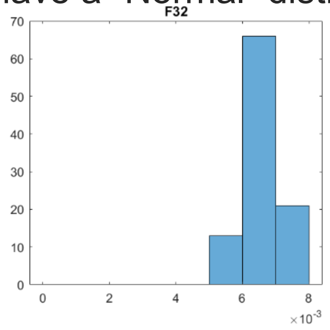
CR Loop BW: 106 kHz



- EOJ Mean: 6.3mUI
- EOJ Min – Max: 5.0mUI - 7.5mUI (2.5 mUI)

“ALL” and individual edges have a “Normal” distribution.



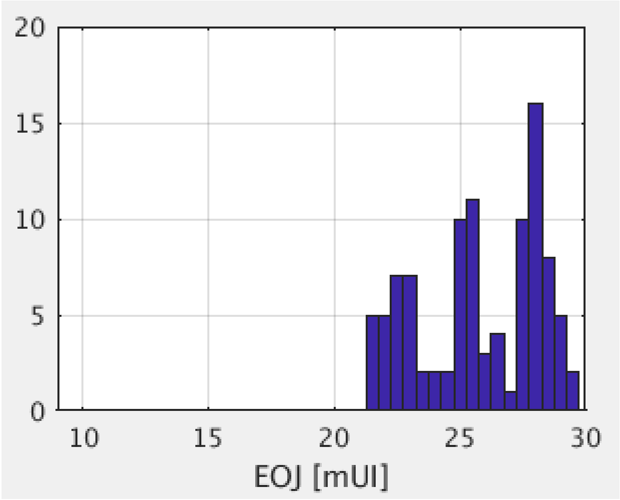


Effect of lowering loop BW used to measure EOJ:

- Mean is reduced (as expected per item#1 on slide 6)
- Bi-modal distribution is mitigated (as expected per item#2 on slide 6)
- Lower CR loop BW can improve EOJ measurement accuracy.

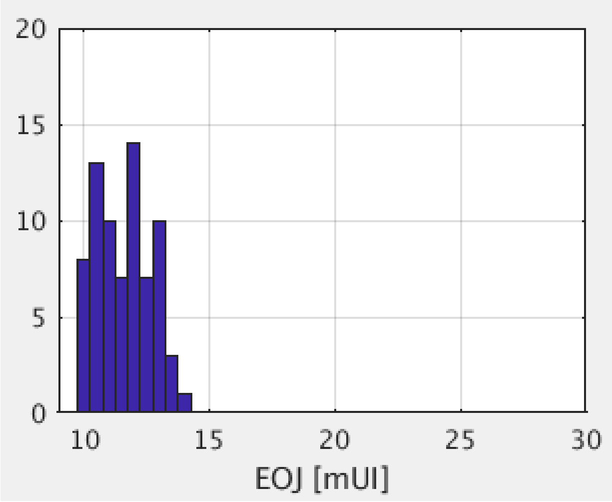
DUT 2: 53.125 GBd PAM4 TX

CR Loop BW: 4 MHz (current spec)



- EOJ Mean: 25.8 mUI
- EOJ Min-Max: 21.5mUI - 29.5mUI (8 mUI)

CR Loop BW: 1.06 MHz



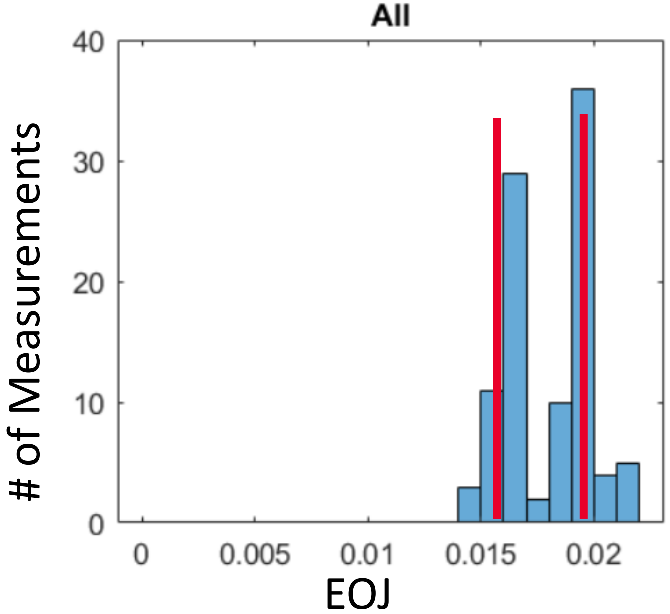
- EOJ Mean: 11.6 mUI
- EOJ Min-Max: 10 mUI – 14 mUI (4 mUI)

Effect of lowering loop BW used to measure EOJ:

- Mean is reduced (as expected per item#1 on slide 6)
- Lower CR loop BW can improve EOJ measurement accuracy.

DUT 3: 106 Gb/s PHY

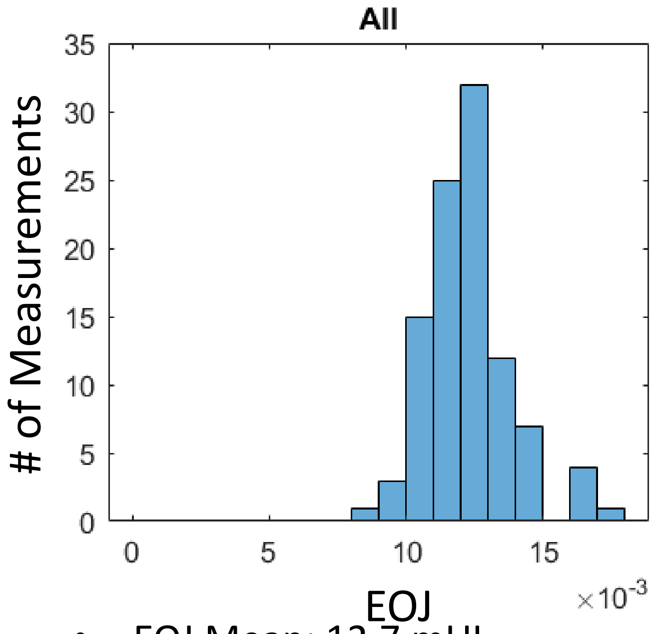
CR Loop BW: 4 MHz (current spec)



- EOJ Mean: 18.1 mUI
- EOJ Min-Max: 15.0 mUI - 21.0 mUI (6 mUI)

Bi-modal distribution in the “ALL” result (max of the 12 transitions).

CR Loop BW: 106 kHz



- EOJ Mean: 12.7 mUI
- EOJ Min-Max: 9.0 mUI - 17.0 mUI (8 mUI)

Normal distribution in “ALL” results and individual 12 transitions.

Effect of lowering loop BW used to measure EOJ:

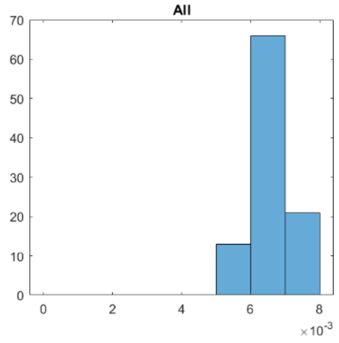
- Mean is reduced (as expected per item#1 on slide 6)
- Bi-modal distribution is mitigated (as expected per item#2 on slide 6)
- Lower CR loop BW can improve EOJ measurement accuracy.

EOJ Measurement Repeatability

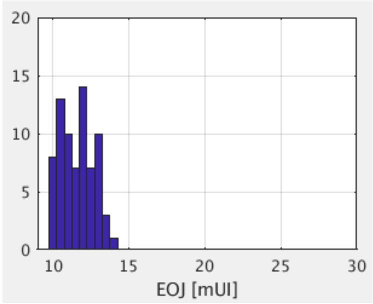
- Degraded signals (closed eyes, slower dV/dt, jitter, skew) generated by a “real” DUT will impact EOJ repeatability.

- @ 53.125 GBd:
  - EOJ max: 19 mUI = 358 fs
  - 1 mUI < 19 fs

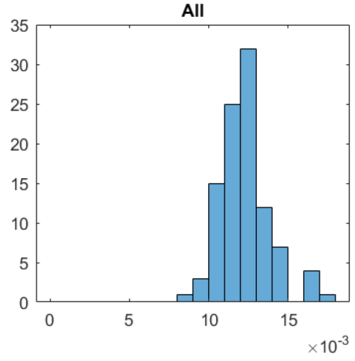
➢ **Consider an increase EOJ max spec**
to account for measurement repeatability of T&M equipment on “real” PAM4 signals.



- EOJ Mean: 6.3mUI
- **EOJ Min – Max: 5.0mUI - 7.5mUI (2.5 mUI)**



- EOJ Mean: 11.6 mUI
- **EOJ Min-Max: 10 mUI – 14 mUI (4 mUI)**



- EOJ Mean: 12.7 mUI
- **EOJ Min-Max: 9.0 mUI - 17.0 mUI (8 mUI)**

Recommendations to support anticipated comments against Draft 1.3

1. **Change CR Loop BW for EOJ measurements from "4 MHz" to "<= 4 MHz". Add text to IEEE 802.3ck Draft 1.3:**
   a. Section 162.9.3.3
      - "Even-odd jitter is calculated using the measurement method specified in 120D.3.2.8.2 with the exception that EOJ may be measured with a clock recovery unit (CRU) with a corner frequency of <= 4 MHz and a slope of 20 dB/decade.

   b. Annex 120F.3.1.3
      - "Even-odd jitter is calculated using the measurement method specified in 120D.3.2.8.2 with the exception that EOJ may be measured with a clock recovery unit (CRU) with a corner frequency of <= 4 MHz and a slope of 20 dB/decade.

2. **Increase EOJ max spec from 19 mUI to 25 mUI** to account for measurement repeatability of T&M equipment on "real" PAM4 signals.
   a. Table 162-10
   b. Table 120F-1

162.9.3.3 Output jitter

Output jitter is characterized by three parameters, J3u, J_{RMS}, and even-odd jitter. These parameters are calculated from measurements with a single transmit equalizer setting to compensate for the loss of the transmitter package and host channel. The equalizer setting is chosen to minimize any or all of the jitter parameters.

J3u and J_{RMS} are calculated using the measurement method specified in 120D.3.1.8.1. J3u is defined as the time interval that includes all but 10^{-3} of $f_J(t)$, from the 0.05th to the 99.95th percentile of $f_J(t)$.

Even-odd jitter is calculated using the measurement method specified in 120D.3.1.8.2.

120F.3.1.3 Output jitter

Output jitter is characterized by three parameters: J4u, J_{RMS}, and even-odd jitter. These parameters are calculated from measurements with a single transmit equalizer setting to compensate for the loss of the transmitter package and test fixture. The equalizer setting is chosen to minimize any or all of the jitter parameters.

J4u and J_{RMS} are calculated using the jitter measurement method specified in 120D.3.1.8.1.

Even-odd jitter is calculated using the jitter measurement method specified in 120D.3.1.8.2.

Even-odd jitter, pk-pk[d]	162.9.3.3	0.019	UI
Even-odd jitter (max)	120F.3.1.3	0.019	UI

(at 53 GBd, 1 mUI < 19 fs)

Thank you for your time!

Appendix: Supplemental EOJ Measurement Data and material directed towards comments: 186, 187,188,189, 190

Compare EOJ data measured using PRBS13Q and 4MHz CR Loop BW (current method defined in 802.3ck D1.3) to:

1. PRBS13Q / 106 kHz (same pattern, lower CR loop BW vs Standard)
2. PRBS9Q / 4 MHz (shorter test pattern, same CR loop BW vs Standard)

DUT 1: M8040A JBERT Pattern Generator – Setup#1

IMPACT OF LOWER LOOP BW AND SHORTER TEST PATTERN (PRBS9Q) ON O/P JITTER

Current Test Method per 802.3ck D1.3

CR Loop BW: 4 MHz, PRBS13Q, N = 100

- EOJ Mean: 12.3 mUI
- EOJ Min-Max: 11 - 13.5 mUI (2.5 mUI)
- J3u Mean: 69.9 mUI
- J3u Min-Max: 62 – 78 mUI (16 mUI)
- J_{RMS} Mean: 9.7 mUI
- J_{RMS} Min-Max: 9.3 - 10.3 mUI (1.0 mUI)

Lower Loop BW

CR Loop BW: 106 kHz, PRBS13Q, N = 100

- EOJ Mean: 10.0 mUI
- EOJ Min-Max: 9 - 11 mUI (2 mUI)
- J3u and J_{RMS} are not valid (loop BW too low).

Shorter Test Pattern

CR Loop BW: 4 MHz, PRBS9Q, N = 100

- EOJ Mean: 9.9 mUI
- EOJ Min-Max: 9 - 11 mUI (2 mUI)
- J3u Mean: 73.9 mUI
- J3u Min-Max: 70.5 - 78.5 mUI (8 mUI)
- J_{RMS} Mean: : 9.9 mUI
- J_{RMS} Min-Max: 9.6 - 10.3 mUI (0.7 mUI)

Effect of using Lower CR Loop BW and PRBS9Q to measure Output Jitter (EOJ, J3u, J_{RMS}):

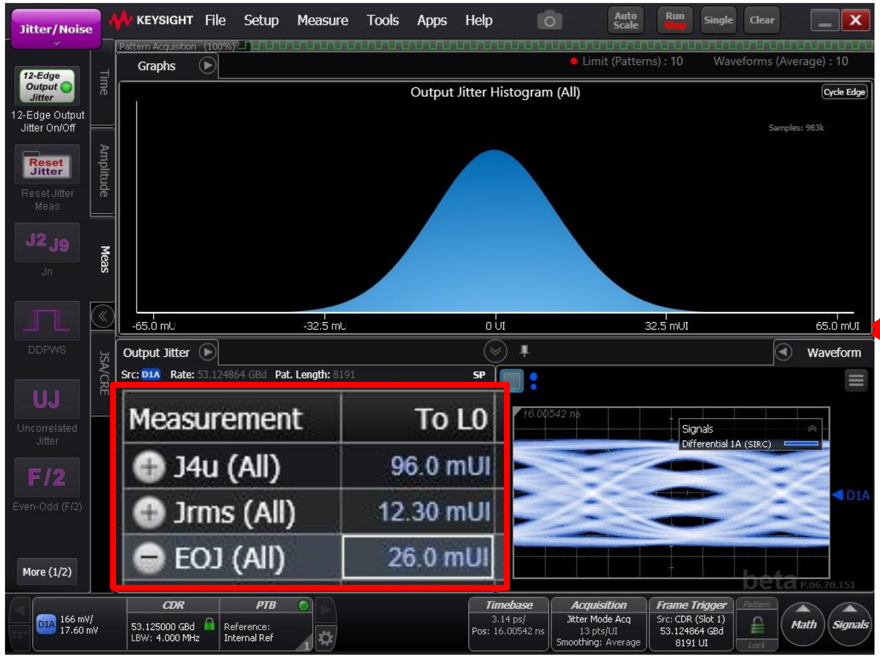
- EOJ Mean is reduced (as expected per item#1 on slide 6)
- Minimal impact on Min-Max range (clean DUT)

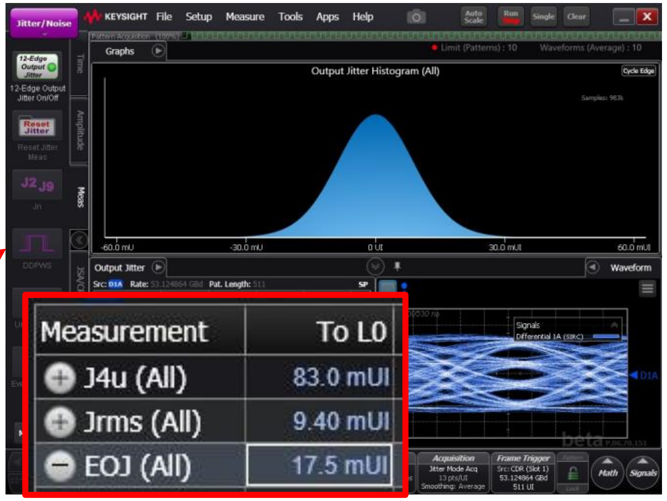
DUT 1: M8040A JBERT Pattern Generator – Setup#2

IMPACT OF SHORTER TEST PATTERN (PRBS9Q / PRBS11Q) ON EOJ

CR Loop BW: 4 MHz, PRBS13Q (current spec)

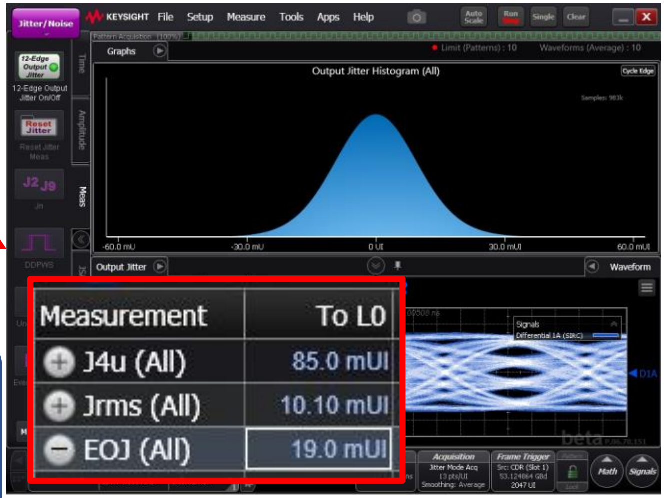
- EOJ: 26 mUI
- J4u: 96 mUI
- J_{RMS}: 12.3 mUI





CR Loop BW: 4 MHz, PRBS9Q

- EOJ: 17.5 mUI
- J4u: 83 mUI
- J_{RMS}: 9.4 mUI



CR Loop BW: 4 MHz, PRBS11Q

- EOJ: 19 mUI
- J4u: 85 mUI
- J_{RMS}: 10.1 mUI

Effect of using PRBS9Q / PRBS11Q to measure Output Jitter:

- EOJ Mean is reduced (as expected per item#1 on slide 6)
- Good Output Jitter correlation using shorter patterns (PRBS9Q, PRBS11Q)

DUT 2: 53.125 GBd PAM4 TX

IMPACT OF SHORTER TEST PATTERN (PRBS9Q) ON EOJ

DUT not available to test with PRBS9Q pattern.

DUT 3: 106 Gb/s PHY

COMPARE IMPACT OF LOWER LOOP BW & SHORTER TEST PATTERN ON EOJ

Current Test Method per 802.3ck D1.3

CR Loop BW: 4 MHz, PRBS13Q, N = 100

- EOJ Mean: 15.5 mUI
- EOJ Min-Max: 10.5 mUI - 21.0 mUI (10.5 mUI)

- J3u Mean: 116 mUI
- J3u Min-Max: 114 - 120 mUI (6 mUI)

- J_{RMS} Mean: 17.6 mUI
- J_{RMS} Min-Max: 17.2 – 17.9 mUI (0.7 mUI)

Lower CR Loop BW

CR Loop BW: 106 kHz, PRBS13Q, N = 100

- EOJ Mean: 12.7 mUI
- EOJ Min-Max: 9.0 mUI - 17.0 mUI (8 mUI)

- J3u and J_{RMS} are not valid (loop BW too low).

Shorter Test Pattern

CR Loop BW: 4 MHz, PRBS9Q, N = 100

- EOJ Mean: 11.7 mUI
- EOJ Min-Max: 9.5 - 13.5 mUI (4 mUI)

- J3u Mean: 118 mUI
- J3u Min-Max: 113 – 123 mUI (10 mUI)

- J_{RMS} Mean: 17.9 mUI
- J_{RMS} Min-Max: 17.1 - 19.1 mUI (2 mUI)

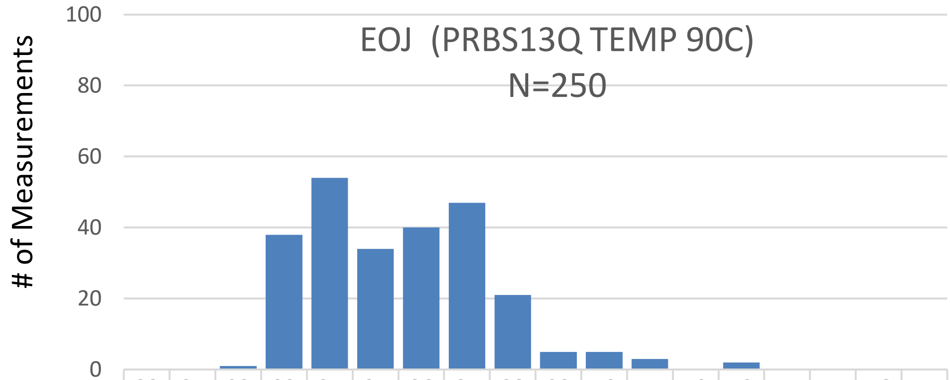
Effect of using PRBS9Q / PRBS11Q to measure Output Jitter:

- EOJ Mean is reduced (as expected per item#1 on slide 6)
- Good EOJ correlation using (i) lower loop BW (12.7 mUI) and (ii) shorter test pattern (11.7 mUI).

DUT 4: 53.125 GBd PAM4 TX (Early silicon .3ck device Data: “Worst Case Condition”)

IMPACT OF SHORTER TEST PATTERN (PRBS9Q) ON EOJ

CR Loop BW: 4 MHz, PRBS13Q (current spec)



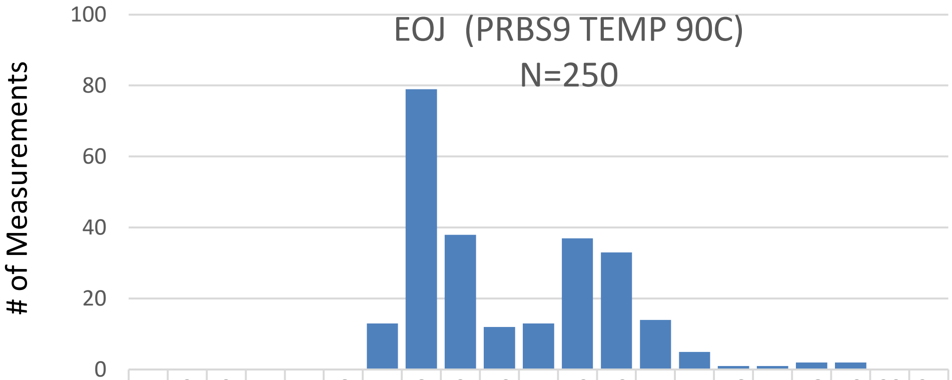
EOJ [mUI]	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47
EOJ freq	0	0	1	38	54	34	40	47	21	5	5	3	0	2	0	0	0	0

- EOJ Mean: 36 mUI
- EOJ Min-Max: 32 mUI – 43 mUI (11 mUI)

- J3u Mean: 96 mUI
- J3u Min-Max: 90 – 140 mUI (50 mUI)
- J3u StdDev: 7 mUI

- J_{RMS} Mean: 16 mUI
- J_{RMS} Min-Max: 15 – 26 mUI (11 mUI)
- J_{RMS} StdDev: 1.8 mUI

CR Loop BW: 4 MHz, PRBS9Q



EOJ[mUI]	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
EOJ freq	0	0	0	0	0	0	13	79	38	12	13	37	33	14	5	1	1	2	2	0	0

- EOJ Mean: 10.6 mUI
- EOJ Min-Max: 7 mUI – 19mUI (12 mUI)

- J3u Mean: 83 mUI
- J3u Min-Max: 75 – 125 (50 mUI)
- J3u StdDev: 6.25 mUI

- J_{RMS} Mean: 12.2 mUI
- J_{RMS} Min-Max: 11 – 21 mUI (10 mUI)
- J_{RMS} StdDev: 1.2 mUI

Effect of using PRBS9Q to measure Output Jitter (EOJ, J3u, J_{RMS}):
- Mean is reduced (as expected per item#1 on slide 6)
- Minimal impact on Min-Max range (likely due to “worst case condition”)