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Current Limitation and New Method to Accurately Estimate Reference Signal Jitter for 100+ Gbps 802.3 and OIF/CEI Interference Tolerance Test

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Information Classification: General

Abstract

IEEE 802.3 Ethernet and OIF/CEI specify the required characteristics of high-speed serial link building blocks to guarantee the interoperability. Interference tolerance test is a critical compliance item for a receiver to work properly with degraded signal. The amount of the signal degradation from the signal source to the input of the receiver under test is calibrated with COM. The test engineer must provide the jitter value of their own signal generator. COM requires random jitter (σ_{RJ}) and dual-Dirac deterministic jitter (A_{DD}), which are converted by the standard-specified equations from the measured jitter values (Jnu, Jrms) of their signal generator.

The issue is that the conversion from (Jnu, Jrm) to (A_{DD}, σ_{RJ}) using the current standard's method can be very inaccurate under certain conditions where the simple approximation used in the standard does not work well. In this paper, we discuss mathematically accurate solution for this conversion. Then, we propose two new methods keeping the existing framework and/or equations as much as possible. The first method is to use a lookup table utilizing the mathematically accurate solution. There is no closed form solution for this set of non-linear equations. Using look table with existing two equations is equivalent to providing the 3rd equation to solve the problem with three unknows. The second method is to add more conditional data processing to improve approximation.

Authors Biography

Masashi Shimanouchi is a design engineer at Intel Corporation. His work on high-speed serial links, transceiver IPs and FPGA products includes link system and component architecture design, mathematical modeling of physical link and forward error correction, link and device characterization, and link jitter and BER simulation tools development with expertise in digital communication, signal processing, signal integrity and jitter/noise.

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Dr. Hsinho Wu is a principal engineer at Intel Corporation. He presently works on high-speed communication systems of FPGA products. His development and research interests include signal integrity, clock and data recovery, equalizations, system modeling and simulation techniques. Dr. Wu was with National Semiconductor from 1999-2011 where he developed high speed interface products.

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1 Introduction

IEEE 802.3 Ethernet and OIF/CEI specify the required characteristics of high-speed serial link building blocks so that the interoperability among them provided by various parties be guaranteed. The three major building blocks of a high-speed serial link are transmitter, channel and receiver. Input signal to a receiver is degraded due to ISI, jitter, noise, etc. Receiver interference tolerance (ITOL) is a capability to work properly with such degraded signal, and therefore interference tolerance test is one of the most critical compliance items.

The 106G Ethernet [1] and the 112G OIF/CEI [2] standards development was started in 2017, and they are now in finalizing phase. While receiver interference test and its methodology has been in these standards since 25+Gbps/lane serial link [3][4][5], one critical parameter "value" change for the conversion from the measured PAM-4 jitter to the reference TX jitter model was made in 2021 to the latest 802.3 Ethernet standard drafts [1][2]. The standard documents do not describe the reason for the change and the associated technical discussion because of the nature of the standards. This paper analyzes the mathematical/theoretical issue in the previous interference tolerance test standards [3][4], and discusses two types of reference TX jitter parameters estimation methods [6][7] to solve or alleviate the issue. While final change in the standards may be less than these proposals, it is an improvement, and it would be beneficial for the practitioners to know the history behind it, especially when they face challenges to literally follow the standards.

2 Basics of Receiver Interference Tolerance Test

Before we discuss our main theme "accurate jitter model parameters estimation from measured jitter values" for ITOL test, we briefly discuss what ITOL test is. While the ITOL test methodology in both 802.3 Ethernet [1][3][4] and OIF-CEI [2][5] is essentially the same, we refer to 802.3 Ethernet specification in the following discussion for convenience.

2.1 Interference Tolerance Test Procedure

The idea is that compliant RX must work with better than or equal to the specified BER or FEC symbol error ratio with controlled/calibrated amount of stress (jitter and noise) being injected into the signal. Random and deterministic jitter injection is controlled/calibrated by the signal source jitter, and random noise injection is controlled/calibrated by the signal source noise and the additionally injected broadband noise. The ISI due to the lossy channel contributes to both the jitter and the noise.

Depending on the type of the serial link, two different broadband noise injection methods/configurations are specified as illustrated in Fig.1-a and Fig.1-b respectively. High quality pattern generator with jitter/noise injection capability is usually used as the signal source in both methods/configurations.

Fig.1-a Interference tolerance Test Setup for 100GBASE-KR1, etc.

Fig.1-b Interference tolerance Test Setup for 100GBASE-CR1, etc.

2.2 Signal Source Jitter Estimation from Measurement

COM (Channel Operating Margin [1][3]) tool is used to calibrate the jitter and the noise being injected into the signal. While COM's reference TX uses jitter model consisting of random jitter (σ_{RJ}) and dual-Dirac deterministic jitter (A_{DD}) components, the pair of jitter components (J3u, J_{RMS}) is used for PAM-4 TX jitter compliance specification, and so they are to be measured.

Therefore, the standard specifies how to convert the measured (J3u, J_{RMS}) values to the COM jitter model (σ_{RJ}, A_{DD}) values. This conversion accuracy is of our concern in this paper.

Note on (J3u, J_{RMS}) measurement:

Because of the modulation induced "apparent" jitter, PAM-4 jitter measurement methodology is different from NRZ jitter measurement methodology. As illustrated in Fig.2, PAM-4 has 6 kinds of rising edge and 6 kinds of falling edge. For each level-to-level transition causing rising or falling edge, different threshold level is specified at the middle of those two levels, and the jitter histogram of each edge is measured. Then, all the twelve jitter histograms (pdfs) are combined as illustrated in Fig.3. Jnu (n=3, 4, …) is defined as the time interval that includes all but 10^{-n} of the overall histogram (pdf) excluding $0.5 \cdot 10^{-n}$ of the population on each side. σ_{RMS} is defined as the standard deviation of the overall histogram (pdf). The standard requires to use PRBS13Q (or alternatively PRBS9Q) test pattern for this jitter measurement, and specifies which twelve edges of the test pattern are to be measured.

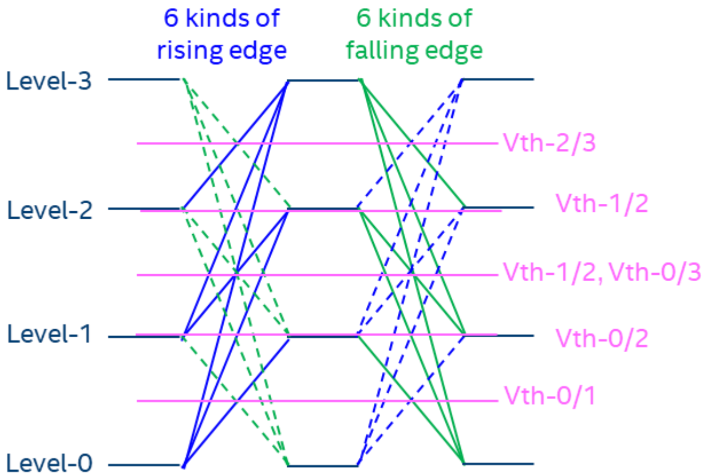

Fig.2 Twelve Kinds of PAM-4 Rising and Falling Edges

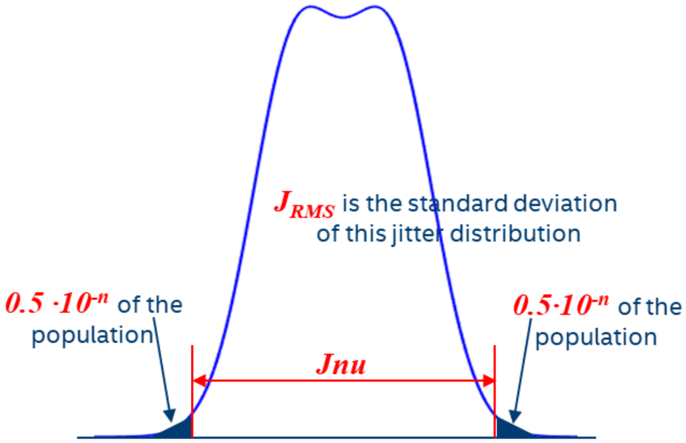

Fig.3 Aggregated PAM-4 Jitter Distribution Excluding Modulation Jitter

3 Analysis of Jitter Estimation Accuracy

Note that the “issue” discussed in this paper was in 802.3ck draft 2.0 [3], and some improvement was made to 802.3ck draft 3.0 (the latest version as of this writing) [1] after the discussion at the standard task force meetings.

3.1 Accuracy Limitation of COM Model Jitter Estimation in Standard [3]

The standard states that the parameters A_{DD} and σ_{RJ} are calculated from the measured values of J3u and J_{RMS} using the two equations, which are the same as described by (802.3 old Eq.1), (802.3 old Eq.2) and (802.3 old Eq.3) below. A note in the standard also states that when the discriminant in (802.3 old Eq.1) is negative, a different transmitter should be used in the test setup.

$$\begin{cases} A_{DD} = \dfrac{\dfrac{J3u}{2} + Q3\sqrt{(Q3^2+1)J_{RMS}^2 - \left(\dfrac{J3u}{2}\right)^2}}{Q3^2+1} & \text{(802.3 old Eq.1)} \\[2ex] \sigma_{RJ} = \dfrac{\dfrac{J3u}{2} - A_{DD}}{Q3} & \text{(802.3 old Eq.2)} \\[2ex] Q3 = 3.2905 = Q^{-1}(5\times 10^{-4}) & \text{(802.3 old Eq.3)} \\[1ex] \qquad Q(x) = \displaystyle\int_x^{\infty} \frac{1}{\sqrt{2\pi}} e^{-\frac{z^2}{2}}\, dz & \end{cases}$$

The conversion from (J3u, J_{RMS}) to (A_{DD}, σ_{RJ}) above assumes Dual-Dirac jitter model as illustrated in Fig.4, and the relation among those parameters are described by (DD-Model Eq.1) and (DD-Model Eq.2).

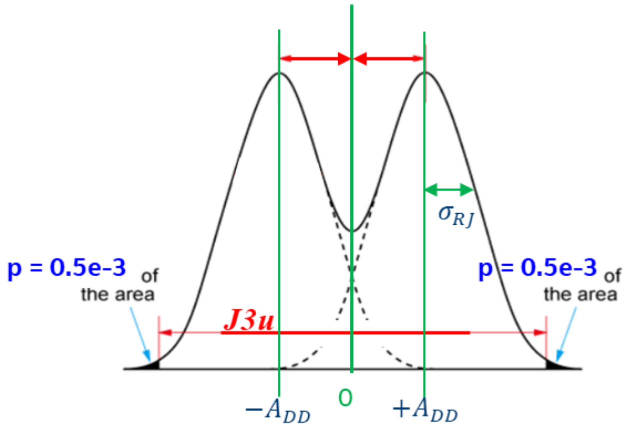

Fig.4 Dual-Dirac Jitter Model

$$\begin{cases} \dfrac{J3u}{2} = A_{DD} + Q3\cdot\sigma_{RJ} & \text{(DD-Model Eq.1)} \\[2ex] J_{RMS}^2 = A_{DD}^2 + \sigma_{RJ}^2 & \text{(DD-Model Eq.2)} \end{cases}$$

By solving the set of equations (DD-Model Eq.1) and (DD-Model Eq.2) for (A_{DD}, σ_{RJ}), another set of equations (802.3 old Eq.1) and (802.3 old Eq.2) is obtained. The challenge is that there are three unknows (J3u, J_{RMS} and Q3) instead of two (J3u and J_{RMS}) in the set of two equations (DD-Model Eq.1) and (DD-Model Eq.2). One more independent equation is needed to solve. Therefore, the standard explicitly provides the Q3 value as described by (802.3 old Eq.3).

The issue, however, is that accurate Q3 value is not constant, but it varies depending on the (A_{DD}, σ_{RJ}) values. For a given (A_{DD}, σ_{RJ}) values and the tail probability (p) in Fig.4, J3u value can be numerically obtained from the Dual-Dirac jitter model (DD-Model Eq.3). Then, true/accurate Q3 value can be obtained from (DD-Model Eq.1). An example results are shown in Fig.5 where A_{DD} value was swept from 0 to 0.02UI with σ_{RJ} =0.01UI. The improved Q3 value by an improvement proposal by [6] is also shown in Fig.5. Note the followings.

- Q3≈3.2905 when A_{DD} is much smaller than σ_{RJ}
- Q3 is smaller than 3.2905 when A_{DD} is relatively small compared with σ_{RJ}
- Q3≈3.0902 when A_{DD} is relatively large compared with σ_{RJ}
  (This value is used in the updated standard [1], newly denoted by "Q3d")

$$\frac{normcdf(x,-A_{DD},\sigma_{RJ}) + normcdf(x,+A_{DD},\sigma_{RJ})}{2} = 1 - 0.5 \times 10^{-3} \quad \text{(DD-Model Eq.3)}$$

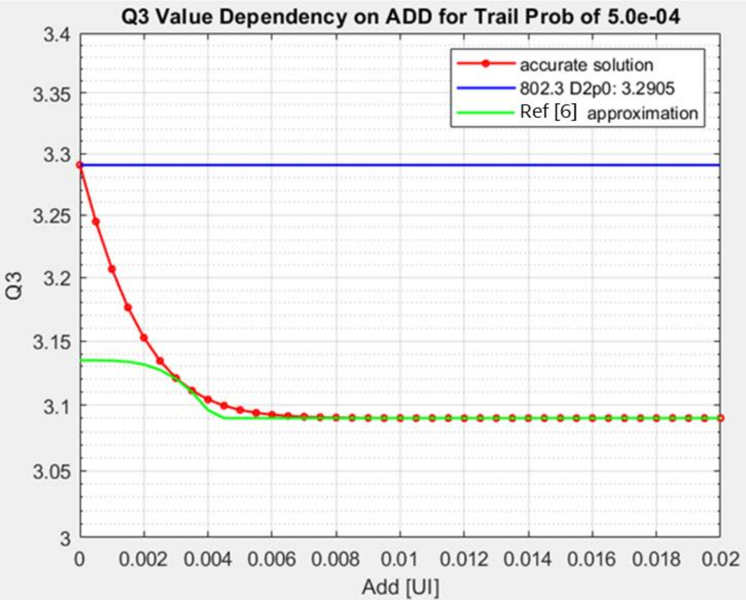

Fig.5 Q3 Value Dependency on (A_{DD}, σ_{RJ})

The conversion from (J3u, J_{RMS}) to (A_{DD}, σ_{RJ}) using (802.3 old Eq.1), (802.3 old Eq.2) and (802.3 old Eq.3) is only an approximation, and the accuracy of the results would be acceptable only under certain conditions.

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3.2 Accurate Mathematical Solution

Our objective here is to find a mathematically accurate method to obtain the (A_{DD}, σ_{RJ}) values from given (J3u, J_{RMS}) values assuming Dual-Dirac jitter model. It is beyond our scope to find general optimum solution for more practical situations such as considering measurement with noise and/or measurement error.

We begin with the set of equations (DD-Model Eq.1) and (DD-Model Eq.2). To solve them for (A_{DD}, σ_{RJ}), we need one more independent equation. Let's consider the ration of (J3u/2)/J_{RMS}, and call it α. This is a function of the ratio A_{DD}/σ_{RJ} as described by (New DD-Model Eq.1). By inversely solving it, the ratio A_{DD}/σ_{RJ} is obtained as a function of (J3u/2)/J_{RMS} as described by (New DD-Model Eq.2), which can be used as the 3rd independent equation.

$$\frac{\frac{J3u}{2}}{J_{RMS}} \equiv \alpha \equiv f\left(\frac{A_{DD}}{\sigma_{RJ}}\right) \qquad \text{(New DD-Model Eq.1)}$$

$$\therefore \frac{A_{DD}}{\sigma_{RJ}} = f^{-1}\left(\frac{\frac{J3u}{2}}{J_{RMS}}\right) \equiv g(\alpha) \equiv g_\alpha \qquad \text{(New DD-Model Eq.2)}$$

From (DD-Model Eq.1), (DD-Model Eq.2), (New DD-Model Eq.1) and (New DD-Model Eq.2), the ratio $(J3u/2)^2/J_{RMS}^2$ is obtained as described by (New DD-Model Eq.3). By solving this equation, accurate Q3 is obtained as described by (New DD-Model Eq.4).

$$\frac{\left(\frac{J3u}{2}\right)^2}{J_{RMS}^2} = \alpha^2 = \frac{(g_\alpha + Q3)^2}{g_\alpha^2 + 1} \qquad \text{(New DD-Model Eq.3)}$$

$$\therefore Q3 = -g_\alpha + \alpha\sqrt{g_\alpha^2 + 1} \qquad \text{(New DD-Model Eq.4)}$$

Substituting A_{DD} in (DD-Model Eq.1) by $g_\alpha \sigma_{RJ}$ obtained from (New DD-Model Eq.2) and using the accurate Q3 obtained above, (New DD-Model Eq.5) is obtained, from which accurate σ_{RJ} is obtained as described by (New DD-Model Eq.6). Then, from (New DD-Model Eq.2) and (New DD-Model Eq.6), accurate A_{DD} is obtained as described by (New DD-Model Eq.7).

$$\frac{J3u}{2} = A_{DD} + Q3 \cdot \sigma_{RJ} = (g_\alpha + Q3)\sigma_{RJ} \quad \text{(New DD-Model Eq.5)}$$

$$\begin{cases} \sigma_{RJ} = \dfrac{\frac{J3u}{2}}{Q3 + g_\alpha} & \text{(New DD-Model Eq.6)} \\ A_{DD} = g_\alpha \sigma_{RJ} & \text{(New DD-Model Eq.7)} \end{cases}$$

Thus, we have shown that mathematically accurate (A_{DD}, σ_{RJ}) values can be obtained from given (J3u, J_{RMS}) values assuming Dual-Dirac jitter model.

4 Two Types of Methods for Reference TX Jitter Parameters Estimation

In section 3, we focused on the mathematical/theoretical aspect of the issue and the solution, and have shown that mathematically accurate (A_{DD}, σ_{RJ}) values can be obtained from given (J3u, J_{RMS}) values assuming Dual-Dirac jitter model. In this section, we discuss the two methods / procedures, to convert measured PAM-4 jitter (J3u, J_{RMS}) values to the COM reference TX jitter parameters (A_{DD}, σ_{RJ}) values. The method-1 is our proposal to implement accurate formulas discussed section 3, and the method-2 includes three progressive accuracy improvement with approximation formulas.

4.1 Method-1: Accurate Estimation Using Lookup Table

As discussed in section 3, one more independent equation is needed for mathematically accurate solution, and we showed that (New DD-Model Eq.2) can be used for this purpose. Since this equation is not in a closed form, we propose to use a lookup table as shown in Table.1 with interpolation if needed.

$J3u/2/J_{RMS}$	A_{DD}/σ_{RJ}	$J3u/2/J_{RMS}$	A_{DD}/σ_{RJ}	$J3u/2/J_{RMS}$	A_{DD}/σ_{RJ}	$J3u/2/J_{RMS}$	A_{DD}/σ_{RJ}
3.29052673	0.00	3.28612098	0.22	3.03807708	0.80	1.92590056	3.00
3.29052671	0.01	3.28532567	0.23	2.96602742	0.90	1.90041853	3.10
3.29052639	0.02	3.28443584	0.24	2.89226854	1.00	1.87621900	3.20
3.29052500	0.03	3.28344629	0.25	2.81866747	1.10	1.85321463	3.30
3.29052126	0.04	3.28235203	0.26	2.74654361	1.20	1.83132499	3.40
3.29051341	0.05	3.28114832	0.27	2.67677303	1.30	1.81047605	3.50
3.29049919	0.06	3.27983066	0.28	2.60989485	1.40	1.79059962	3.60
3.29047590	0.07	3.27839483	0.29	2.54620285	1.50	1.77163289	3.70
3.29044038	0.08	3.27683688	0.30	2.48581818	1.60	1.75351795	3.80
3.29038907	0.09	3.27515320	0.31	2.42874420	1.70	1.73620140	3.90
3.29031802	0.10	3.27334047	0.32	2.37490675	1.80	1.71963392	4.00
3.29022293	0.11	3.27139570	0.33	2.32418290	1.90	1.70376998	4.10
3.29009919	0.12	3.26931625	0.34	2.27642109	2.00	1.68856745	4.20
3.28994190	0.13	3.26709981	0.35	2.23145516	2.10	1.67398735	4.30
3.28974592	0.14	3.26474438	0.36	2.18911370	2.20	1.65999355	4.40
3.28950592	0.15	3.26224833	0.37	2.14922637	2.30	1.64655257	4.50
3.28921639	0.16	3.25961034	0.38	2.11162781	2.40	1.63363331	4.60
3.28887171	0.17	3.25682944	0.39	2.07616016	2.50	1.62120690	4.70
3.28846618	0.18	3.25390495	0.40	2.04267435	2.60	1.60924644	4.80
3.28799406	0.19	3.21682624	0.50	2.01103080	2.70	1.59772695	4.90
3.28744960	0.20	3.16660322	0.60	1.98109951	2.80	1.58662509	5.00
3.28682712	0.21	3.10594193	0.70	1.95275992	2.90		

Table.1 Lookup Table: A_{DD}/σ_{RJ} vs. $(J3u/2)/J_{RMS}$, for (New DD-Model Eq.2)

The procedure to obtain (A_{DD}, σ_{RJ}) from (J3u, J_{RMS}) using the lookup table is shown in Fig.5.

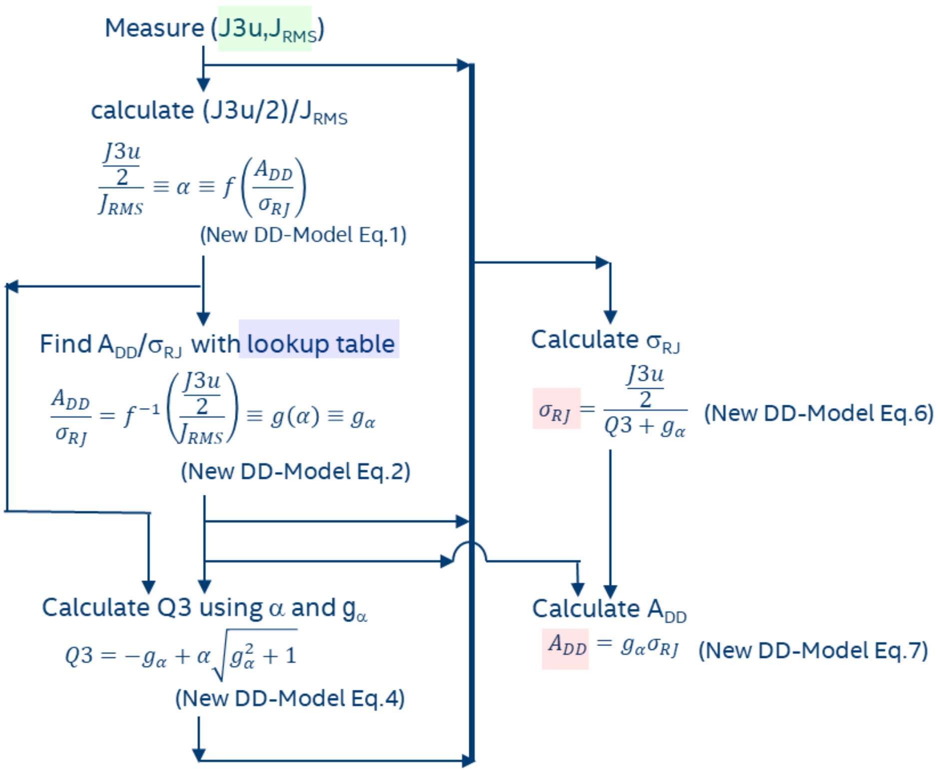


Fig.5 Procedure to obtain (A_{DD}, σ_{RJ}) from (J3u, J_{RMS}) using Lookup Table

Another diagram for the same procedure as in Fig.5 is shown in Fig.6, which may be easier to compare with the data processing diagrams with approximation formulas discussed in the next subsection.

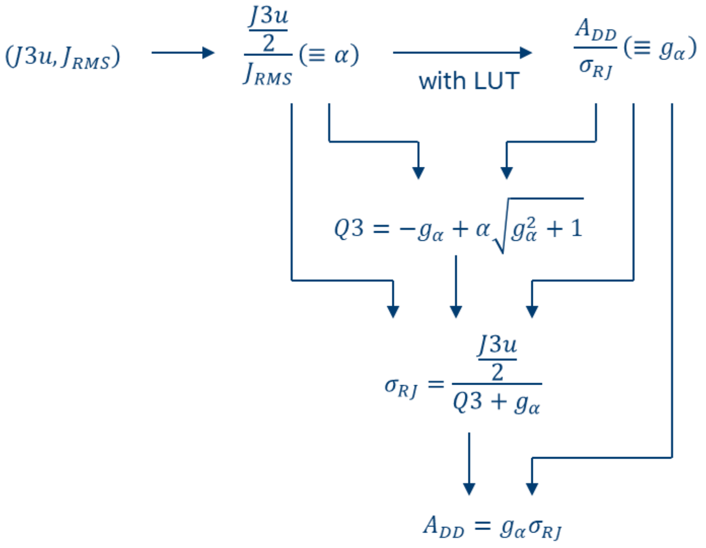


Fig.6 Simplified Data Processing Diagram for Lookup Table Method

Note on the (J3u/2)/J_{RMS} range for the lookup table:

COM reference TX jitter values for channel compliance test are specified as A_{DD} = 0.02UI and σ_{RJ} = 0.01UI respectively [1]…[5]. To find proper lookup table range and to validate the algorithm discussed above, pairs of (A_{DD}, σ_{RJ}) values around and below the specification were randomly generated, and the corresponding (J3u, J_{RMS}) values were calculated. Fig.6 shows the theoretical curve (function) for the lookup table and the randomly generated test data.

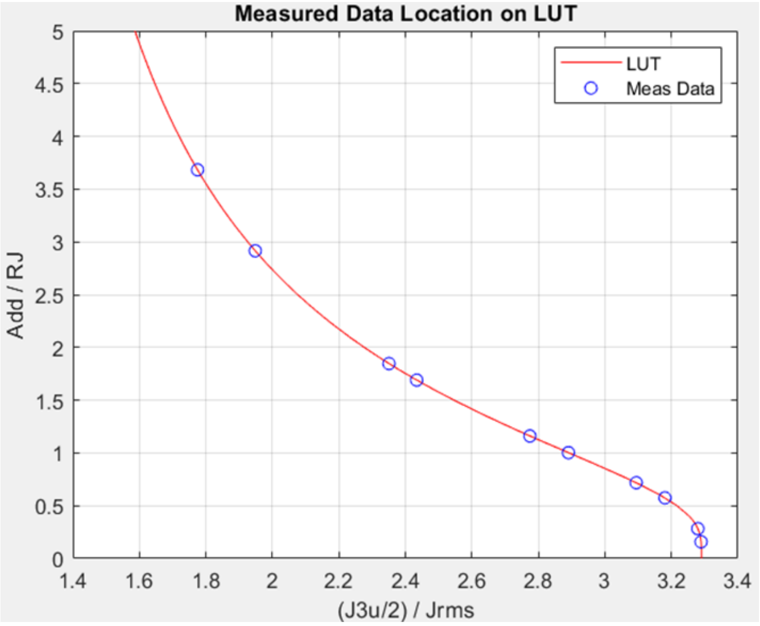
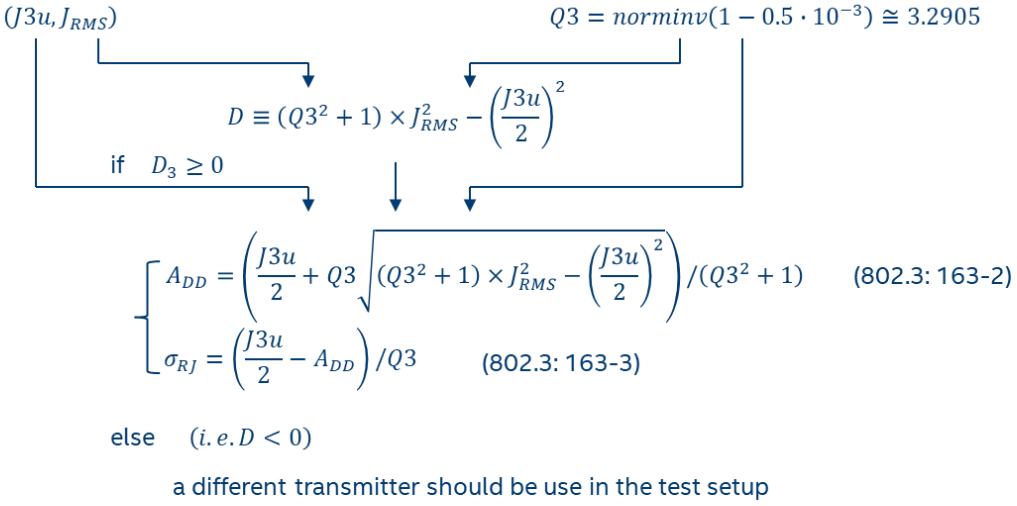


Fig.7 Theoretical Curves for Lookup Table and Random Test Data

4.2 Method-2: Progressive Accuracy Improvement with Approximation Formulas

4.2.1 Procedure up to 802.3ck D2.0 [3][4]

The old standard procedure to obtain (A_{DD}, σ_{RJ}) from (J3u, J_{RMS}) is shown in Fig.8.



$$D \equiv (Q3^2 + 1) \times J_{RMS}^2 - \left(\frac{J3u}{2}\right)^2$$

$$\begin{cases} A_{DD} = \left(\frac{J3u}{2} + Q3\sqrt{(Q3^2 + 1) \times J_{RMS}^2 - \left(\frac{J3u}{2}\right)^2}\right) / (Q3^2 + 1) & \text{(802.3: 163-2)} \\ \sigma_{RJ} = \left(\frac{J3u}{2} - A_{DD}\right) / Q3 & \text{(802.3: 163-3)} \end{cases}$$

Fig.8 Data Processing Diagram up to 802.3ck D2.0

Forcing Q3 = 3.2905 as a constant value, the two equations (DD-Model Eq.1) and (DD-Model Eq.2) can be solved for (A_{DD}, σ_{RJ}) when the discriminant D is not negative. When the discriminant is negative, the standard asks to find and use other signal source whose (J3u, J_{RMS}) values make the discriminant non-negative.

4.2.2 Accuracy Improvement by [6]

Two improvements were proposed by [6], and its procedure is shown in Fig.9. As supposed from the accurate Q3 curve for various A_{DD} in Fig.5, Q3 for wide range of A_{DD} would be rather close to 3.0902 = norminv(1-1e-3). Therefore, the default value of Q3 = 3.0902 was proposed, and it was adopted in the updated standard draft [1]. The second improvement was to perform different data processing when the discriminant is negative. With this conditional calculation, the estimated (A_{DD}, σ_{RJ}) values can be obtained even when the discriminant is negative, and one does not need to look for another signal source.

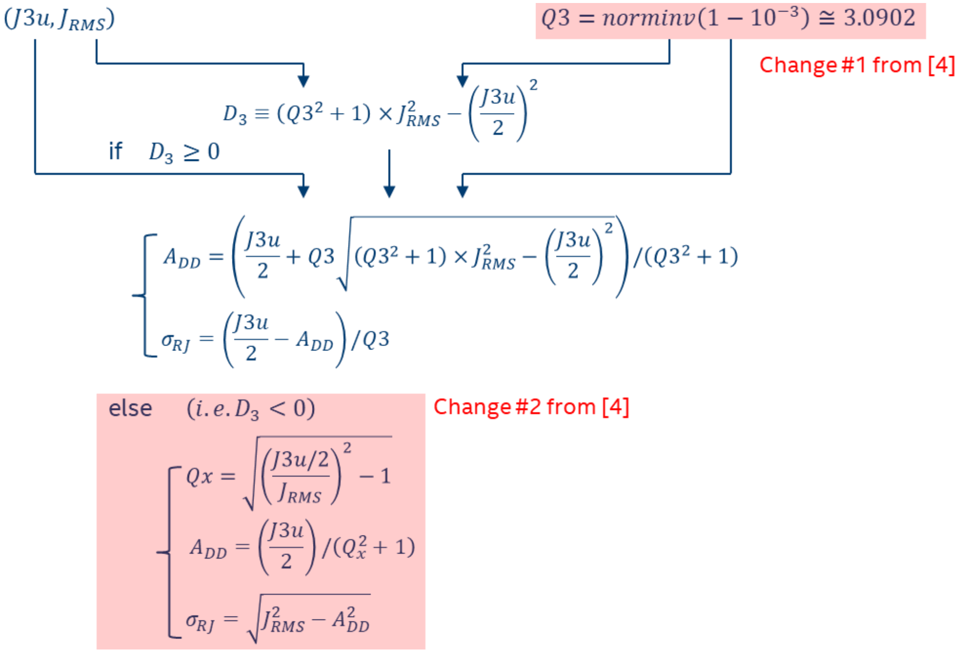


Fig.9 Conditional Data Processing

4.2.3 Further Accuracy Improvement

As shown in Fig.5, the Q3 estimation by [6] is not very accurate when A_{DD} is very small compared with σ_{RJ}. The range of A_{DD}/σ_{RJ}, however, is very small when the Q3 estimation by [6] is not very accurate as inferred from Fig.7 and Fig.5. To further improve approximation accuracy, we proposed additional conditional calculation, which is shown in Fig.10. The default Q3 value is the same as [6]. While the first conditional processing is the same as [6], the branching condition is different from [6], which uses (J3u/2//J_{RMS} indicating how close the Q value is to 3.2902 = norminv(1-0.5e-3). The second conditional processing is performed when the discriminant is negative, and the first branching condition is not met as shown in Fig.10.

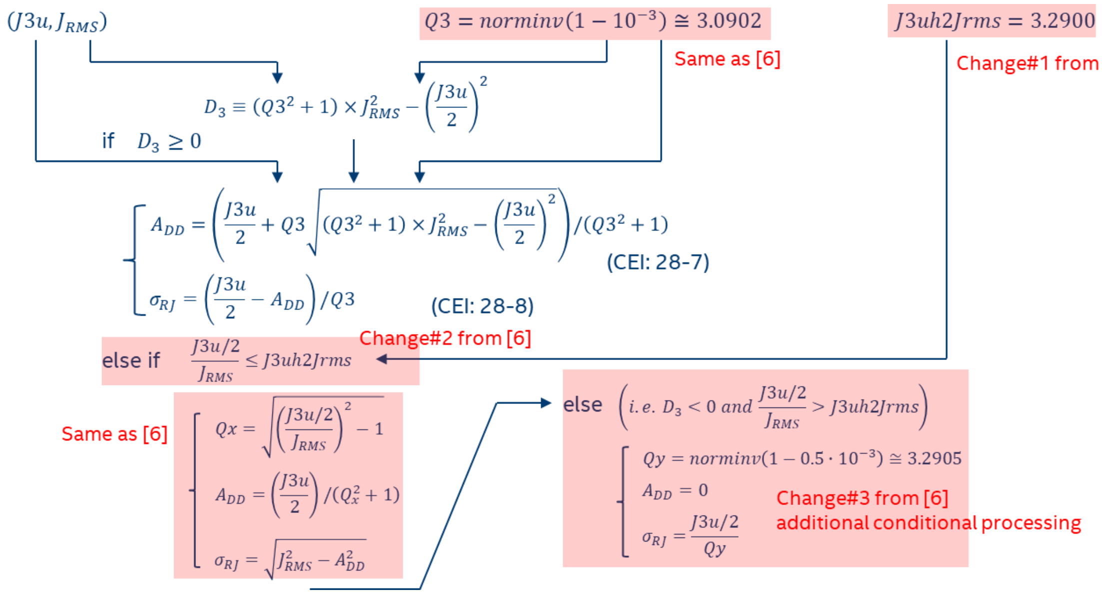


Fig.10 Additional Conditional Processing

5 Summary and Conclusion

For receiver interference tolerance test, the signal degradation from the signal source to the receiver input is calibrated with COM. The test engineer must measure the signal source jitter (Jnu, Jrms) values, which are converted to the COM reference TX jitter (A_{DD}, σ_{RJ}) values using the formulas provided by the standard.

This conversion, however, can be very inaccurate under certain conditions. In this paper, we discussed the reason for the inaccuracy, and how mathematically accurate solution can be obtained. Then, we proposed two new methods keeping the existing framework and/or equations as much as possible. The first method is to use a lookup table for mathematically accurate solution. The second method is to add more conditional data processing to improve approximation.

References

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