80SJNB Jitter Measurement Results Correlation

Several measurements done with the 80SJNB are compared to other jitter measurement tools. The jitter breakdown into its horizontal and vertical components is verified. The BER jitter bathtub is compared to that of a BERT. All of these results demonstrate good match between 80SJNB and other tools.

1. Introduction

The 80SJNB application software provides jitter, noise and Bit-Error-Ratio analysis for the Tektronix 8000 series sampling oscilloscope platform. It performs advanced jitter and noise separation into its main components and so enables both compliance test results as well as diagnostic information for debug and validation of system components used in high bit-rate serial data links.

While some of the functionality of the 80SJNB software is quite new, some of its functionality, e.g. the jitter analysis, can be achieved by other measurement devices. It is the primary goal of this paper to present:
- The correlation of the 80SJNB’s jitter analysis to several other methods of jitter analysis.
- The stability and correctness of the jitter analysis results produced by 80SJNB in its ability to separate the components of jitter.

Both of the abovementioned goals are accomplished by measurements on a signal where one impairment is varied while others remain constant – and the measurement results are expected to match this.

- The match of extrapolated Bit-Error-Ratios (BER) to low probability levels to the BER reported by a Bit-Error-Ratio Tester (BERT)).

In addition it is demonstrated how 80SJNB is capable of accurately separating signal impairments into fundamental timing and amplitude components.

For the sake of measurement correlation we focused (in this paper) on signals which can be handled by several methods; there is substantial functionality in the 80SJNB which goes beyond the scope of other solutions and which is therefore not discussed in this correlation paper.

2. Setup

A serial data stream will be impaired with varying levels of RJ, PJ, ISI, RN, and PN. In each case, the reported values will be examined and compared between the following four systems which are of nearly equivalent nominal performance:

- A Tektronix CSA8200 equivalent-time sampling oscilloscope with 80SJNB application software for jitter, noise and BER analysis. The data is acquired with a low-noise 80E03 electrical sampling module with 30GHz bandwidth. An 82A04 Phase Reference module provides a state-of-the-art jitter noise floor of less than 200fs (rms). In addition, the CSA8200 is equipped with an 80A06 PatternSync module which provides automatic pattern triggering capabilities.

- An equivalent-time sampling oscilloscope by vendor X which will be referred to as ETSS x. This instrument contains built-in jitter analysis software and is setup with a 26GHz electrical sampling module. It provides a random jitter noise floor of 200fs (rms).

- A Tektronix TDS6154C real-time oscilloscope with TDSJIT3 V2 jitter analysis application software. This instrument features an industry-leading 15GHz bandwidth at a sampling rate of 40Gsamples/s and has a jitter noise floor of 420fs (rms).

- An Advantest D3286 Error Detector, usually referred to as a BERT Receiver, with an operating frequency range of 150MHz to 12GHz.
Figure 1 Schematic diagram of the signal source and jitter generation setup.

Figure 1 shows the overall setup including the signal generation and distribution to the measurement systems. The left half of the diagram presents the signal source and jitter generation instrumentation. The Vector Signal Generator (R&S SMU200A, 100kHz-4GHz) supplies a 2.5GHz clock signal to the data source, a 12.5Gb/s Advantest D3186 Pattern Generator which is set to emit a pseudo-random-bit-sequence at 2.5Gb/s with a pattern length of $2^7-1$ (127 bits). The output of the pattern generator is 2Vp-p and is resistively split into four equal signals of about 450mVp-p amplitude and applied to the four test instruments. A clean 2.5Ghz clock signal is provided to the jitter analyzing instruments in the same manner by a Wiltron 68047B Frequency Synthesizer which is locked to the Vector Signal Generator via an external 10MHz reference signal. The way in which different jitter and noise impairments are injected into the data signal are described separately in each of the following sections.

At this time only single-ended signals are examined since not all instruments accept differential signals. During data acquisition all instruments (with the exception of the Bit Error Detector) were given equal amounts of time to arrive at their respective results. The automatic vertical threshold selection is turned on for all instruments. Since the D3286 BERT purely reports bit error ratios and not jitter sub-component values we will limit the analysis of its results to horizontal bathtub curve comparisons with 80SJNB (see Section 8).

3. RJ

Random jitter (RJ) is created by vertically summing amplitude noise onto the sinusoidal clock signal from the Vector Signal Generator to the Pattern Generator via a 10/90 resistive power combiner. The fixed threshold of the phase detector circuitry in the pattern generator then converts amplitude noise into timing noise in the transmitted data pattern. The conversion of the amplitude noise distribution to a timing noise distribution is highly linear as long as the noise amplitude is kept small compared to the clock signal amplitude. The amplitude noise is provided by a custom noise source which possesses a Gaussian distribution to beyond ±7σ, where σ is the standard deviation of the noise distribution, thereby resulting in truly Gaussian jitter tails down to a bit-error-ratio level of $10^{-12}$. The amount of RJ can be controlled by lowering the drive level from the R&S SMU200A while keeping the noise source output amplitude constant, thereby intentionally reducing the SNR of the clock signal into the Pattern Generator’s phase detector. The resulting range over which Gaussian RJ can be controlled in the transmitted data pattern is from 0.3ps (rms) up to 6ps (rms).
Figure 2 Eye diagram of 2.5Gb/s PRBS7 pattern with injected RJ of 5ps (rms)

Figure 2 shows the eye diagram resulting from injecting RJ into a 2.5Gb/s PRBS7 data pattern with no other jitter or noise impairments applied to the data signal. Figure 3 shows reported RJ values as a function of several levels of the R&S SMU200A clock output amplitude. We observe very good agreement between all instruments; in particular the measured values differ by less than 200fs between the instruments for each injected jitter amount. For clock levels above 3dBm the injected jitter is negligible and the reported jitter values of 310 to 420fs (rms) are due to the intrinsic random jitter between the two locked clocks in the setup.

4. DDJ

Data Dependent Jitter (DDJ\(^1\)) is created by simply transmitting the signal through various lengths of lossy microstrip transmission line on a FR-4 printed circuit board. DDJ values of over 150ps (p-p) can readily be generated at data rates of 2.5 Gb/s.

Figure 4 shows the resulting eye diagram after 46 inches of propagation through FR-4 and the reported values for various trace lengths can be seen in Figure 5. The DDJ results track extremely well between the instruments.

\(^1\) DDJ is the primary result of the physical problem called ISI, or Inter-Symbol Interference. While in some older literature ISI and DDJ are used interchangeably the industry appears today (Summer 2005) to settle on calling the physical effects ISI, and the resulting timing impairment DDJ. 80SJNB is capable of also measuring the vertical impact of ISI on the signal, the DDN (Data Dependent Noise).
Figure 4 Eye diagram after propagation through a 46” trace on FR-4.

Figure 5 Reported DDJ values after propagation through various trace lengths on PCB.

5. PJ

Periodic jitter (PJ) is applied by I/Q modulation of the SMU200A Vector Signal Generator. For this test, a sinusoidal phase modulation at a frequency of 10MHz is programmed into the 2.5Ghz clock signal that feeds the D3186 Pattern Generator. PJ amplitudes of up to 40ps (p-p) can be precisely generated.

Figure 6 Eye diagram for 40ps of injected sinusoidal jitter.
Figure 7 Reported PJ versus nominally injected PJ as programmed into the Vector Signal Generator.

As evidenced by Figure 7 JIT3 and 80SJNB track each other well and report correct PJ values, whereas sampling scope ETSS overestimates PJ for injected values above 20ps (50mUI). JIT3 and 80SJNB both use a direct spectral separation algorithm to determine PJ; they do not rely on simplified models, and are more robust and accurate as a result.

Note that ETSS reports PJ as a dual-Dirac (δ-δ) value, while Tektronix oscilloscopes provide the direct peak-to-peak value of PJ. In the case presented here the DJ:RJ ratio is large, for which the dual-Dirac and peak-to-peak values should be approximately identical, thereby (unusually) justifying a direct comparison. In any case, the correct dual-Dirac value should always be smaller than the corresponding direct-peak-to-peak value which is direct contrast to what is observed in Figure 7.

Another interesting aspect of PJ measurements is the sensitivity of the reported DDJ to the amount of PJ.

Figure 8 Sensitivity of reported DDJ to PJ (DDJ held constant)

From viewing Figure 8, it is apparent that the ETSS exhibits sensitivity to PJ (in its DDJ result), and as more and more PJ is injected the error in the reported DDJ is several times larger than the expected value. This behavior is an artifact of the simple edge models and very limited sample set used by the ETSS. JIT3 is the most well-behaved in this regard as evidenced by a nearly flat line in this plot.

In general, the Tektronix TDS6154C real-time oscilloscope is at an advantage when it comes to periodic jitter measurements due to its real-time sampling rate of up to 40GS/s. Such a high sampling rate allows the capture of cycle-to-cycle jitter and the capture of the true periodic jitter spectrum, while equivalent-time sampling oscilloscopes are limited to an aliased spectrum of jitter and noise components above 100kHz. Nevertheless, with a robust direct
spectral decomposition algorithm as used in 80SJNB accurate periodic jitter evaluation can be obtained from the aliased spectrum as well.

6. Combined Jitter Injection

After evaluating the instruments for single jitter component injection we now move to increased complexity by simultaneously injecting various combined levels of all jitter components as described in the above sections. We consider three examples with low, medium and high overall jitter content. The tabulated results and corresponding sampled eye diagrams are shown in Figures 9-15.

![Eye Diagram](image)

**Figure 9** Low jitter level: After injecting ~2.5ps (rms) of RJ, 10ps of PJ at 10MHz, and propagation through 12” PCB.

<table>
<thead>
<tr>
<th></th>
<th>80SJNB</th>
<th>ETSS x</th>
<th>JIT3</th>
</tr>
</thead>
<tbody>
<tr>
<td>RJ</td>
<td>2.44</td>
<td>2.45</td>
<td>2.51</td>
</tr>
<tr>
<td>ISI</td>
<td>14.9</td>
<td>17.1</td>
<td>16.5</td>
</tr>
<tr>
<td>DCD</td>
<td>2.4</td>
<td>3.1</td>
<td>1.6</td>
</tr>
<tr>
<td>PJ</td>
<td>11.8</td>
<td>8.7</td>
<td>9.6</td>
</tr>
<tr>
<td>TJ (10^{-12})</td>
<td>55.7</td>
<td>56.7</td>
<td>56.2</td>
</tr>
</tbody>
</table>

**Figure 10** Reported results for low level of combined jitter injection.

![Eye Diagram](image)

**Figure 11** Medium jitter level: RJ=3.5ps (rms), PJ=20ps, 24” PCB.

<table>
<thead>
<tr>
<th></th>
<th>80SJNB</th>
<th>ETSS x</th>
<th>JIT3</th>
</tr>
</thead>
<tbody>
<tr>
<td>RJ</td>
<td>3.48</td>
<td>3.55</td>
<td>3.98</td>
</tr>
<tr>
<td>ISI</td>
<td>41.3</td>
<td>48.2</td>
<td>50.7</td>
</tr>
<tr>
<td>DCD</td>
<td>3.9</td>
<td>3.5</td>
<td>0.4</td>
</tr>
<tr>
<td>PJ</td>
<td>22.6</td>
<td>21.4</td>
<td>20.9</td>
</tr>
<tr>
<td>TJ (10^{-12})</td>
<td>115.4</td>
<td>114.6</td>
<td>116.6</td>
</tr>
</tbody>
</table>

**Figure 12** Medium jitter level results.
While the reported values for the jitter subcomponents show some small variation between the instruments, they nevertheless perform a remarkable job in providing matching estimates for total jitter at the selected BER level of $10^{-12}$, where reported values differ by only 5mUI in the worst case.

7. Vertical Signal Impairments (RN, PN)

Unique to 80SJNB is the capability to separate all signal impairments into horizontal and vertical components, i.e. into timing jitter and vertical noise. 80SJNB separates the uncertainties into their fundamental horizontal and vertical components, and then performs a 2-D convolution to assemble a full BER Eye. This BER Eye implicitly reflects all of the subtle interactions of the horizontal uncertainty, the vertical uncertainty, and the full curvature of the correlated waveform. These orthogonal components interact through the slew rates at bit transitions. For example, crosstalk is really a vertical signal impairment and can be quantified by random, periodic and deterministic noise components. Jitter analyzers other than 80SJNB however interpret crosstalk as jitter and thus do not provide designers of high performance devices, modules, and systems with detailed information required to identify and correct sources of eye closure.

In the following examples random noise (RN) and periodic noise (PN) are created by summing Gaussian noise and a sinusoidal signal (Frequency Synthesizer A), respectively, onto the data signal via a resistive power coupler as shown in Figure 1, thus emulating the effect of an aggressor source such as coupled transmission lines or a clock in an electrical circuit.

A 2GHz 4th-order Bessel-Thompson low-pass filter is inserted into the data signal path in order to reduce the slew rate of the edge transitions, thereby accentuating the effect of vertical noise on the observed horizontal jitter on the edges.

A. Random Noise (RN)

The eye diagram resulting from injection of vertical random noise (RN) can be observed in Figure 15. For this example a residual amount of horizontal jitter (1ps rms) was applied to the bit stream to better illustrate the vertical versus horizontal separation capabilities of 80SJNB. Figure 16 shows how all instruments reported rising values of RJ as increasing levels of RN are injected into the bit stream. JIT3 measures slightly higher RJ values due to its higher intrinsic instrument noise compared to both sampling scopes.
80SJNB, however, is the only analysis solution that can correctly distinguish crosstalk from jitter as illustrated in Figure 17. The blue line is the observed RJ we already plotted in Figure 16. The red and green lines represent the orthogonal sub-components of RJ which are due to vertical and horizontal random noise as reported by 80SJNB as RJ(v) and RJ(h) respectively. One immediately observes that the horizontal component of RJ (RJ(h), green line) remains unchanged as more and more amplitude noise is injected into the signal. It also becomes obvious that for observed RJ values above 2ps the dominant contributor is in fact vertical noise as represented by RJ(v) (red line). Note that at the lowest RN level the injected noise is actually zero and the residual value of 0.7mV is due to the sampling module’s noise floor.

So while the observed jitter value RJ is the same for all instruments, 80SJNB’s horizontal vs. vertical separation enables an engineer to identify the source of a BER violation, i.e. whether high BER originates from crosstalk or vertical noise rather than from pure horizontal timing jitter.
Figure 17 80SJNB reveals the horizontal and vertical sources of RJ.

B. Periodic Noise (PN)

Here we first inject various levels of periodic amplitude noise PN at a frequency of 10MHz into the data signal with the Frequency Synthesizer B.

Figure 18 Eye diagram impaired by sinusoidal periodic noise with a magnitude of 22% relative to the signal amplitude.

Analogous to the case of RN we plot the observed PJ value as reported by all three instruments in Figure 19, as well as 80SJNB’s decomposition of PJ into its horizontal and vertical sub-components (see Figure 20). Again 80SJNB correctly reveals that virtually all of PJ originates from vertical, i.e. amplitude, modulation.

Figure 19 Reported PJ values as a function of the level of injected periodic amplitude noise.
Figure 20 80S\text{JNB} decomposes PJ into vertical (amplitude) and horizontal (timing) source components.

The following are two more examples of h/v separation, this time in the presence of both injected periodic noise and directly injected periodic jitter. The resulting eye diagram is seen in Figure 20a.

Figure 20a.

Example 1 (Figure 21): We apply a constant amount of direct PJ (10ps p-p at 1MHz) and vary the level of injected PN (10 MHz):

Figure 21 Orthogonal PJ decomposition in the presence of constant level of applied PJ and varying levels of injected PN.
Example 2 (Figure 22): We apply a constant amount of PN (10ps p-p at 1MHz) and vary the level of directly injected PJ:

![Orthogonal PJ decomposition](image)

**Figure 22** Orthogonal PJ decomposition in the presence of constant level of applied PN and varying levels of directly injected PJ.

8. **BERT Bathtub Curves**

In this section we compare the horizontal bathtub curves, i.e. horizontal slices of the 2-dimensional BER map at the threshold level, provided by 80SJNB with the BER bathtub curves that are measured directly by the Advantest D3286 Error Detector at levels down to BER=10\(^{-12}\). For reasons that will be explained in the next sections we will initially limit the data pattern to a simple 1010… bit pattern at a rate of 2.5Gb/s. The purpose of these tests is to demonstrate 80SJNB’s ability to accurately estimate TJ at low BER levels as compared to a direct measurement with a BERT.

The horizontal temporal resolution of the BERT is 1ps. For signals with low RJ (<400fs) typically only 2 points can be scanned on the steep random jitter tails.

Note: the BER of 10\(^{-12}\) measurement by the BERT (the red dot on the -12 level) typically represents an upper limit and results from an extrapolation by the BERT software in cases where the BERT didn’t encounter enough bit failures.

![Baseline BER curves](image)

**Figure 23** Baseline BER curves for unimpaired 2.5Gb/s 1010… pattern with RJ<300fs (rms), TJ=5.1ps.
The following three plots show the measured bathtub curves for a PRBS $2^7-1$ pattern and increasing levels of combined injected jitter.
Figure 26 Baseline bathtub curve for PRBS7 pattern at 2.5Gb/s, TJ=9.8ps.

Figure 27 Bathtub curve for PRBS7 pattern after propagation through 24" of a PCB trace and injected RJ=5.9ps, TJ=123.9ps.
A trend becomes apparent of increasing deviations as higher levels of DDJ are injected into the data pattern, i.e. the BERT reports more eye closure than 80SJNB. Why? See next section (the BERT is wrong).

9. Caution – BERTs Are Not Perfect

The Error Detector used for this investigation was chosen for its high timebase linearity and its ultra-low intrinsic random clock sampling jitter of less than 300fs (rms) and the results in the previous section attest to this performance level.

On the flip side, many BERT models are inherently designed as digital receivers whose analog signal fidelity is not of primary concern. A common measure for the analog signal fidelity of a measurement instrument is to record its impulse or edge response. This is straightforward with an oscilloscope but hard to do on a BERT. Fortunately, the Advantest D3286 Error Detector provides a monitoring port which outputs a copy of the data signal that the internal decision circuitry "sees" after passing through a limiting amplifier stage in the BERT's data input path. Even though this monitor signal does not include the response of the decision circuitry one can still gain valuable insight into its signal fidelity limitations.

Figure 29 compares the response of the Tektronix 80E03 sampling module used for this study with the monitor signal from the BERT for a 100MHz square wave stimulus. Clearly the BERT’s impulse response is not nearly as flat and clean as that of the sampling scope. Generally, sampling scopes have the flattest frequency response, highest bandwidth and unmatched signal fidelity. The 80E03 provides excellent (and traceable) signal fidelity of a diode sampler as opposed to the less well understood fidelity of the decision circuitry in a BERT. The observed ringing and long settling time in the BERT’s response results in data dependent distortions of the signal under test. Ultimately this leads to increased DDJ measurements and overestimation of total jitter. The BERT induced error is small for situations where BER is dominated by horizontal impairments or primitive signal patterns such as the 1010…bit pattern used in the previous section. However, under conditions where vertical impairments (RN, PN, DN) are dominant or for high-ISI signals the error can become substantial.
Figure 29 Comparison of responses to a 100MHz square wave between the D3286 Error Detector and the Tektronix 80E03 electrical sampling module.

The following is an example that illustrates a situation in which the BERT largely overestimates TJ due to its inferior impulse response. We consider a CEI-6G+ signal at 6.25Gb/s with a PRBS2⁹ bit pattern after propagating through an 18 inch trace on FR-4. Figure 30 shows the eye diagram for the same input signal as “seen” by the two sampling oscilloscopes and the BERT’s decision circuit. While both sampling scope eyes are nearly identical, the waveform from the BERT exhibits noticeable vertical and horizontal eye closure due to its intrinsic ISI distortion. This obviously leads to overly pessimistic bathtub curves along the horizontal as well as along the vertical axis. This behavior is demonstrated in Figure 31 where the bathtub curves for this signal are compared between 80SJNB and the BERT.

Figure 30 6.25Gb/s PRBS9 signal. a) and b) show the eye diagrams acquired by the Tektronix 80E03 and the sampling scope ETSS. c) shows the signal from the BERT’s “Monitor Output” port acquired by the same 80E03.
Conclusion

All three oscilloscope based results show good match with the exception of ETSS’s sensitivity to DDJ in reported PJ result, and the real-time oscilloscope’s somewhat larger noise floor (relative to the sampling oscilloscopes). The TJ results in particular are remarkably well matched.

The 80SJNB can separate the horizontal and vertical components of jitter.

The 80SJNB bathtub result matches that of a BERT except for where the BERT’s hardware limitations are distorting the result; this is of a particular concern as the BERT is often considered the “golden standard”