Application Note

GAIN NEW INSIGHTS IN JITTER ANALYSIS

Using a single model-based approach

Products:

- R&S®RTO2000
- R&S®RTP

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Contents

1 Overview

Current signal integrity measurement methods concentrate on eye patterns and analyzing the signal threshold crossing times to determine total jitter as well as all of its component parts. Rohde & Schwarz offers a new method that addresses the shortcomings of the current methods - namely non-stationarity and the root cause of DDJ which is among the most important sources of jitter. An overview of this method is presented and illustrated with measured results.

2 Introduction

In any digital system, the primary goal is error-free transmission. Imperfections in signal periodicity, called jitter, are a major cause of transmission errors. Total jitter (TJ) is the overall quantity, and it is comprised of random jitter (RJ) and deterministic jitter (DJ), which has several subcomponents.

Digital interfaces are continuously evolving, with data rates increasing and voltage swings decreasing. Consequently, jitter is becoming a significant percentage of the signaling interval and therefore an increasingly likely source of transmission failures.

This is one reason why virtually every modern digital standard mandates jitter separation and analysis: Ethernet, USB, PCIe, HDMI, and more (Figure 1). As a result, designers rely on jitter analysis during the debugging of their designs. Detailed analyses can reveal the root causes of transmission errors and other signal-integrity issues.

Symbol	Description	Min	Max	Units	Comments
UI	Minimum Unit Interval	99.97	100.03	ps	The minimum UI value corresponds to the Link baseline speed of 10.0 Gbps with an uncertainty range of -300 ppm to 300 ppm. See Note 4.
AC_CM	TX AC Common Mode voltage	--	100	mV pp	
TJ	Total Jitter	--	0.38	UI pp	See Note 2 and Note 3.
UJ	Sum of uncorrelated DJ and RJ components (all jitter components except for DDJ)	--	0.31	UI pp	See Note 2.
DDJ	Data-Dependent Jitter	--	0.15	UI pp	See Note 5.
UDJ	Deterministic jitter that is uncorrelated to the transmitted data	--	0.17	UI pp	
UDJ_LF	Low Frequency Uncorrelated Deterministic Jitter	--	0.04	UI pp	See Note 6.
DCD	Even-odd jitter associated with Duty-Cycle-Distortion	--	0.03	UI pp	
Y1	TX eye inner height (one-sided voltage opening of the differential signal)	140	--	mV	Measured for 1E6 UI. See Note 1, Note 2, and Figure 3-15.

Figure 1: The required USB 3.2 Gen2 transmitter-compliance measurements provide an example of the jitter components included in many of today's digital standards.

However, for projects on tight timelines, there is one fundamental problem: jitter measurements can take a very long time. One reason: modern digital systems are designed to achieve a bit error rate (BER) of 10^{-12}—one error in every trillion bits. Because direct measurements of BER are typically time-consuming and impractical, oscilloscopes are often used to measure timing error over a much smaller data set that is used to estimate jitter over the full sample of 10^{12} bits.

A new method from Rohde & Schwarz uses a signal model-based approach to help engineers gain new insights into the jitter characteristics of high-speed designs. Because the signal model accounts for vertical and horizontal disturbances in the signal, it provides previously unavailable information about channel characteristics and individual jitter components. The algorithm also provides reliable measurements of very long test patterns (e.g., PRBS31) as well as live data traffic (non-repetitive pattern) when there is no access to test-pattern control.

3 Defining Total, Deterministic and Random Jitter

Total Jitter is composed of unbounded or “random” jitter (RJ) and bounded or “deterministic” jitter (DJ). In general, RJ has a Gaussian probability density function (PDF). Common causes of RJ include thermal noise, shot noise, oscillator instabilities, and external sources such as radiated electromagnetic interference (EMI).

Deterministic Jitter has several underlying components (Figure 2). Because all are bounded in nature, the range of DJ will not grow over any given observation time (i.e., the value doesn’t increase with an extended measurement interval).

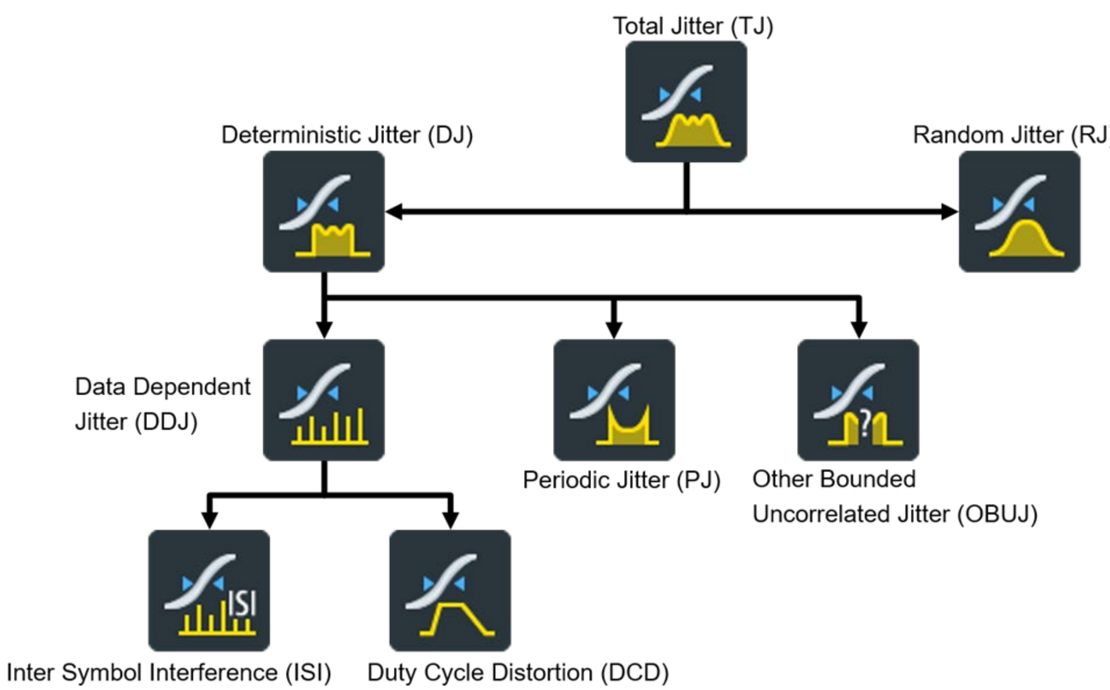


Figure 2: This tree diagram illustrates the range of factors that contribute to Total Jitter.

Within the DJ tree, the biggest problem area tends to be data-dependent jitter (DDJ), which includes inter-symbol interference (ISI) and duty-cycle distortion (DCD). These affect the shape of the digital waveform as it travels down a bus, wire or fiber, and any distortion in the waveform will show up as DDJ.

Fortunately, DDJ is the area in which a designer can most easily make changes and exert control over the problem. Several factors are potential contributors to DDJ: transmission losses, frequency-dependent losses, bandwidth of the transmission medium, reflections, impedance mismatches, and dielectric absorption (e.g., non-ideal dielectrics and dispersion, especially in optical fiber).

The causes of DCD include offset errors in either the transmitter or receiver, and imbalances or offsets in square-wave rise and fall times.

The contributor called periodic jitter (PJ) is not necessarily sinusoidal, but it does have a period. Examples include noise from sources such as EMI and switched-mode power supplies (SMPS). PJ has a long list of potential causes: injected noise; circuit instabilities; SMPS and oscillators plus associated harmonic content; stability problems and overshoot in phase-locked loops (PLLs); loop bandwidth (e.g., tracking and overshoot); and more.

Finally, the catchall category within DJ is other bounded, uncorrelated jitter (OBUJ). Crosstalk is the primary root cause, and it typically comes from adjacent lanes (e.g., PCIe).

4 Typical measurement methods

To measure the actual errors, an oscilloscope must acquire a long waveform record of the signal under test (SUT). This waveform must be sampled in real time at a rate that is at least 2.5 times the signal bandwidth to prevent aliasing or erroneous "foldback" signals.

While "more data is better" when estimating jitter components, this requires a lot of memory. In practice, the length of the acquired waveform is limited to the installed memory capacity of the oscilloscope: millions, tens of millions, or perhaps hundreds of millions of samples. The sequence of signal-threshold crossing times is measured from the sampled waveform (Figure 3). Measuring just the crossing times reduces the data set by a factor of typically 2:1 to 10:1; the actual ratio depends on the sample rate relative to the data rate.

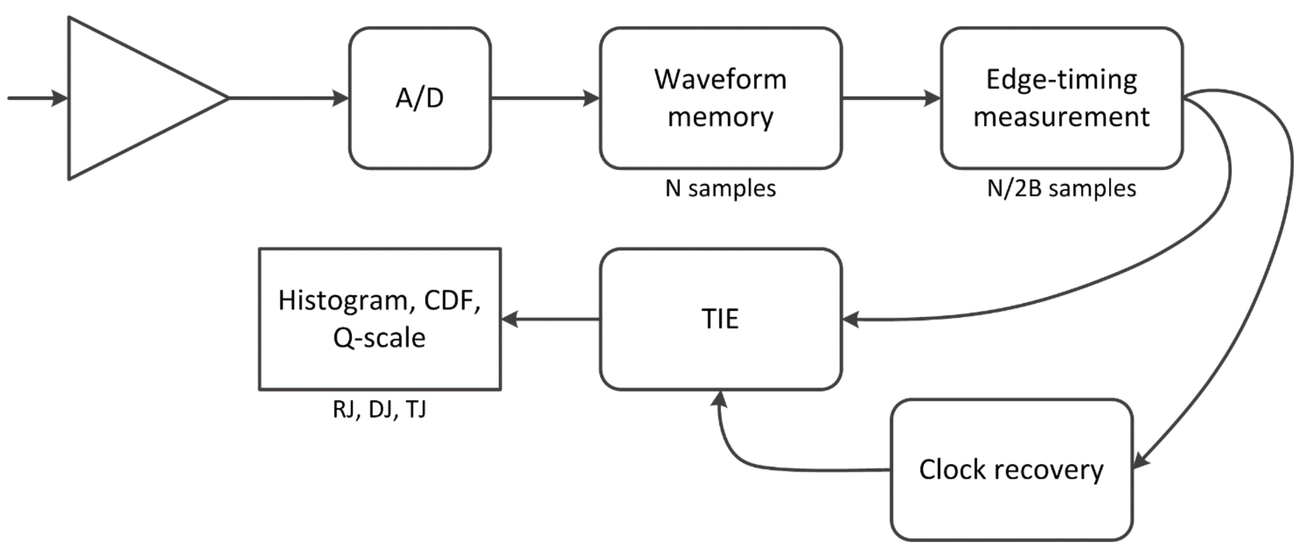


Figure 3: Inside an oscilloscope, the measurement process proceeds as shown, resulting in the histogram, cumulative density function (CDF) and Q-scale information needed to decompose the jitter components.

Next, to establish a reference, the oscilloscope must compute or recover the reference clock from the measured crossing times. Called clock data recovery (CDR), the process is performed mathematically using a phase-locked loop (PLL) algorithm, focusing on long-term time variations. It can then measure the time-interval error (TIE) of each crossing point relative to the recovered clock. This yields a sequence of TIE measurements.

At this point, the oscilloscope can derive a histogram from the TIE measurements, yielding an estimate of the jitter probability density function (PDF). Next, it applies a tail-fitting algorithm to the estimated PDF in order to fit the commonly used Dual-Dirac model to the measured TIE histogram. This model yields the RJ and DJ parameters and estimates the total TJ at the desired BER (Figure 4).[1]

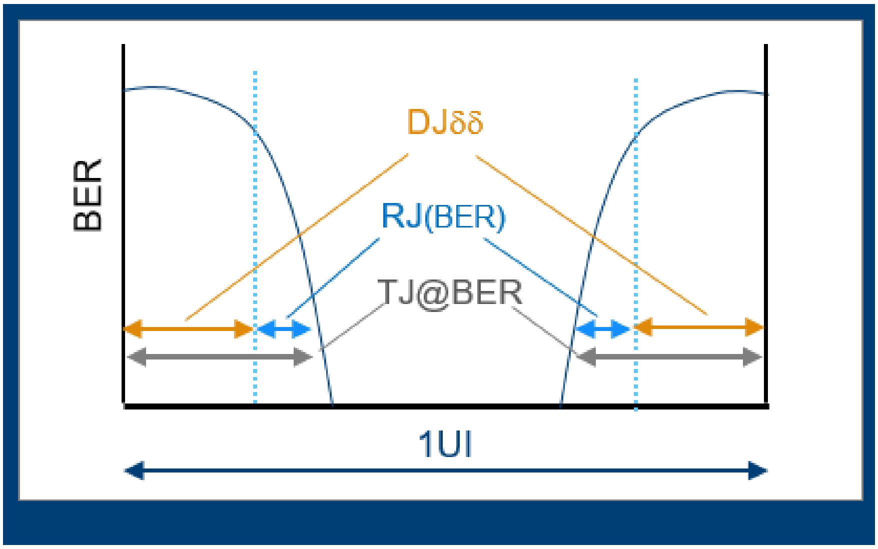


Figure 4: The oscilloscope must capture sufficient crossing data on both the left and right to perform tail-fitting and estimate the entire bathtub curve.

In general, the oscilloscope must acquire a large enough data set to generate a credible estimate of the TJ related to a certain BER. Referring back to the bathtub curve in Figure 3, the gap (or margin) between it and the left or right sides of the 1-UI sampling interval must be wide enough (open data eye) to ensure error-free transmission and reception over a sample interval consistent with the desired BER performance (e.g., 10^{12} bits for a BER of 10^{-12}).

5 New insights from a signal model

Rohde & Schwarz has developed an approach that adds valuable insights. This method is based on a parametric signal model that fully characterizes the behavior of the transmission link under test. It uses an analytical approach to separate the individual components of jitter: RJ, DJ, DDJ, PJ, and so on.

The core benefit: the jitter model includes the complete waveform characteristic of the SUT. This is in contrast to conventional methods that reduce the data to a set of TIE measurements. With the R&S approach, key results include consistent measurement data, even for relatively short signal sequences, plus previously unavailable information such as the step response and the vertical and horizontal contributions to PJ.

A quick walkthrough of the respective block diagrams will illustrate the DJ and RJ decomposition processes. For a more detailed look at the inner workings of the algorithm, please see the whitepaper Signal Model-based Approach to a Joint Jitter & Noise Decomposition.

[1] On the plus side, tail-fitting is a mature technique that has been widely used since the 1990s. On the negative side, it can incorrectly identify components as RJ or DJ based on assumptions about its distribution.

5.1 Extracting the deterministic components

Figure 5 illustrates the process flow (rectangles) and the key results (circles) for the extraction of DJ components. It starts with the acquisition of a long data record (scope input, far right) and, as with the traditional method, performs CDR to establish a reference (far left).

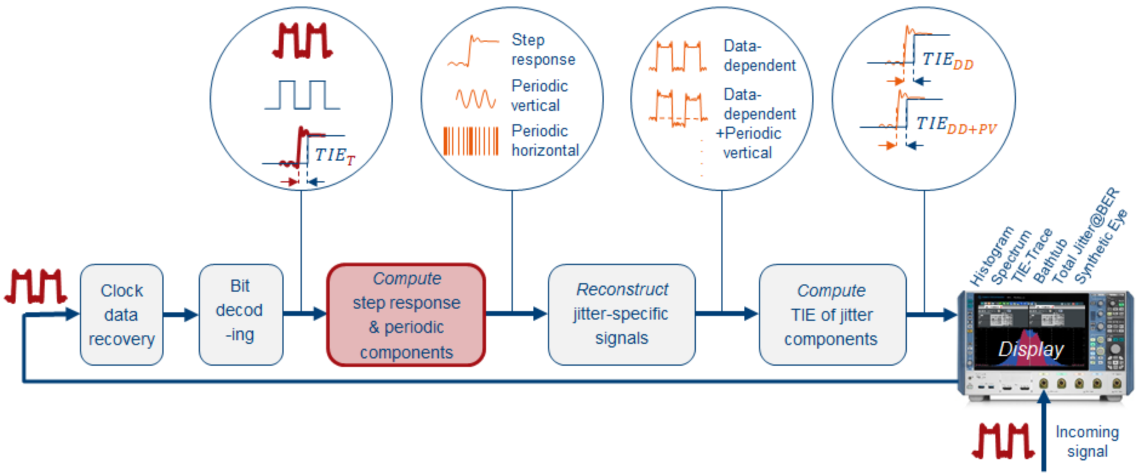


Figure 5: The signal model-based approach extracts the various elements of DJ from computed step response, vertical PJ and horizontal PJ results.

Next, it performs bit decoding and computes the TIE (total jitter) of the acquired waveform. After that the new algorithm starts to estimate the step response and the periodic jitter components (e.g., horizontal and vertical, or time and amplitude).

Using the bit decoding result and the step response, the algorithm then computes synthetic waveforms for DDJ and DDJ+PJ. Applying the TIE measurement to the synthetic waveforms, the process generates the numerical values needed to produce the histograms and tracks for these individual deterministic jitter components.

5.2 Extracting random jitter

The extraction of RJ proceeds as shown in Figure 6. The algorithm calculates RJ by subtracting the calculated DJ components from the original waveform. Note that at this stage OBUJ components might be included. To obtain RJ with a truly Gaussian distribution, OBUJ can be extracted as a final step. At this point, the BER bathtub curve, eye diagrams for the synthetic waveforms, and so on, can be calculated.

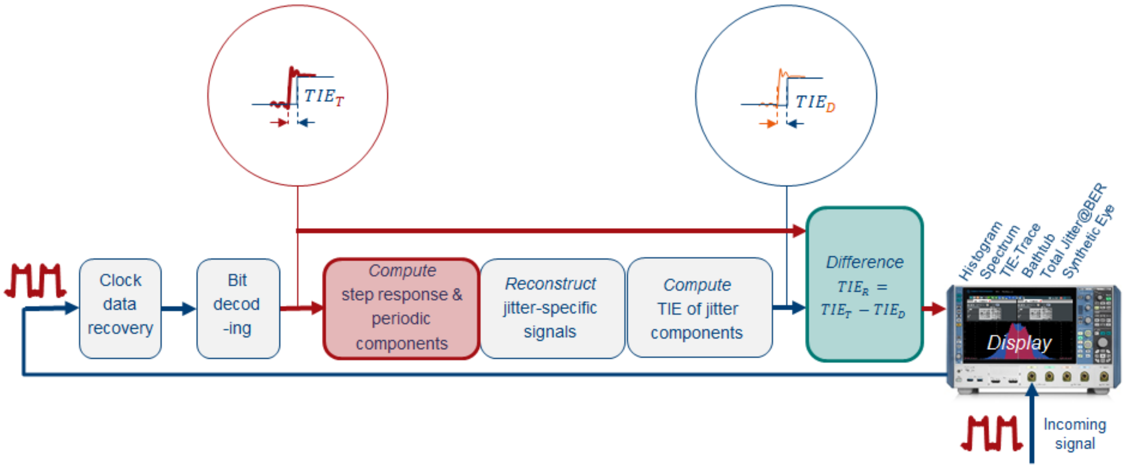
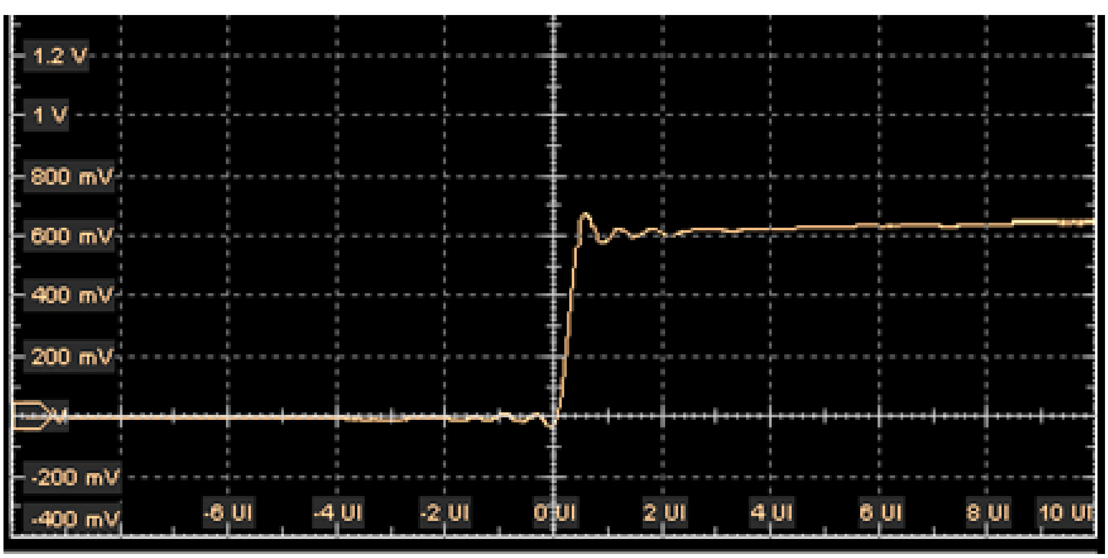


Figure 6: After extracting the DJ components, the signal model-based can then derive RJ.

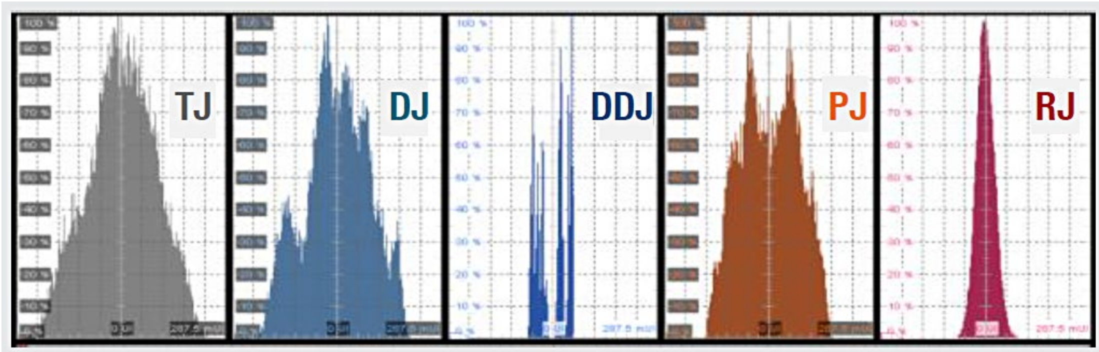
6 Exploring example results

The ability to measure jitter using all of the waveform information makes it possible to separate out the sources of jitter and thereby enable in-depth analyses of many jitter components. For instance, the algorithm can be directed to measure only specific components, individually or in combination, and thus facilitate the exploration of different jitter pathologies.

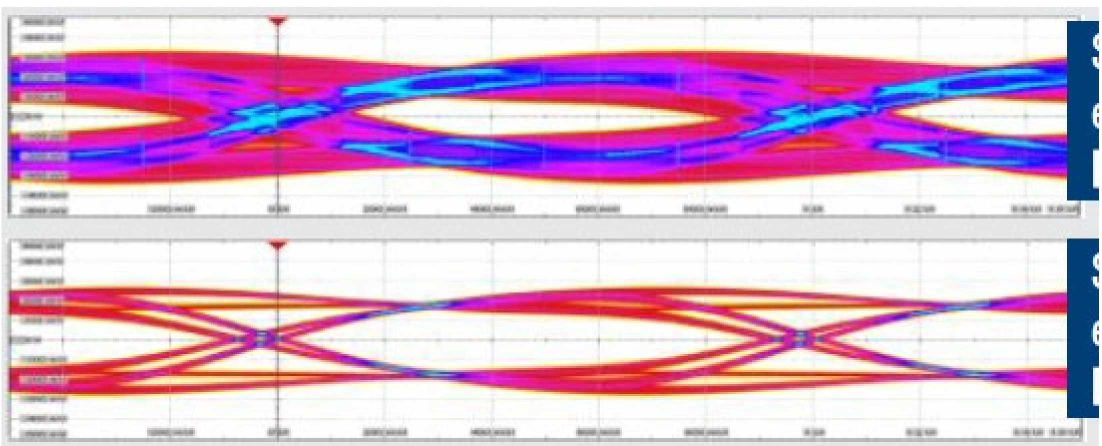
Examples include the step response, histograms and synthetic eye diagrams as well as tabular, track and spectrum displays. The following gallery of screen images illustrates a variety of result views.



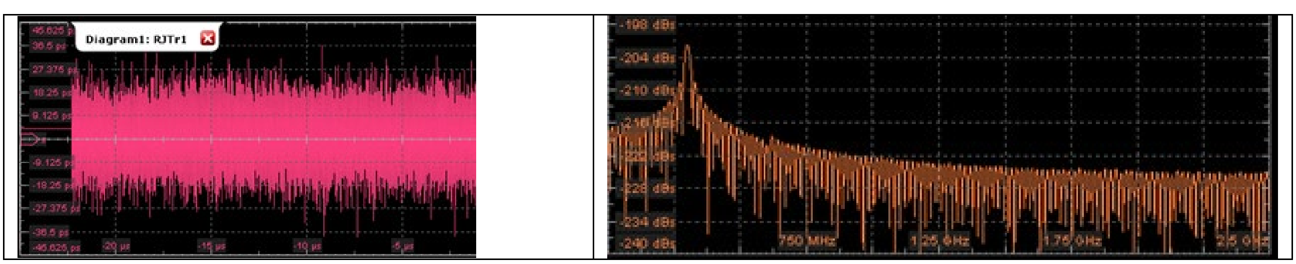
Step response: This is the starting point, and it provides a time-domain view of the channel frequency response. For those accustomed to using time-domain transmissometry (TDT), this is similar to the step view of the waveform. When using the R&S method during debugging, the presence of a significant amount of DDJ and a misshapen step response are most likely to be the result of reflections, bad connections, or poor impedance matches.



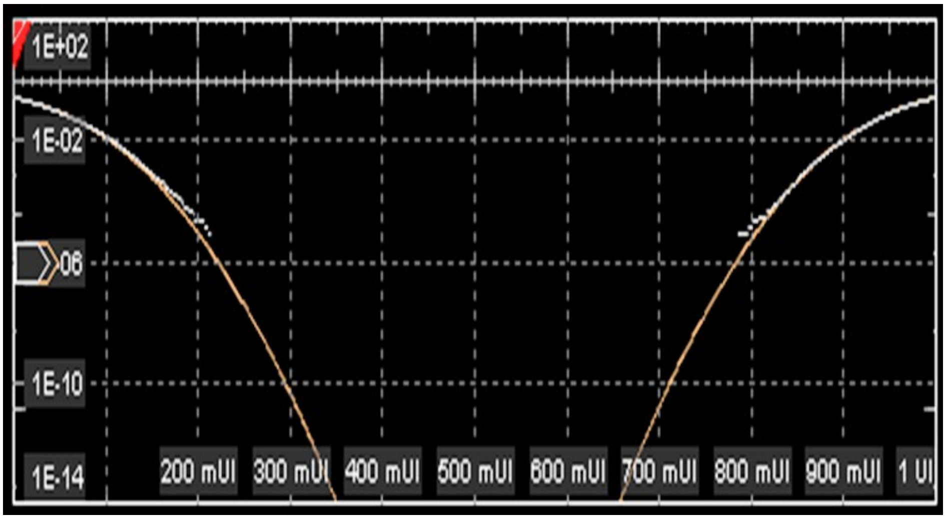
Histograms: The process can produce and display histograms of the individual jitter components. Things to look for in histograms include symmetry and the “tail” probability.



Synthetic eye: Derived from the signal model, these can show DDJ or DDJ+PJ. This enables the exploration of jitter-related “what if?” scenarios. The ability to create individual views of the potential causes of eye closure is a useful diagnostic tool.



TIE as track or spectrum: The R&S method can also compute and display the familiar TIE track (left) and TIE spectrum (right) for individual jitter components. Tracks are a useful way to visualize the variation of jitter versus time, potentially revealing the shape of a periodic source of jitter (e.g., from an SMPS).



BER bathtub plot: In this example, the white dotted curve is the BER curve measured from the acquired waveform and the orange trace is a bathtub curve calculated from the jitter-separation algorithm. Note that the measured (white) bathtub curve does not fit the modeled one (orange) all that well near its bottom. This is because the number of measurements at these offsets is very small and the repeatability is poor. Interestingly, this is exactly the data that is used for traditional tail fitting algorithms.

Adv. Jitter Results

Advanced jitter results 1 — Unit UI

	σ	abs/pp
TJ@BER	---	642.6 mUI
RJ	41.115 mUI	369.65 mUI
TJ	50.079 mUI	430.14 mUI
DDJ	28.852 mUI	134.38 mUI
PJ	1.7827 mUI	11.42 mUI
ISI	---	133.63 mUI

Periodic components 1

	Frequency	Value	Direction
1	35.502 MHz	12.947 ps	Horizontal
2	58.19 MHz	365.11 fs	Horizontal
3	5 GHz	7.1649 mV	Vertical
4	7.1608 GHz	354.19 µV	Vertical
5	4.1 GHz	320.02 µV	Vertical

Tabular results: As shown on the left, the algorithm calculates standard deviation (σ) and peak-to-peak values for all jitter components (when applicable). In this example, all values are given in terms of one UI; these can also be shown in time units. On the right, the process can also display a table of the periodic components, distinguishing between those of horizontal or vertical origin.

7 Conclusion

This new approach provides noteworthy advantages over the entrenched methods. For example, traditional measurements require strictly repeating patterns because they repeatedly measure waveform edges. While these methods can handle nonrepeating waveforms, compromises are necessary.

The R&S signal model-based approach includes the entire set of signal data needed for detailed analyses. This results in higher accuracy, deeper signal insights, and greater consistency between the decomposed jitter components and the BER bathtub curve.

These capabilities are available as options for the R&S®RTO2000 series oscilloscopes and R&S®RTP high-performance oscilloscopes (RTO-K133 and RTP-K133, respectively). Working in combination, these exceptional tools enable engineers to gain valuable insights into the individual jitter components of transmitter interfaces. Ultimately, this enables a deeper understanding of the jitter budget and makes it easier to identify the root causes of transmission failures.

8 Product Information

R&S RTP High-performance Oscilloscope
is a high-performance oscilloscope combines high-class signal integrity with a fast acquisition rate. Customized frontend ASICs and realtime processing hardware enable highly accurate measurements with unprecedented speed in a compact form factor.

R&S RTO2000 Series Oscilloscopes
Offering bandwidths from 600 MHz to 6 GHz, RTO®2000 Series oscilloscopes excel at both time domain and frequency domain testing needs. With excellent signal fidelity, responsiveness of 1M waveforms/sec, and up to 16-bit vertical resolution, quickly measure with confidence. The capacitive touchscreen with SmartGrid makes for easy and intuitive use.

R&S RTx-K133: Jitter Decomposition for R&S RTO2000 and R&S RTP oscilloscopes -- Gain more inside into the individual jitter components of your transmitter interface to characterize the jitter budget or to identify the root causes of failures. The R&S RTO/RTP-K133 option provides the decomposition of the commonly known jitter components Random Jitter (RJ) and deterministic jitter components such as Data-Dependent Jitter (DDJ) or Periodic Jitter (PJ).

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Data without tolerance limits is not binding | Subject to change