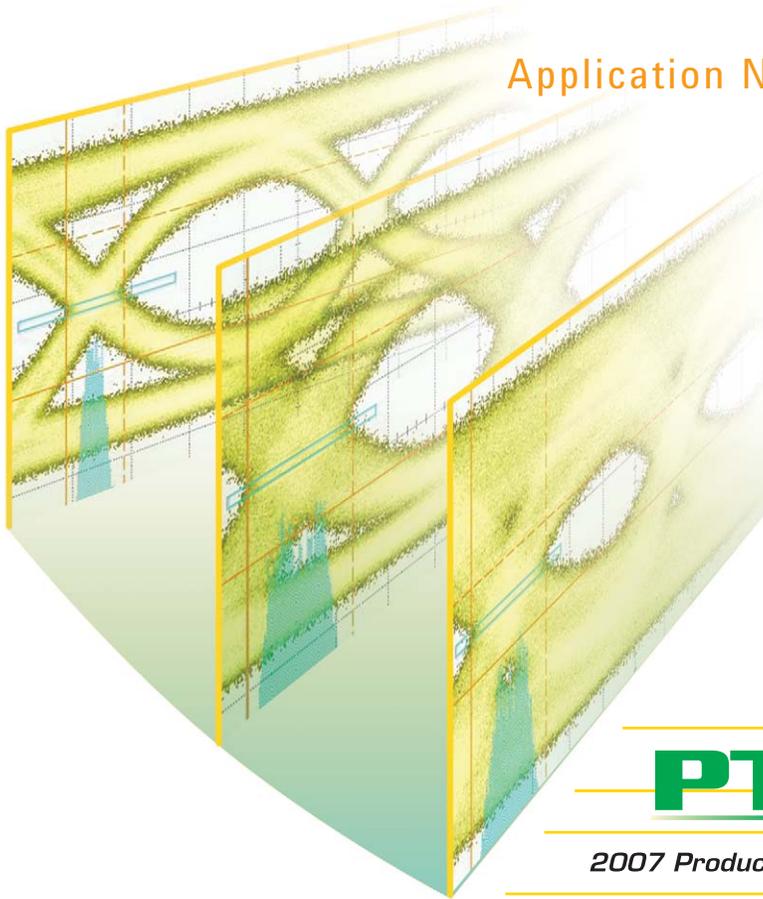


Calibrating optical stress signals for characterizing 10 Gb/s optical transceivers

Application Note



PTB

2007 Product of the Year



Agilent Technologies

What is optical stress? (Example 10 GbE)



Figure 1. The N4917A with the option E01, the Receiver Stress Conditioning Unit 10 GBASE-LR/-ER, 10 G Fibre channel and automation software (CD is not shown)

The N4917A Optical Receiver Stress Test solution with the conditioning unit N4917A-E01 as shown in figure 1 targets the standards for 10 GbE [1] and 10 GFC [2].

Figure 2 illustrates an optical stressed signal which has to be applied to an optical receiver. While such a signal is applied to the optical input, the bit error ratio at the receiver's output has to be below a certain level (typically $1e-12$) to be compliant.

Figure 3 shows the requirements of such stress signal generation from the IEEE 802.3ae standard. The fourth-order Bessel-Thomson filter is used to create ISI-induced vertical eye closure penalty (VECP). The sinusoidal amplitude causes additional vertical eye closure, the sinusoidal phase modulation represents jitter for the jitter tolerance test according to the jitter mask.

Figure 4 illustrates the whole setup of the Optical Receiver Stress Test Solution including electrical and optical cabling and including the 86100C DCA-J as calibration tool.

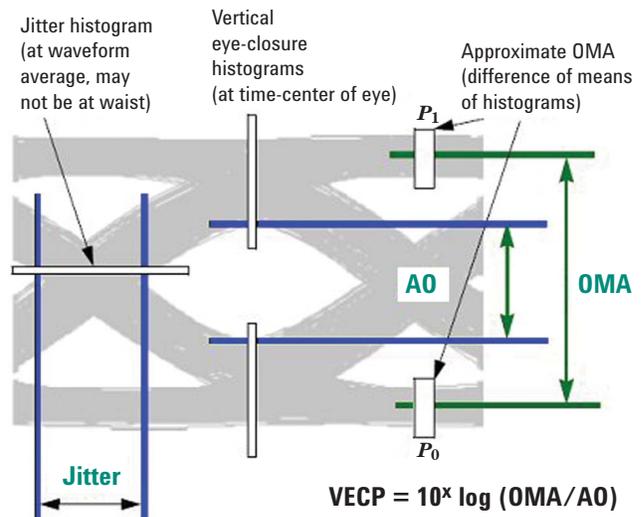
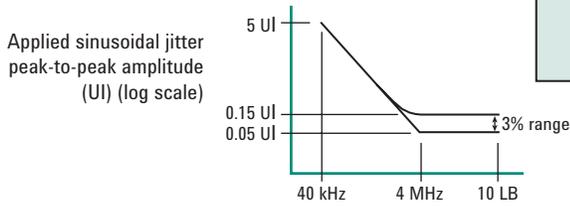


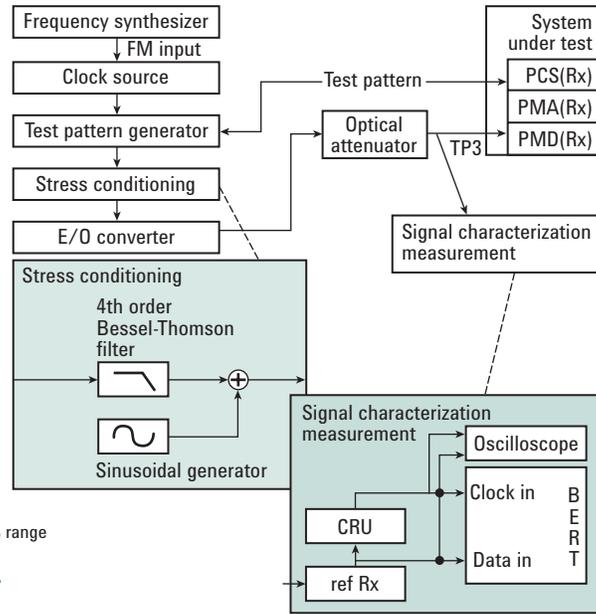
Figure 2. Definition of the optical parameters

- OMA:** Optical Modulation Amplitude, measured in $[\mu W]$ ("average signal amplitude")
- ER:** Extinction Ratio, high-level to low-level, measured in [dB] or [%]
- UI:** Unit Interval (one bit period)
- LR, SR, ER:** Flavors of 10 Gb Ethernet standard for Long Reach (10 km), Short Reach (300 m), Extended Reach (40 km)
- AO:** Vertical eye opening ("innermost eye opening at center of eye") [dBm or μW]
- VECP:** Vertical Eye Closure Penalty

- The **fourth-order Bessel-Thomson filter** is used to create ISI-induced vertical eye closure penalty (VECP)
- The **sinusoidal amplitude interferer** causes additional eye closure.
- The **sinusoidal phase modulation** represents low frequency jitter.



Mask of the sinusoidal component of jitter tolerance (informative)



Stressed receiver conformance testblock diagram

Figure 3. IEEE 802.3 ae: 52.9.10.1 Stressed Receiver Conformance Test Block Diagram

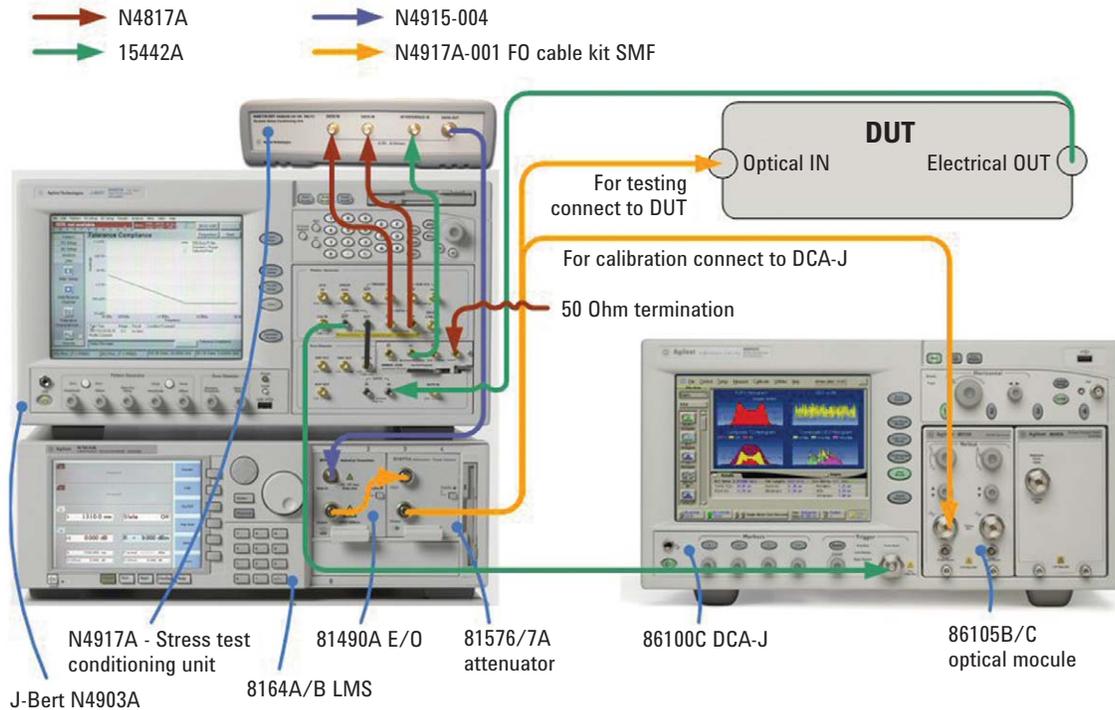


Figure 4. Test Setup Optical Receiver Stress with the N4917A

How to measure the optical parameters with the 86100C DCA-J

The main optical parameters are given in figure 2. However the following are also important to note:

- ▶ the crossing point must be kept at the 50 % of the levels
- ▶ the total jitter must include:
 - Random Jitter (RJ)
 - Duty Cycle Distortion (DCD)
 - Inter-Symbol Interference (ISI)

Examples for the measurement of all the parameters are shown in figures 5 to 8. All measurements use the PRBS pattern $2^{11}-1$ unless otherwise specified.

Extinction Ratio (ER)

The measurement of ER is shown in figure 5. There is a predefined routine available in the eye diagram mode. There is an Extinction Ratio Correction Factor (ERCF) that must be applied for measuring large ER as discussed in [3].

Crossing Point

The eye diagram mode also provides a routine for the measurement of the crossing point.

Optical Modulation Amplitude (OMA)

The OMA is measured as shown in figure 7. For this measurement a ..0011.. pattern is used. The OMA measurement is equivalent to the Eye Amplitude routine available in the eye diagram mode. By using this pattern and the Eye Amplitude routine this is equivalent to the definition as shown in figure 2.

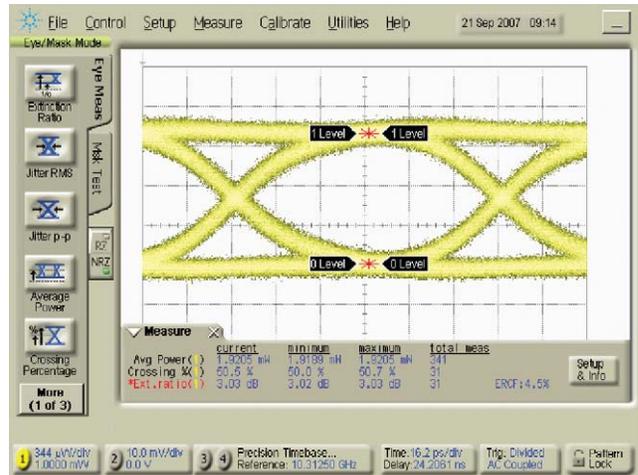


Figure 5. ER & crossing point by Eye Diagram Mode (PRBS pattern, ERCF enabled)

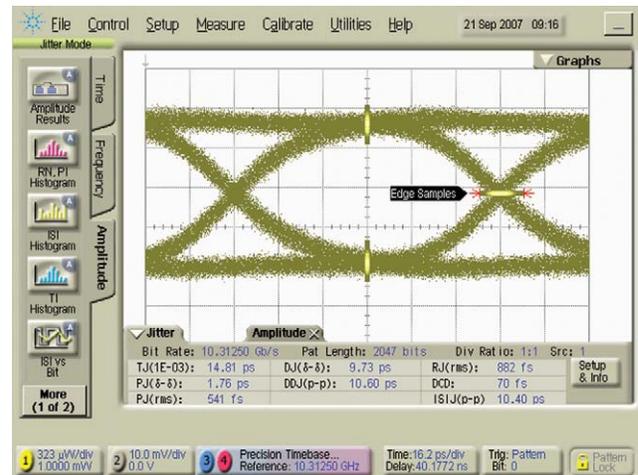


Figure 6. TJ (BER 1E-3), RJ, DCD & ISI by Jitter Mode in time

Jitter, A0 and VECP

Jitter and A0 are measured with the Jitter Mode. TJ is available from the Time Menu as shown in figure 6. A0 is available as Eye Opening from the Amplitude Menu as shown in figure 8. VECP can not be measured directly, it is calculated by the formula:

$$VECP = 10 * \log(OMA/A0).$$

Requirements

Jitter Measurements in time and amplitude require specific options (200, 300) of the 86100C DCA-J.

The measurements shown here are taken with help of a Precision time base module (86107A-010). This is recommended to verify the sub-ps RJ performance. However it is not a requirement for the calibration of the setup.

Sufficient optical power must be provided to the optical inputs of the DCA-J optical modules (1 mW for 86105B, 0.2 mW for 86105C). This is important for the verification of RJ jitter.

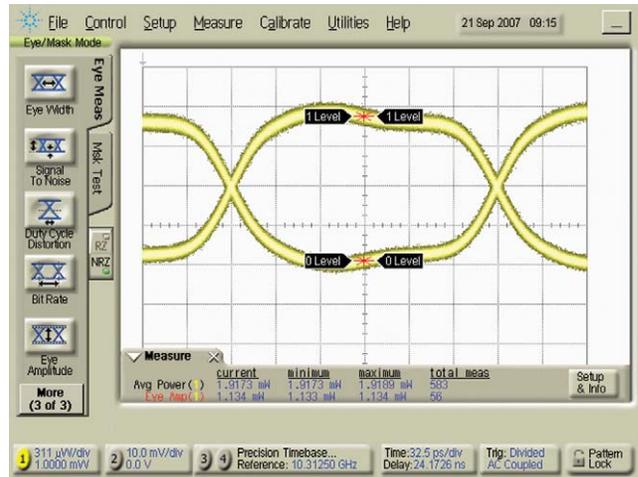


Figure 7. OMA by Eye Diagram Mode (..1100.. pattern, Routine: Eye Amplitude)

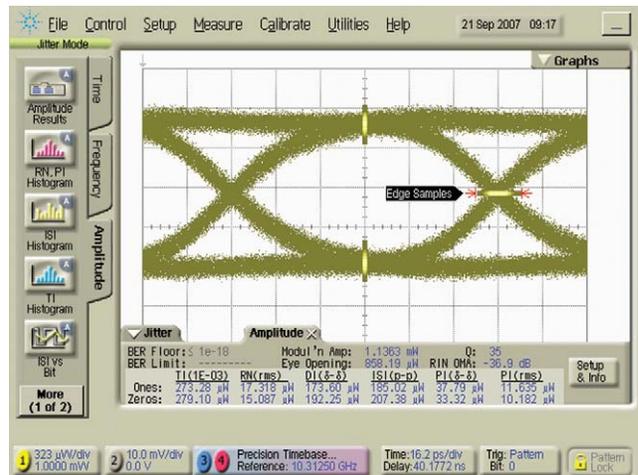


Figure 8. A0 (BER 1E-3) by Jitter Mode in Amplitude, Parameter: Eye Opening

Configuring the Measurements of the 86100C DCA-J

For the Jitter and A0 measurement there is an important statement in the IEEE 802.3ae standard saying:

The test signal includes vertical eye closure and high-probability jitter components. For this test, these two components are defined by peak values that include all but 0.1% for VECP and all but 1% for jitter of their histograms. Histograms should include at least 10,000 hits, and should be about 1%-width in the direction not being measured. Residual low-probability noise and jitter should be minimized—that is, the outer slopes of the final histograms should be as steep as possible down to very low probabilities. (from: 52.9.9.2 Stressed receiver conformance test signal characteristics and calibration)

Basically this means that random jitter during the calibration of the stressed eye should be eliminated. The definition of the peak values can be mapped to the capabilities of the 86100C DCA-J by defining the TJ and Eye Opening value as:

TJ based on (BER 1e-2),
 A0 (and VECP) based on (BER 1e-3)
 (OMA is not dependent on BER)

The 86100C DCA-J does not allow to set BER to 1e-2 directly, the lowest BER can be set for 1e-3. So the TJ for BER 1e-2 is calculated by:

$$TJ (BER 1e-2) = TJ (BER 1e-3) - 2 * RJ$$

This is derived from the nature of random jitter being Gaussian distributed. Figure 9 shows the properties of the Gaussian distribution. Figure 10 shows the histogram of a jitter measurement excluding x % of the events.

The Gaussian distribution helps to describe something which is basically infinite like random jitter.

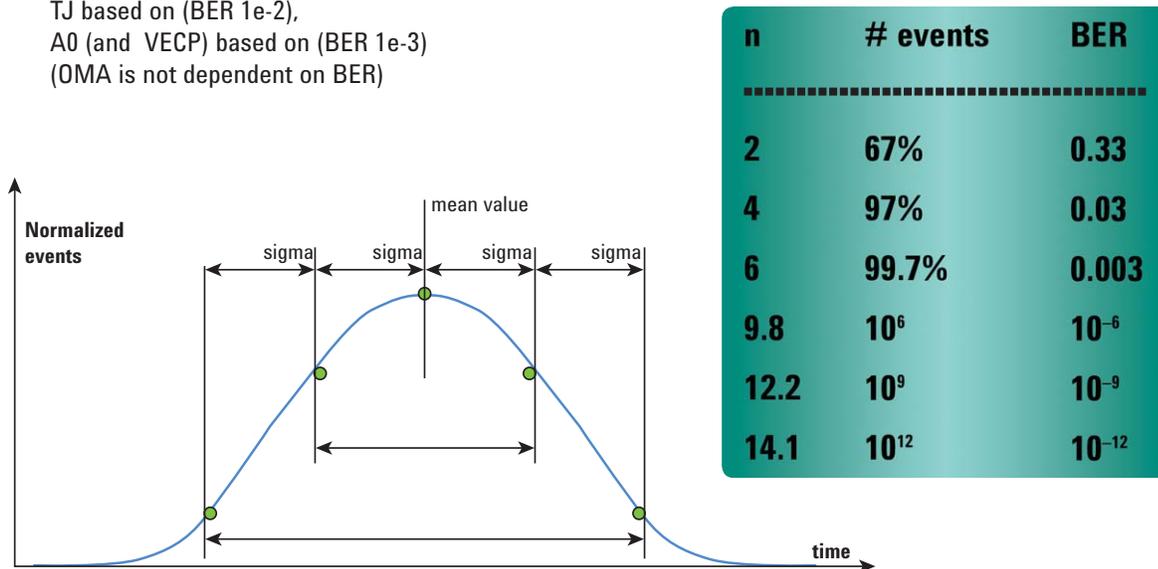


Figure 9. Gaussian distribution and the relation of BER = 1 - # events (%) / 100

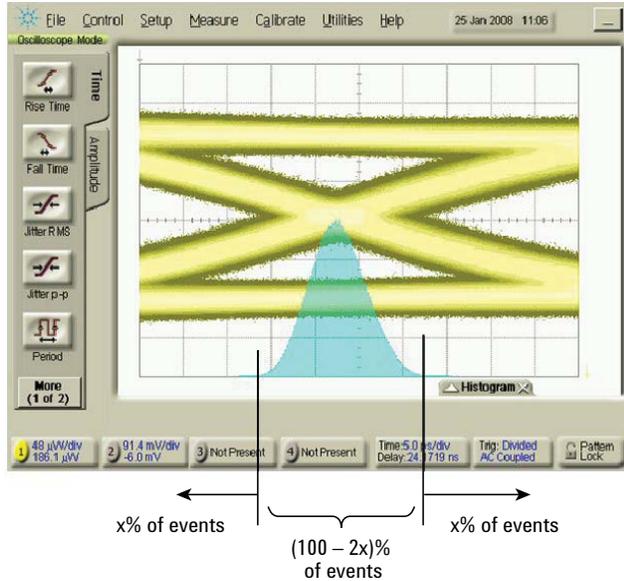


Figure 10. Histogram measurement with excluding x % of the measured events

We'd like to give a more intuitive explanation here, see [4] for a more scientific explanation:

The distribution is described by the mean value and the standard deviation sigma. As more of the events are included the more times sigma has to be included:

$$\# \text{ events} = n * \sigma$$

The table in figure 9 lists the relation with n. On the other side this can be expressed as a BER threshold. The relation of BER can be expressed as:

$$\text{BER} = 1 - \# \text{ events} (\%) / 100$$

From the table in figure 9 it gets obvious that the difference between TJ (BER 1E-2) and TJ (BER 1E -3) is 2 x sigma. In this case sigma is the reading for RJ.

Figure 11 shows the BER contour measurement. This is a measurement available on a Bit Error Ratio Test System (BERT). It shows the eye contour as a function of BER. The eye width/amplitude can be directly read according to the

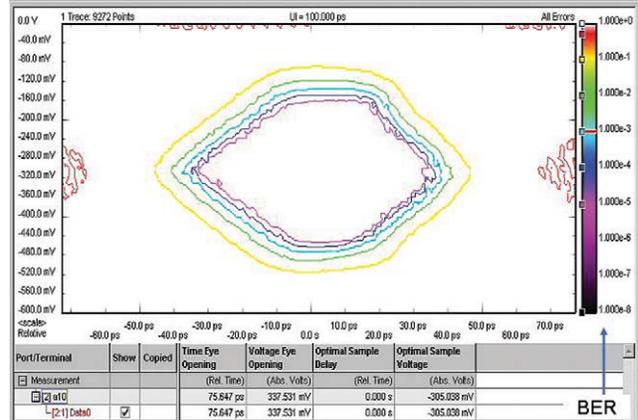


Figure 11. ISO BER measurement from a Bit Error Ratio Tester (BERT)

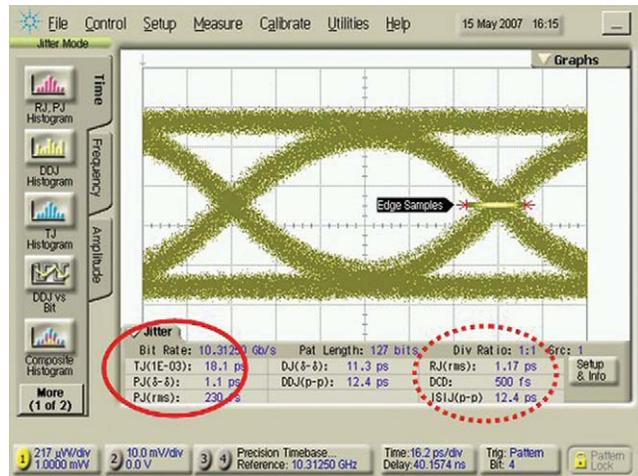


Figure 12. 86100C DCA-J Jitter measurement configured for BER 1e-3

desired BER threshold. In this example the color coding on the right side is the key for the BER threshold in the picture.

The eye width or the corresponding jitter and the eye amplitude as a function of BER can also be measured with the 86100C DCA-J with the jitter measurements. Figure 12 shows the jitter measurement in time while the DCA-J is configured for BER 1E-3.

Dependencies of Parameters

Pattern Dependency

The IEEE802.3ae defines a bandwidth limitation within the stress conditioning. The bandwidth is set to 0.75 of the data rate. This ensures the amplitude of a single bits does not achieve the 100% amplitude level. This introduces ISI type of jitter.

The standard requires to use a Bessel Thompson Filter which is also called a Gaussian filter. Compared to filter types like Butterworth or Chebyshev, a Gaussian filter provides a clean step response, see Figure 13.

Jitter and Pattern Dependency

The individual jitter parameters, as discussed in the following paragraphs, are measured with the DCA-J as shown in Figure 6.

The Figures 14 & 15 show the influence of the pattern on the total jitter and its subcomponents. The patterns used are:

- PRBS 2⁷-1
- PRBS 2¹¹-1
- PRBS 2¹⁵-1
- clock pattern (.. 0011 ..)
- K28.5
- CJTPAT

The measurements were done at a data rate of 10.3125 Gb/s. The plots in both figures compare:

- The Total Jitter (TJ)
- Inter-symbol Interference (ISI)
- Random Jitter (RJ)
- Periodic Jitter (PJ)
- Duty Cycle Distortion (DCD).

The curves compare a pure electrical filter of 7.46 GHz bandwidth with Bessel-Thompson characteristic (called electrical filter, see Figure 13) and the N4917A setup once without any jitter injection (called optical) and once with jitter injection of sinusoidal interference = 100 mV @ 1GHz and PJ = 100 mUI @ 4 MHz (called optical w jitter).

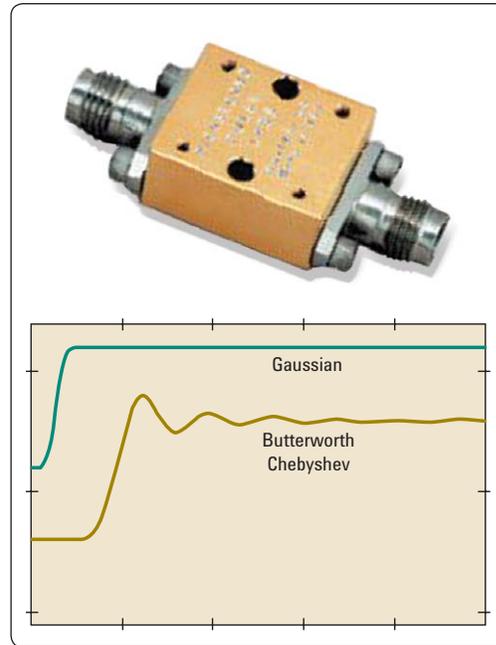


Figure 13. Example of a Bessel-Thompson Filter (Gaussian) with cut-off at 7.46 GHz and the step response compared to Butterworth/Chebyshev filter type

Results:

Figure 14:

- the ISI is pattern dependent, N4917A is very similar to the pure filter,
- TJ follows ISI behavior while the jitter modulation affects the total jitter as expected

Figure 15:

- RJ & DCD are not pattern dependent, N4917A is very similar to pure filter.
- PJ is not pattern dependent, N4917A w/o jitter modulation is marginally higher than the pure filter, with jitter modulation PJ behaves as expected.

Conclusion:

- The specifications of filter and pattern create a specific ISI content in the total jitter budget
- The use of alternate patterns for compliance tests must be avoided
- The other jitter components beside ISI can be added flexibly and calibrated at any pattern

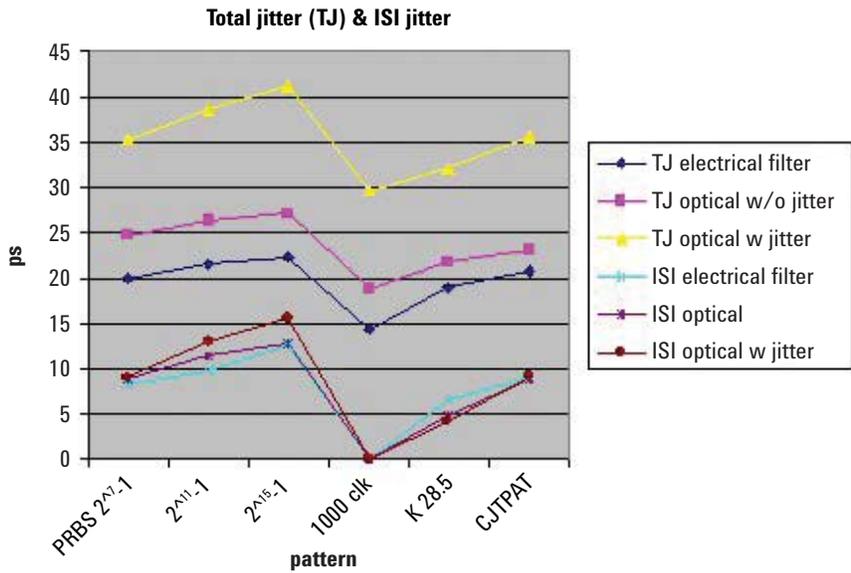


Figure 14. Total Jitter (TJ) and Inter-Symbol Interference (ISI)

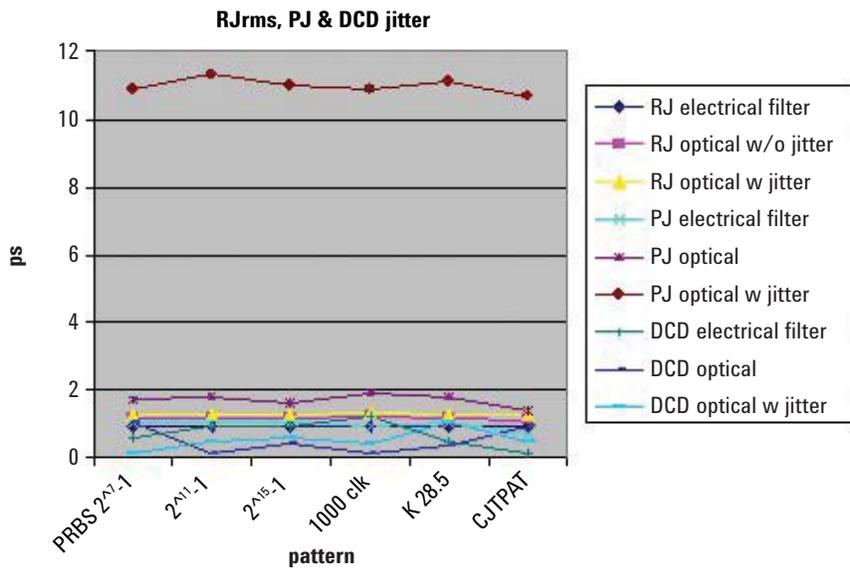


Figure 15. Random Jitter (RJ), Periodic Jitter (PJ) and Duty Cycle Distortion (DCD)

Validation of the methodology used

The following is a key recommendation in the IEEE 802.3ae standard:

A short pattern may be used for calibration if the conditions described in 52.9.9.1 are met, but increases the risk that the longer test pattern used during testing will overstress the device under test. In any case, a pattern shorter than PRBS10 is not recommended. (from: 52.9.9.2 Stressed receiver conformance test signal characteristics and calibration)

The impact of using longer patterns

The question remains:

how much jitter is added when switching from PRBS $2^{11}-1$ to $2^{31}-1$?

This can be measured with the 86100C in Eye/Mask mode with help of the histogram measurement. The results are shown in figure 16 & 17 as p-p values, see the red circles. The difference is measured as 1.33 ps for the N4917A optical signal (Figure 16 PRBS $2^{11}-1$ p-p = 23.67 ps, Figure 17 PRBS $2^{31}-1$ p-p = 25 ps, difference = 1.33 ps).

Conclusions:

Based on the standard's recommendation and the measurement capabilities of the 86100C DCA-J the PRBS $2^{11}-1$ is used for the calibration of the N4917A.

The use of shorter PRBS pattern for calibration creates a marginal impact.

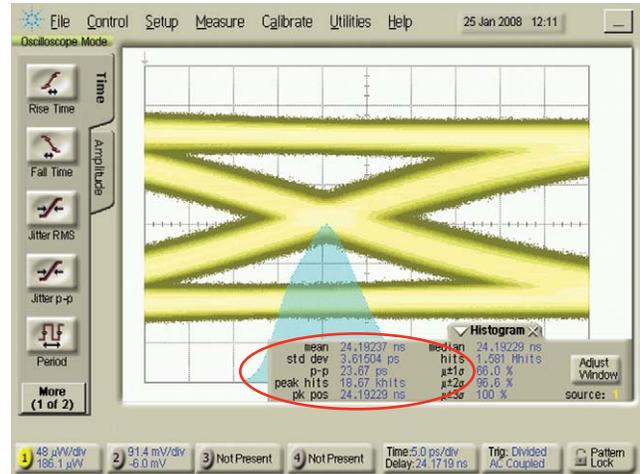


Figure 16. Histogram Measurement of the optical signal with a PRBS $2^{11}-1$

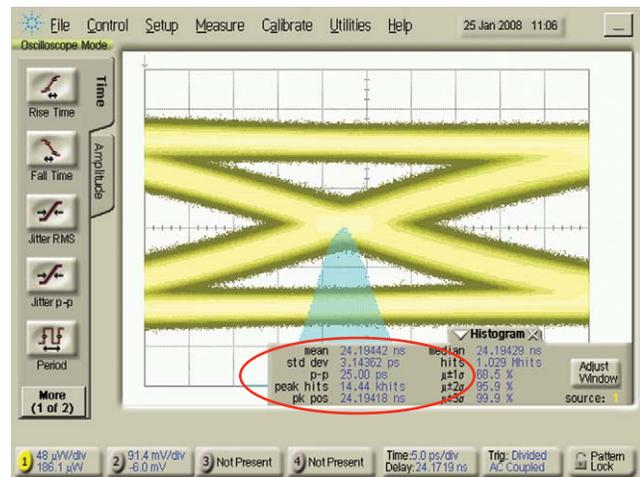


Figure 17. Histogram Measurement of the optical signal with a PRBS $2^{31}-1$

Data Rate Dependency

Figure 18 & 19 show the linearity of ER and OMA over the data rate.

Conclusions:

- A calibration has to be performed at the actual data rate
- A change of the data rate after performing a calibration must be avoided

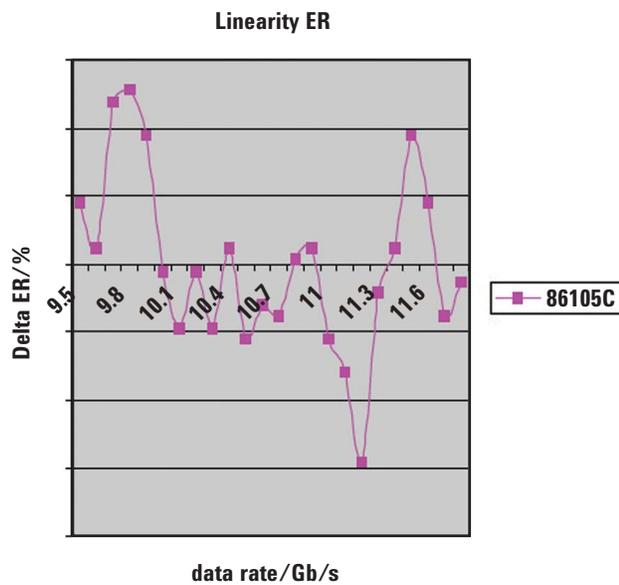


Figure 18: ER vs. data rate, linearity

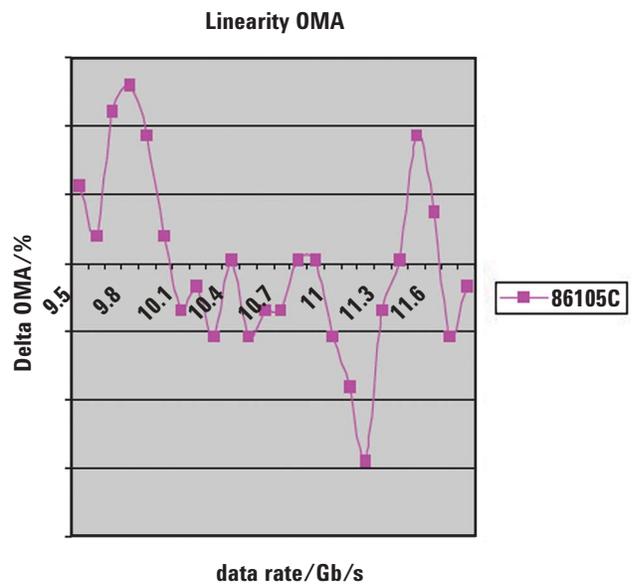


Figure 19: OMA vs. data rate, linearity

Dependencies of Optical Avg. Power, ER, OMA & A0

Figure 20 shows the dependency of OMA, A0 and optical average power as function of ER. As ER depends on the electrical amplitude of the data signal, all the optical parameters depend directly on the amplitude of the electrical data signal. Figure 20 includes a 3-point extrapolation for OMA and A0. 3 points from the measured curve are taken (referenced as Calculate A0/OMA) and used to extrapolate the curve (referenced as 3 point cal A0/OMA).

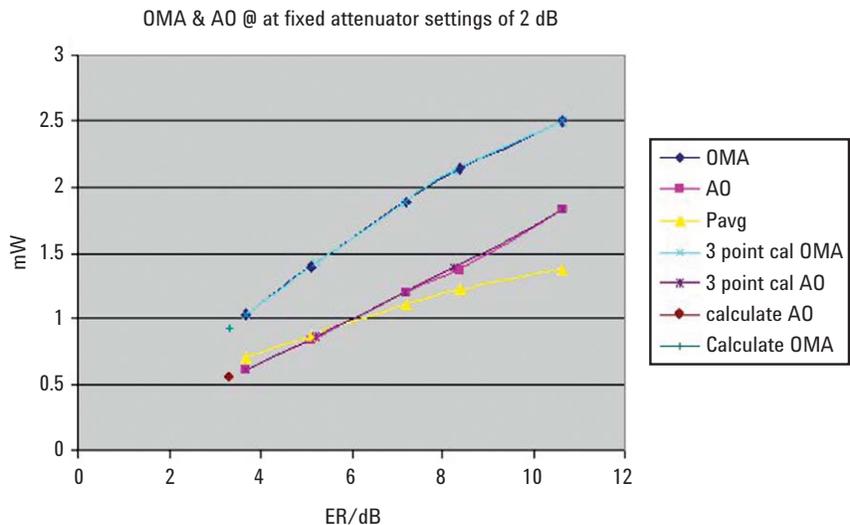


Figure 20. Optical avg. Power, MA and AO as a function of ER at fixed attenuator

Figure 21 shows the relationship of ER, OMA and optical power to the attenuator setting: ER is not affected by the attenuator setting, while OMA and optical power is a linear function of the attenuation.

Conclusions:

The deviation of the approximation of ER, OMA and A0 is marginal, so this is proven to be a valid algorithm for the calibration.

The attenuator does not need a calibration. A single power measurement as a reference is sufficient

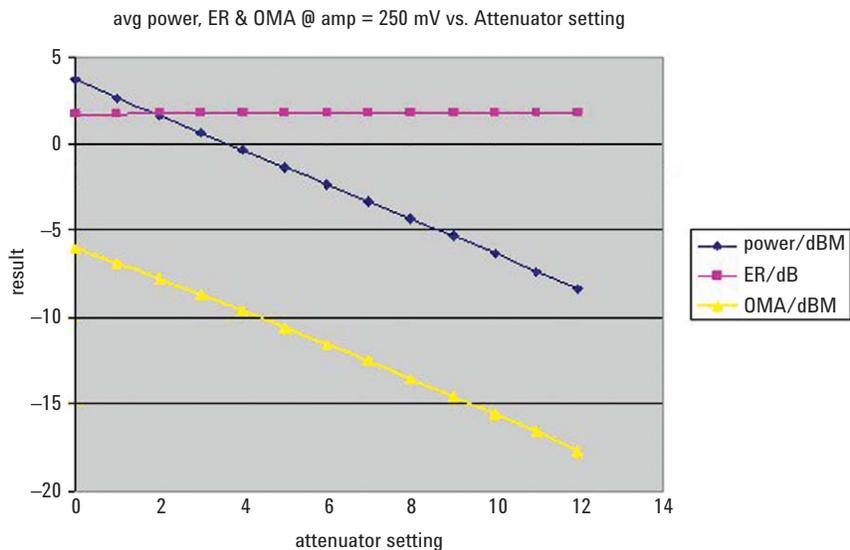


Figure 21. Optical avg. Power, OMA & ,ER as a function of attenuator setting

Dependencies of Periodic Jitter (PJ) and Sinusoidal Interference (SI)

Figure 22 to 24 are examples of histogram measurements of the optical signal with various SI & PJ modulation.

Figure 22:
PJ = 0 ps
SI = 0 mV
TJ = 19.8 ps
A0 = 372 uW
VECP = 2.66

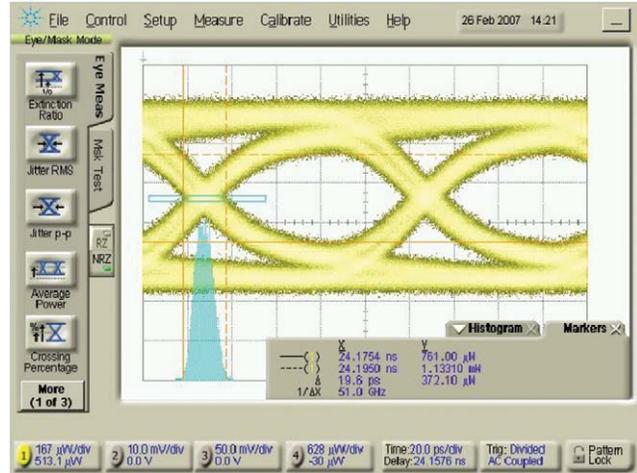


Figure 23:
PJ = 20 ps
SI = 0 mV
TJ = 37.6 ps
A0 = 354 uW
VECP = 2.87

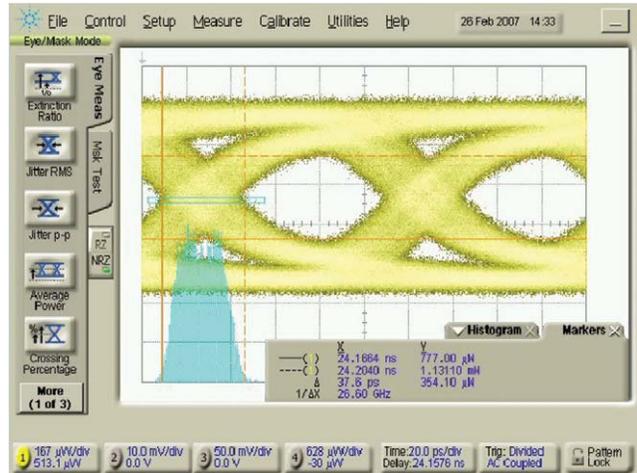
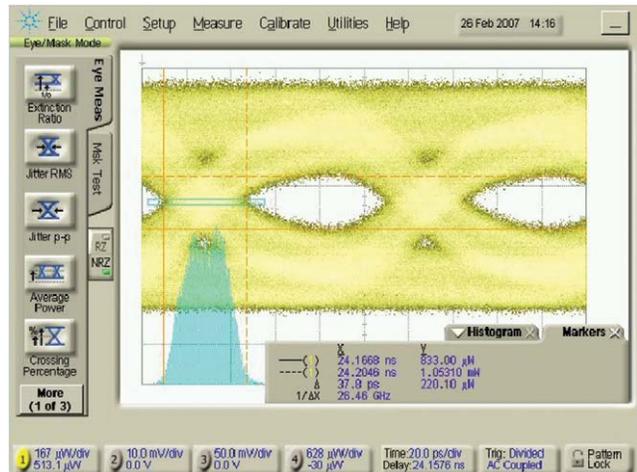


Figure 24:
PJ = 0 ps
SI = 100 mV
TJ = 37.8 ps
A0 = 220 mW
VECP = 4.94



How to get numbers for TJ, A0 & VECP

It should be noted that TJ, A0 and VECP are dependent on both SI and PJ. So it is impossible to provide numeric entries for TJ, A0 and VECP and convert this straight forward into numbers for SI and PJ.

However it is possible to calculate TJ, A0 and VECP from numeric entries for PJ and SI values.

Figure 25 and 26 show the relation of A0 and VECP as a function of Sinusoidal Interference (SI) programming and periodic jitter (PJ) programming.

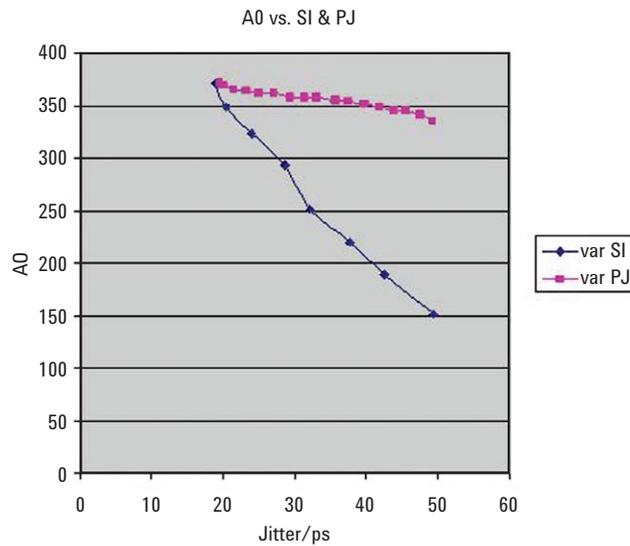


Figure 25. A0 as a function of SI and PJ

Conclusions:

- As the relationship of A0 and VECP versus SI and PJ is mostly linear, this can be modeled with a 2-point approximation
- This is similar for the total jitter, this depends also on SI and PJ programming

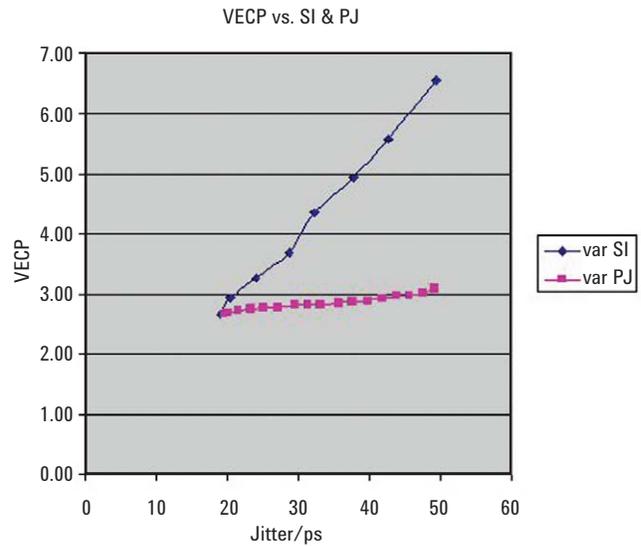


Figure 26. VECP as a function of SI and PJ

Summary on Calibration Conclusions

- Pattern affects TJ/ISI. The IEE 802.3 ae standard recommends a calibration using a PRBS $> 2^{10}-1$. It could be shown that the use of $2^{11}-1$ is acceptable and can be effectively used with the automated routines of the 86100C DCA-J.
- The data rate affects all parameters significantly. The calibration must be performed at a given rate.
- ER, OMA, A0/VECP and total jitter depend on electrical amplitude, optical attenuation and the programming of SI and PJ. The calibration can be performed with help on look-up tables based on linear approximation.

The N4917A Calibration Software

The Agilent N4917A optical receiver stress test calibration and automation software takes these findings into account. It automatically calibrates the optical stress signal with the DCA-J according to a list of selectable standards and with user adjustable parameters. Additionally it allows automated receiver sensitivity measurements, such as BER versus OMA.

Calibration Modes

1. At fixed data rate and compliance point of standard specific Compliance Mode: ER, OMA, fixed jitter for meeting compliance window, except variable PJ (50 .. 150 mUI requested), fixed pattern (PRBS $2^{11}-1$ for cal, $2^{31}-1$ for measurement)
2. At fixed data rate of standard with variable ER, OMA, SI & PJ jitter standard specific Manual Mode: with reading for TJ, A0 and VECP depending on ER, OMA, SI and PJ parameter setting, fixed pattern (PRBS $2^{11}-1$ for cal, $2^{31}-1$ for measurement)
3. At non-standard data rate with variable ER and OMA, SI & PJ Custom Standard: with variable data rate & wavelength, ER, OMA, SI and PJ parameter setting, fixed pattern (PRBS $2^{11}-1$ for cal, $2^{31}-1$ pattern for measurement), no reading for TJ, A0 and VECP

Calibration steps performed by the N4917A

- Step 1: instrument check
 - check for required Models & Options
- Step 2: cabling check
 - check for correct electrical and optical cabling
- Step 3: instrument preparation
 - Scope User Cal, E/O optimization for DCD
 - cabling optimization
 - optimization of intrinsic ISI due to cable tolerances
- Step 4: parameter calibration, reference point measurements for the look-up table for:
 - 3-point extrapolation for ER, crossing point, OMA, A0, TJ
 - 2-point extrapolation for SI and PJ on A0 and TJ

Implementation of the signal conditioning

The channel impairment

Figure 28 to 31 explain why it is hardly possible to implement the signal conditioning as simply as the standard states. It is shown that a signal compensation is needed to create the stress signal as requested by the standard. Figure 28 shows a typical S21 curve of an optical modulator. The relationship between attenuation and frequency is not linear, the higher the frequency the higher the attenuation (the losses). This looks pretty similar to the characteristics of a PC Board used at gigabit speed. This behavior creates especially ISI type jitter as can be seen in the screen shot of figure 30.

The standard requests signal conditioning using a Bessel-Thompson filter and an adder for sinusoidal interference (as shown in figure 29). When combining such a modulator with the simple conditioning circuit the resulting figures for intrinsic jitter and VECP are shown in figure 31. The result is a TJ which is already exceeding the compliance limit and a VECP which comes close to the limit without required adding of PJ and SI type of jitter for the compliance point.

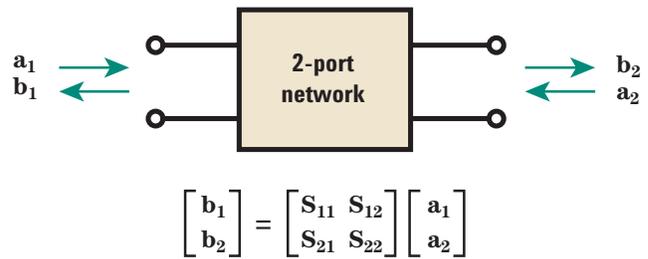


Figure 27. S- (or scattering) parameters describe the input (S11; S22) and the transmission (S21, S12) behavior of a two or multi-port device. They are complex figures and depend on frequency. The graph in Figure 28 shows just the magnitude. For more information on S-parameters see [5].

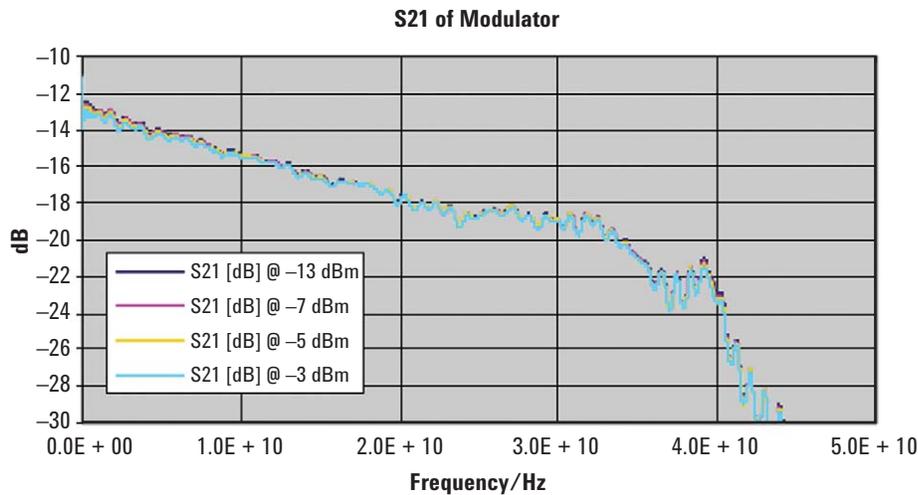


Figure 28. The S21 Parameter of an optical modulator (attenuation vs. frequency)

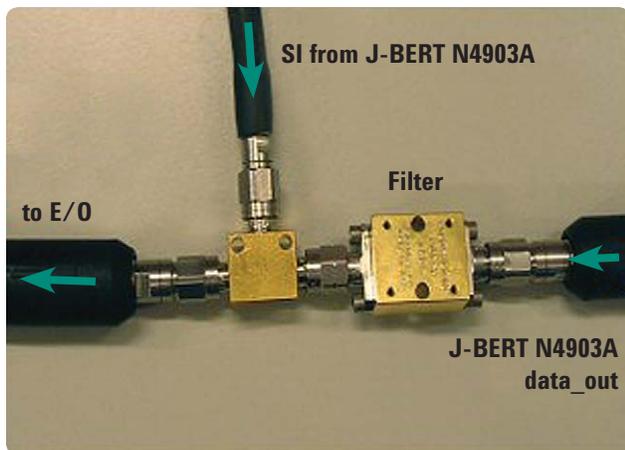


Figure 29. A simple conditioning circuitry with filtering and SI modulation

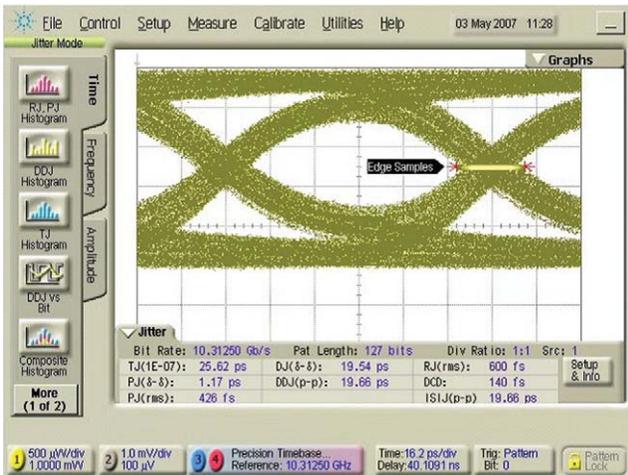


Figure 30. A measurement of ISI/TJ using the conditioning circuitry from Figure 29 together with an optical modulator with the typical S21 parameter from Figure 28

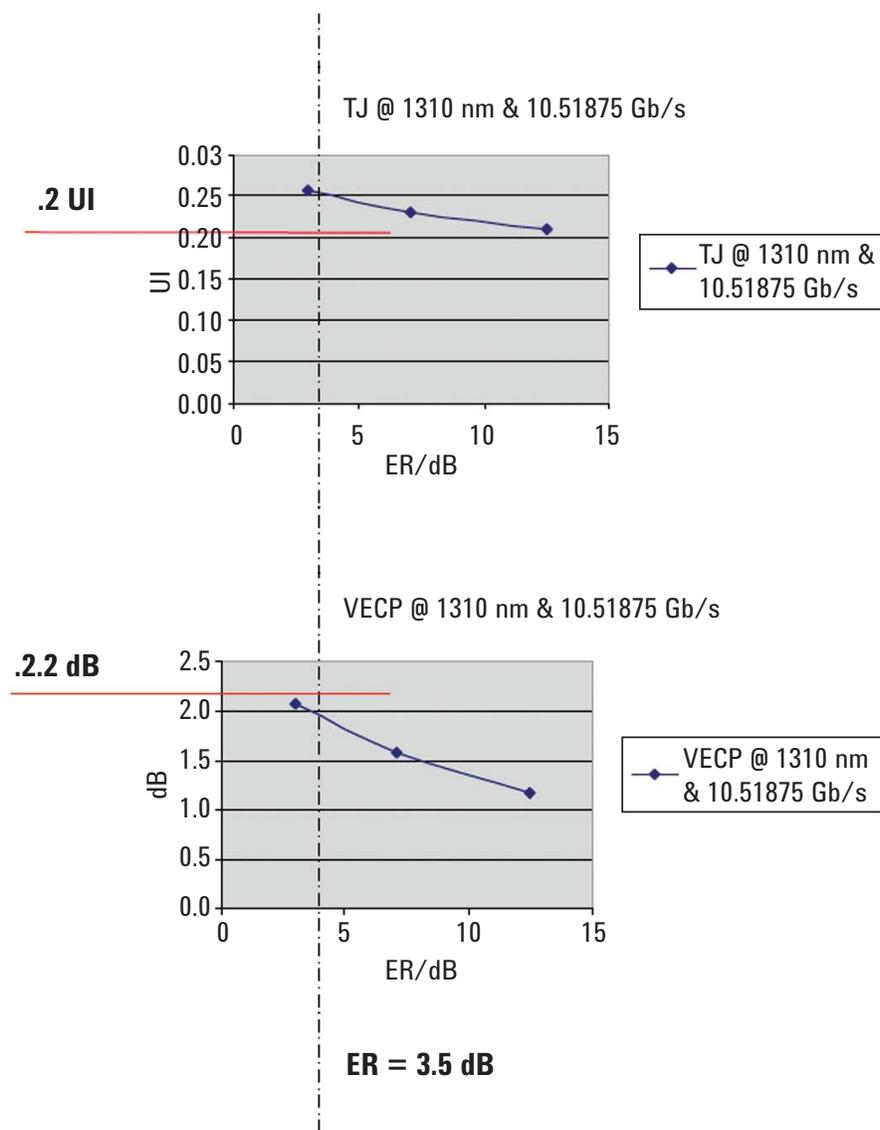


Figure 31. The TJ and VECP as function of ER of the conditioning circuitry from Figure 29 together with an optical modulator with the typical S21 parameter from Figure 28

Signal Conditioning including compensation of ISI

The solution to this behavior is adding a compensation into the stress conditioning circuitry which compensates for the losses of the cabling and the S21 of optical modulator while keeping the desired stress of the bandwidth limitation by the Bessel-Thomson filter. The resulting waveforms with the built-in compensation are given in Figure 32 & 33. Figure 32 is the signal without any added jitter, Figure 33 adds PJ and SI jitter to compliance point requirements.

The built-in compensation is designed in such a way that the resulting ISI of the optical signal resulting from the whole electro-optical setup equals mostly the ISI obtained from a Bessel-Thompson filter with the electrical bandwidth required by the standard. The ISI values in Figure 14 (ISI = 10 ps) and Figure 32 (ISI = 10.4 ps) shall be compared.

Final Conclusions:

The 86100C DCA-J is an effective tool for calibrating the optical parameters, it offers all necessary automated routines. The configuration of the automated routines is easy to make.

The dependency of parameters is a little more complex. There is some data pattern dependency, but it could be shown that using the PRBS $2^{11}-1$ for calibration has a marginal compared to effect for measuring with a PRBS $2^{31}-1$ which the standard requires. The data rate affects the parameters significantly, so this needs a calibration at the actual rate.

The implementation of the stress conditioning N4917A-E01 is not as easy as one might believe from the standard's definition. It was shown that a compensation is needed for maintaining proper stress condition according to the standard's requirements of adding stress. It could be shown that this is possible to achieve it to exactly the stress as required by the standard.

The parameters affecting Jitter and VECF are calibrated with help of 2- and 3-point extrapolation. The accuracy achieved is better than 10% at the compliance point. This was verified using a set of two different BERTs, three different stress conditioning units, three different E/O converters and three different optical scope modules in a random combination.

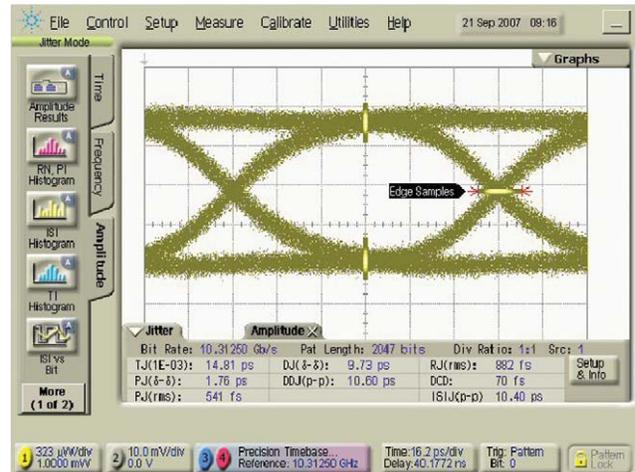


Figure 32. The jitter measurement on the optical signal of the N4917A setup with no jitter injection

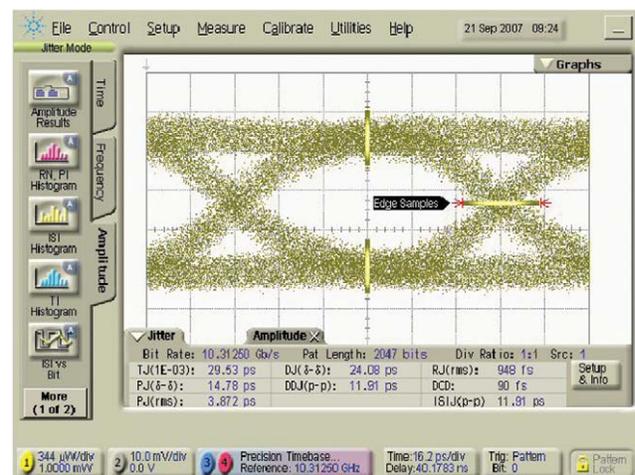


Figure 33. The jitter measurement on the optical signal of the N4917A setup with SI and PJ jitter injection according the compliance requirements

N4917A Optical Receiver Stress Test Set Photonics Tech Briefs Product of the Year 2007.

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- [2] Fibre Channel — 10 Gigabit (10GFC), American National Standard for Information Technology
- [3] *Improving the Accuracy of Optical Transceiver Extinction Ratio Measurements*, Agilent Technologies Application Note 1550-9, 2005, 5989-2602EN
- [4] *Digital Communications Test and Measurement*, Dennis Derickson & Marcus Müller, Prentice Hall 2007, ISBN13: 978-0-13220910-6
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Related Literature

- *Agilent N4917A Optical Receiver Stress Test Solution*, Data Sheet, Literature Number 5989-6315EN
- *Agilent J-BERT N4903A High-Performance Serial BERT with Complete Jitter Tolerance Testing*, Data Sheet, Literature Number 5989-2899EN
- *Agilent 86100C Wide-Bandwidth Oscilloscope Mainframe and Modules Technical Specifications*, Literature Number 5989-0278EN
- *Agilent Technologies 81490A Reference Transmitter Technical Specifications*, Literature Number 5989-7326EN
- *Agilent 81495 Reference Receiver Technical Specifications*, Literature Number 5989-7526EN

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