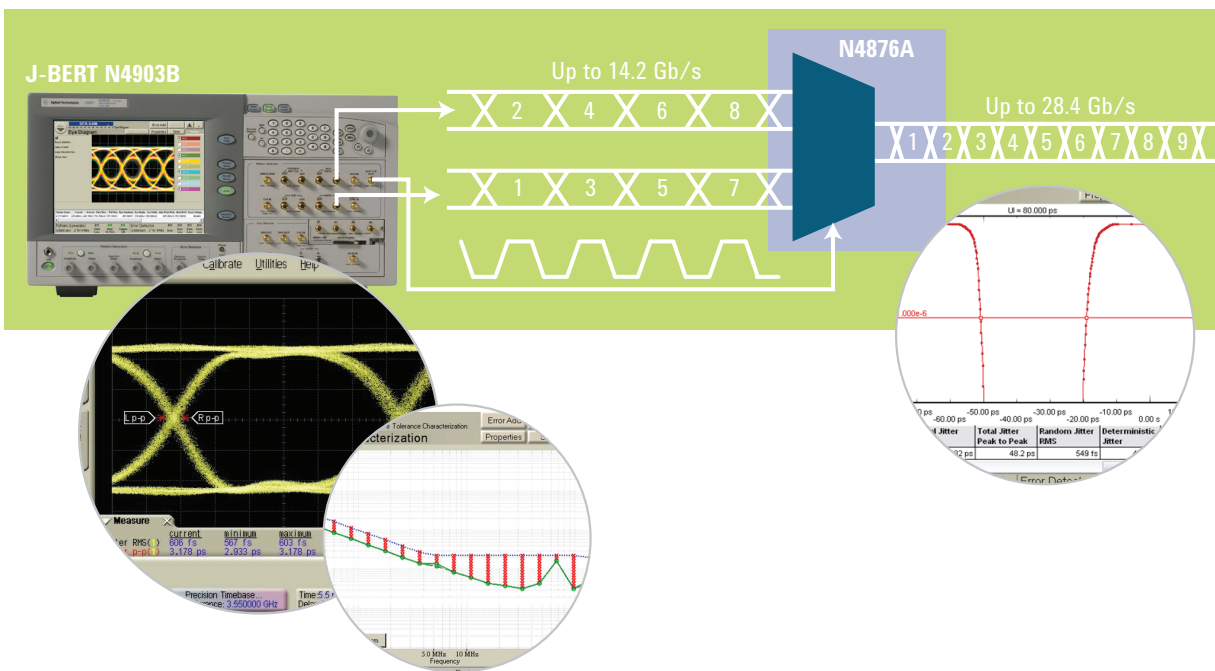


## Error Detection Up to 28.4 Gb/s During Receiver Test with the Agilent J-BERT N4903B Using Under-Sampling Techniques

### Application Note



- Sampling all relevant data bits
- Analyzing all effects leading to errors
  - Data-correlated jitter
  - Data-rate-correlated jitter
  - Uncorrelated jitter
- Ensuring statistically-significant BER results



# 1. N4903B J-BERT Data Generation Expanded up to 28.4 Gb/s

The Agilent Technologies N4903B J-BERT high-performance serial BERT with a second channel (Option 002) and the Agilent Technologies N4876A 2:1 multiplexer can easily be extended beyond 12.5 Gb/s up to 27 Gb/s (or 28.4 Gb/s using Option D14) as shown in Table 1.

How this is achieved is explained in the following sections.

## Pattern generation

This topic is easily comprehensible taking into account that J-BERT has two generator channels; these two parallel data streams are externally multiplexed by the N4876A,

resulting in a serial data stream that is twice the data rate. Proper timing for the N4876A is provided using the auxiliary (aux) clock output of the N4903B and the Agilent Technologies N4915A-011 accessory cable kit.

The main output channel of J-BERT generates the odd bits of the desired serial bit stream, while the second output channel of J-BERT, the aux channel, generates the even bits. Patterns are defined on the serial side of the MUX and the distribution of the bits is automated by an N4903B with Option 002. Consequently, the user does not have to perform this task manually and can continue using all patterns created earlier.

	N4903B	N4903B with Option D14
N4903B	12.5 (13.5) <sup>1</sup> Gb/s	14.2 Gb/s
N4876A with Option 002	25.0 (27.0) <sup>1</sup> Gb/s	28.4 Gb/s

<sup>1</sup> Numbers in parentheses are achieved with over-programming.

Table 1. Achievable generator data rates per configuration (combination of instrument and option)

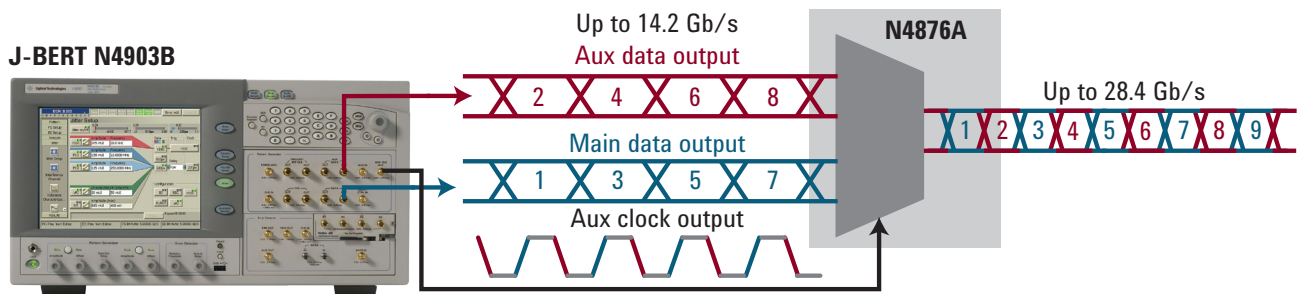


Figure 1. Generating a serial data stream > 12.5 Gb/s with J-BERT N4903B Opt D14 and Opt 002 and N4876A

## Error detection

Compared to pattern generation it is probably not as obvious how error detection can be achieved without a second channel or even a DEMUX but it is in fact simpler because no additional accessories or instruments are required.

The maximum sampling rate of the J-BERT error detector (ED) is 12.5 Gb/s. Using the under-sampling technique allows error detection beyond 12.5 Gb/s with statistical significance. Its principle functionality and how to use it for maximum confidence in the measurement results is explained in the course of this paper.

## Under-sampling

The technique, using only a fraction of the bits out of a bit stream for analysis, is called under-sampling. Figure 2 shows an example of under-sampling, where every second bit is compared and counted for BER measurements (and other subsequent measurements). The fraction of used bits is  $1/2$  and the under-sampling factor is 1:2.

Several questions may arise about how to use this technique to its best advantage, what its implications are, and perhaps most importantly, whether it is a valid measurement method. We will discuss most of these issues in the context of receiver (Rx) testing.



Figure 2. PRBS-7 with a length of  $2^7-1 = 127$  bits, under-sampled by 1:2; samples taken marked by arrows

## 2. Rx Testing Using Under-Sampling Techniques

As shown in Figure 3, the hardware set-up of a J-BERT is not much different from the setup without a MUX when no under-sampling is used. The only difference is that the error detector (ED) must be clocked by J-BERT's main clock output delivering a full-rate clock with respect to the main and/or aux data output and a half-rate clock relative to the serial data-rate. This is necessary, because J-BERT's clock recovery cannot be used above 12.5 Gb/s. Using J-BERT's main clock output is advantageous to achieving proper, error free sampling because of the many jitter adjustment capabilities of this output.

### 2.1. Using under-sampling technique efficiently

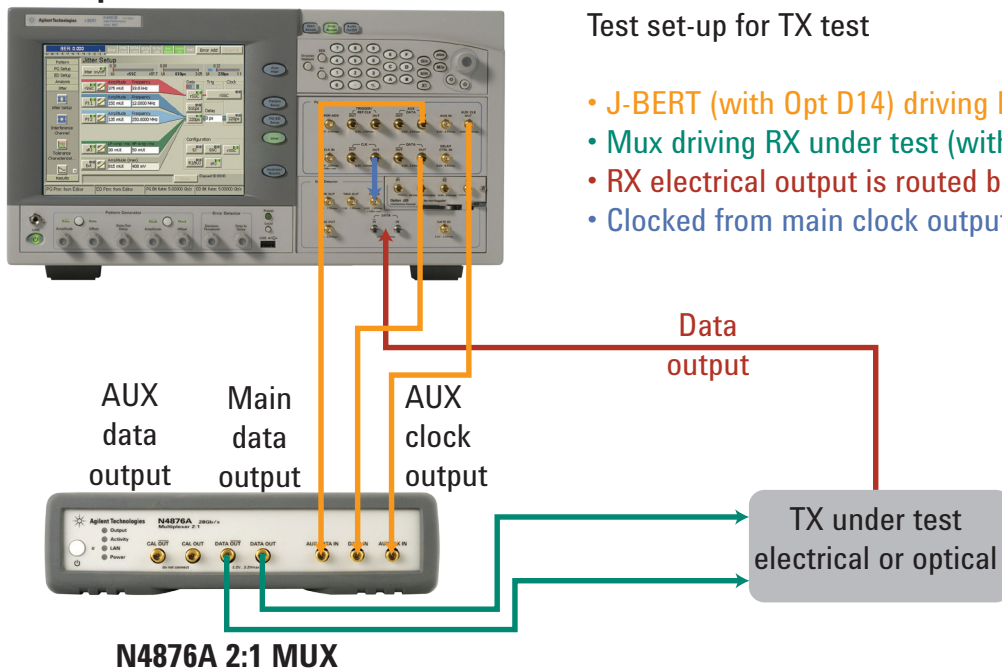
During Rx jitter tolerance test we stimulate the device under test (DUT) with a signal that is deliberately impaired (deteriorated) with certain types and amounts of jitter while the BERT-ED receives the data directly, if the Rx output is accessible, or looped back through the DUT's Tx.

The BERT-ED then compares the incoming data against the expected data. With respect to the under-sampling technique used, three different types of jitter can be distinguished:

- Jitter correlated to data (ISI and DCD)
- Jitter correlated to the data rate (e.g. 1/2 rate jitter)
- Completely uncorrelated jitter (random jitter, sinusoidal jitter, periodic jitter (assuming  $f(SJ/PJ)$  is not an integer multiple or integer divisor of the data-rate))

The following sections, 2.1.1 and 2.1.2, will show how to set up expected data and how to adapt the measurement method in order to completely capture all errors caused by jitter types 1 and 2 (data- and data-rate-correlated). For the third jitter type, completely uncorrelated, it does not make a difference if every consecutive bit or only a subset is measured, as long as the sample size, i.e. the number of measured bits, is identical. Thus, a separate discussion is not needed for this jitter-type.

### J-BERT N4903B, up to 28.4 Gbs with Opt D14 and N4876 2:1 MUX



### Test set-up for TX test

- J-BERT (with Opt D14) driving N4876A MUX
- Mux driving RX under test (with or without jitter)
- RX electrical output is routed back to J-BERT ED
- Clocked from main clock output

Figure 3. Test set-up for Rx working beyond 12.5 Gb/s

### 2.1.1. Set-up of expected data in order to capture all data-correlated errors

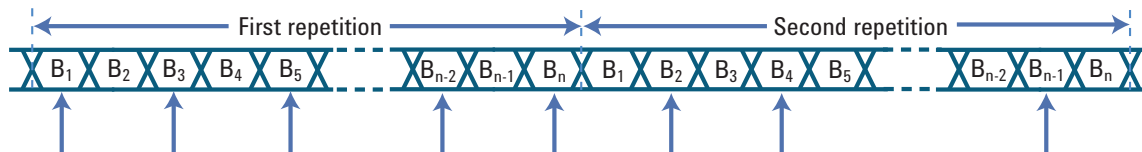
For proper detection of errors caused by this type of jitter it is important to sample every bit in the data stream not necessarily every time it appears, but often enough to achieve statistical significance. This can be achieved by set-up of appropriate expected data.

#### Odd pattern length

Let us first assume that the test pattern is an odd length. This example is always true for a pseudo random binary sequence (PRBS) with a length of  $2^n - 1$ , regardless of the polynomial. This case of odd pattern length is depicted in Figure 3. Even though only every other bit is sampled, every bit of the pattern sequence has automatically been sampled after every second repetition of the test pattern.

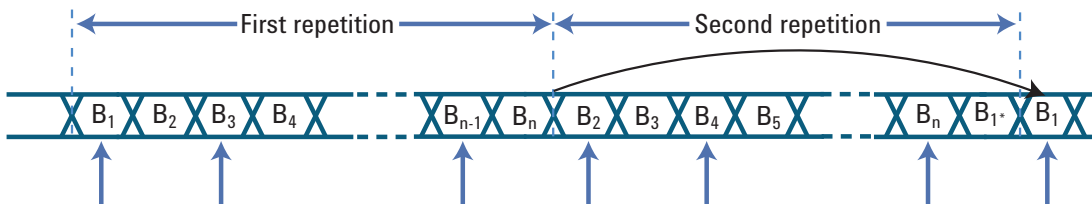
In order to perform a BER measurement, the ED needs a suitable expected data pattern observing the conditions of under-sampling. For PRBS this is very simple, since the bit stream resulting from every second bit out of a repeating PRBS follows the same exact PRBS-polynomial (only with a different starting point or seed, that is automatically determined during the J-BERT's bit synchronization). Consequently, the expected pattern for the ED is the same as the generated PRBS polynomial.

When the test pattern is a user-defined repeating pattern with an odd length, then, as shown in Figure 4, the sampled bit sequence consists of all odd bits followed by all even bits (or vice versa) and consequently the expected pattern must be set up accordingly (see Figure 4).



Expected pattern (when it is an odd number):  $B_1, B_3, B_5, \dots, B_{n-2}, B_n, B_2, B_4, \dots, B_{n-1}$

Figure 4. Proper construction of expected pattern for ED when doing 1:2 under-sampling



Expected pattern for a modified even-length pattern:  $B_1, B_3, B_5, \dots, B_{n-1}, B_2, B_4, \dots, B_n$

Figure 5. Construction of the expected pattern when the original pattern is of even length

#### Even pattern length

Now let us assume that the test pattern is an even length. If it is acceptable in the target application to add or drop a single bit to or from the original pattern, then we would effectively convert the even length pattern into an odd length pattern, as discussed in the previous section. However, there is one drawback with this method, due to the internal multiplexing architecture within the J-BERT. Let us assume the original pattern observed the boundary condition<sup>1</sup> for pattern segments in complex sequences with looped segments. In other words, the original pattern segment is divisible by 1024 and the new pattern is not. Multiplying the pattern until this condition is fulfilled may result in a new segment that is longer than J-BERT's pattern memory, or it may leave no room for the other segments of the sequence.

The following method only doubles the length of the pattern, enabling measurement on every bit in the sequence every second time, preserving the DC-balance, and only altering transition density at two positions of the pattern. This new pattern is composed like the sequence of the two original patterns with one exception: for the second repetition, the first bit is removed and inserted at the end<sup>2</sup>, as illustrated in Figure 5.

If none of the above is possible or allowed, it is necessary to perform two separate measurements, with two different expected data segments, one containing the odd and another containing the even bits.

1. If the "sequence" only consists of this one segment, then the pattern will automatically be multiplied and the boundary condition will be practically non-existent (unless the resulting, multiplied segment is larger than the total pattern memory).
2. A more general method is removing any bit,  $B_k$ , at a position with a medium number of consecutive bits and insert it at the same position for the second repetition.

### Under-sampling factor 1:4

When a data stream with data rates above 25 Gb/s is analyzed, as shown in Figure 6, the error detector operates with 1:4 under-sampling. Proper ED-clocking is achieved by operating the main clock output at  $\frac{1}{2}$  rate. The same mechanisms for the construction of expected data are valid; i.e., for a pattern with an odd length, every bit of the serial pattern is measured after every fourth repetition (in this particular case), as depicted in Figure 6. For PRBS patterns the undersampled pattern again is a PRBS of the same polynomial as the serial pattern. For odd patterns, the expected pattern must be constructed such that it contains  $B_1, B_5, B_9, \dots B_2, B_6, B_{10}, \dots B_3, B_7, B_{11}, \dots B_4, B_8, B_{12}, \dots$  When not convertible to odd-length patterns even-length test patterns require four sets of expected patterns containing bit numbers 1, 5, 9, ... 2, 6, 10, ... and so on.

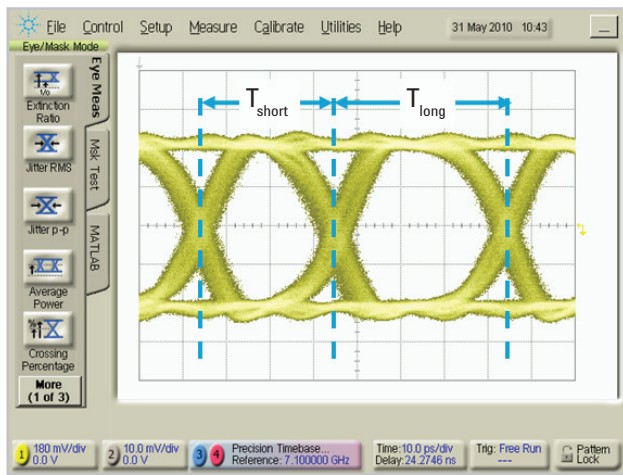


Figure 7. Signal with deliberately generated  $f/2$  jitter

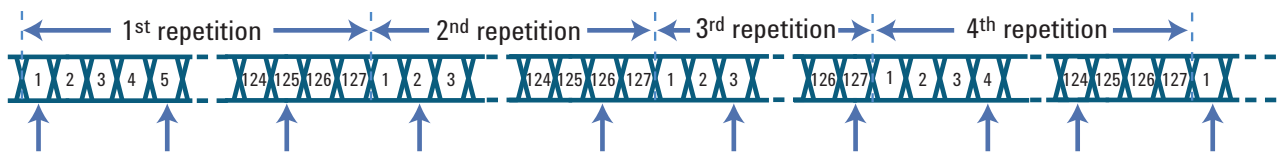


Figure 6. PRBS-7 under-sampled by 1:4, every data bit sampled after four repetitions

### 2.1.2. Adapt measurement procedure in order to capture all errors caused by data-rate-correlated jitter

Let us assume application of a periodic jitter for which the following equation is valid:

$$f_{data} / f_{jitter} = n * k$$

with  $n = 1, 2, 3, \dots$

and  $k =$  under-sampling factor

This would be the case (see Figure 7), when we generate  $f/2$  - jitter, which can appear in half-rate clocked transmitters, where every other bit is longer (or shorter) than it should be. There is a large likelihood that an error will occur more often during the shorter bits.

In those cases, it is important to actually switch sampling between the two possible options. In other words, sampling is switched between bits that are too long or too short. For all odd patterns, this can be achieved by shifting the sample point one unit interval (UI) as it relates to the serial rate, or half a UI of the main and aux data rate and initiating bit resynchronization afterwards. For even patterns, this can be accomplished by changing the phase of the generated half rate jitter and keeping the sample point constant. The latter is a more elegant method and is always valid. It can be achieved manually or under program control.

## 2.2. Implications on measurement time due to under-sampling

As stated previously, to achieve the same statistical relevance (the same BER with the same confidence level (CL)), the same number of bits must be measured. This means that a measurement with 1:2 (1:4) under-sampling takes twice (or four times) as long as full sampling. Depending on the applied test patterns and jitter, additional actions are required and they will also slightly increase the test time. Other than this, the measurement results are identical. For example, Figure 8 shows a jitter tolerance measurement performed on an SFP+ device (looped back

on the optical side) running at 10.3125 Gb/s (10 GbE). For both full rate sampling and under-sampling at 1/2 rate, the J-BERT ED was clocked from the main clock output, that carried the same jitter as the generator. The minimal differences that can be seen for three measurement points are typical “quantization errors”—which is normal when the actual limit lies between two test points and the errors appear even when the same measurement is repeated and are therefore not due to the under-sampling method.

The measurement time using under-sampling is a little less than twice the normal time due to some overhead in the measurement which does not scale.

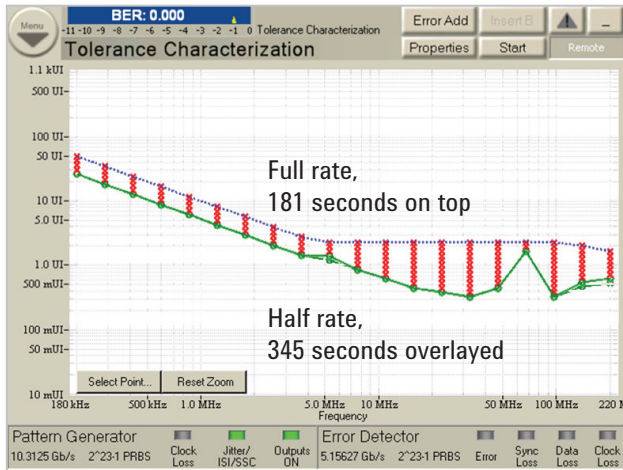


Figure 8. Jitter tolerance sweep with full sampling and 1:2 under-sampling

### 3. N4903B J-BERT ED Bandwidth

This chapter shows that the J-BERT ED has sufficient bandwidth (BW) for correct ( $BER < 10^{-12}$ ) detection of a signal with a data rate up to 28.4 Gb/s.

Let us first consider the effects of ED BW:

- Signal amplitude will be reduced, the ED will be less sensitive, and for proper detection a higher signal amplitude will be required
- ISI could be increased

The eye diagram measurement in Figure 9 shows that the amplitude is reduced with almost no additional jitter. This is due to the fact that the filter characteristic of the ED is close to a Bessel function with constant group delay introducing no jitter. This allows the use of the ED for error detection up to 28.4 Gb/s.

In Figure 10 the red line shows the decrease in measured amplitude versus the data-rate, relative to the incoming signal. Or stated another way, it shows the difference between the inner eye height and the peak-to-peak amplitude of the diagram in Figure 9. The blue line in Figure 10 shows how much the ED sensitivity is increased.

While the above measurements were made for jitter-free signals, Figure 11 shows a signal where jitter ( $RJ (1.6 \text{ ps}_{\text{rms}}) + PJ (0.3 \text{ UI})$ ) was deliberately added, but which nevertheless the ED still accurately detected with a  $BER < 10^{-12}$ . Measuring BER for  $3 \times 10^{12}$  bits (4 minutes at a sampling rate of 12.5 Gb/s) without getting any error proves, with a confidence level of 95%, that the actual BER is  $< 10^{-12}$ .

The horizontal eye opening of this signal appears to be approximately 10 ps, but taking into account that rare events are not necessarily seen on a sampling scope it is actually much smaller. With a  $UI = 1/(25 \text{ Gb/s}) = 40 \text{ ps}$  and a total peak-to-peak jitter of  $TJ = 14 \times 1.6 \text{ ps}_{\text{rms}} + 0.3 \times 40 \text{ ps} = 34.4 \text{ ps}_{\text{pp}}$  for  $BER = 10^{-12}$ , the remaining eye opening is less than 6ps.

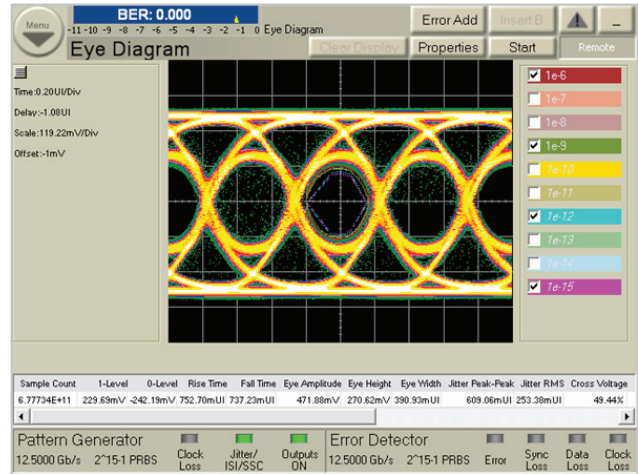


Figure 9. Eye diagram for a 25 Gb/s signal measured with J-BERT using the quick eye measurement

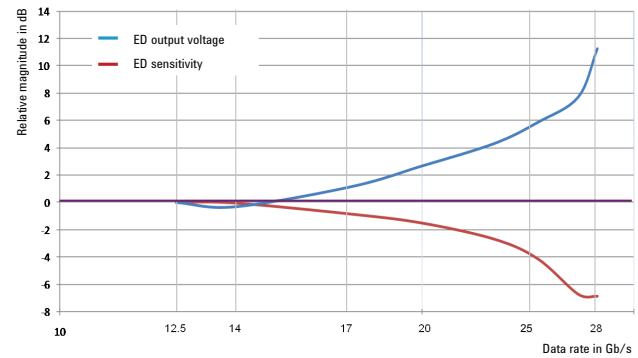


Figure 10. Sensitivity vs. data rate for a clean signal (no jitter added)

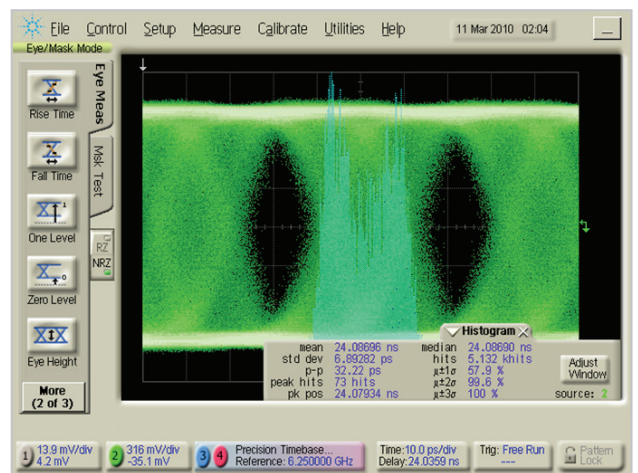


Figure 11. Eye diagram for a 25 Gb/s signal with jitter added ( $PJ = 0.3 \text{ UI}$ ,  $RJ = 1.5 \text{ ps}_{\text{rms}}$ )

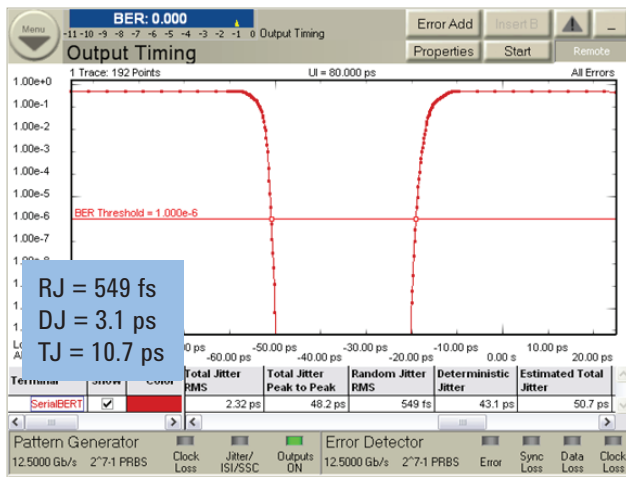


## 4. Typical BERT-Based TX Measurements, Under-Sampled

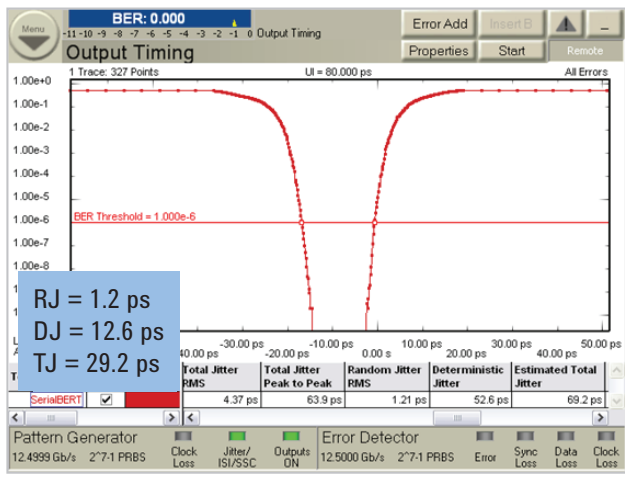
We will now expand our analysis of under-sampling measurements to typical BERT measurements performed on TXs such as a BER-scan with bathtub curve and jitter extraction. For this example, we took measurements of the MUX output signal at a data rate of 25 Gb/s using 1:2 under-sampling with the J-BERT ED. The results are shown in Figures 12a and 12c. For comparison we measured the same signal on a DCA-J 86100C with an 86107A precision time-base reference module and an 86118A remote sampling module, as shown in Figures 12b and 12d. The images on the left show the intrinsic performance of the MUX while jitter was added to those on the right (generated by J-BERT: PJ = 0.3 UI = 12 ps and RJ = 1 ps<sub>rms</sub>).

Before interpreting J-BERT's measurement accuracy, we must understand the results displayed. At first glance, the bathtub curve on the right seems rather narrow. This is due to the fact that the result window always displays 1.5 UI (relative to the ED sampling rate), which, considering under-sampling, is equivalent to 3 UIs of the serial rate.

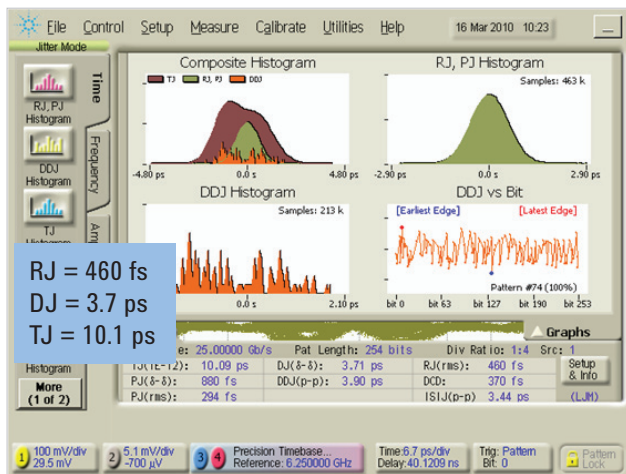
All jitter calculations except RJ refer to the full ED-UI, so it is necessary to subtract the duration of 1/2 the error detector UI (equivalent to one UI of the target data rate, 40 ps) from those values leading to the results inserted in Figure 12 a) and c) on the jitter notes. As a side note, RJ is extracted from the derivative of the bath-tub curve below the specified BER-limit.



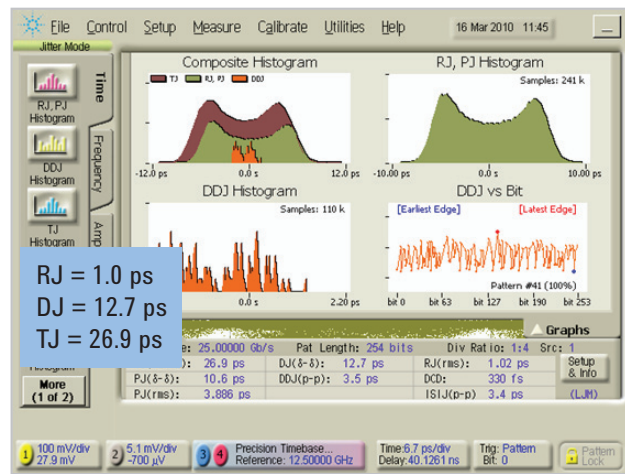
(12a)



(12c)



(12b)



(12d)

Figure 12. BER-scan measurements done at 1:2 under-sampling with and without jitter added (12a and c). Comparison measurements done with DCA-j (12b and d)

Comparison of these results to those achieved with the DCA-j shows very good congruence:

- With no jitter added (Figure 12a and b) the DCA with its precision time base (intrinsic jitter < 200 fs) shows RJ of the N4876A slightly above 400 ps.
- Measurements for DJ and extrapolation of TJ lie within a 600 fs window in cases where no jitter was added, and about 1 ps for TJ in cases where jitter was added.

As shown in Figure 9, the quick-eye measurement should not be used for signal height and mask measurements much beyond 14 Gb/s, as the 3 dB-data rate is approximately 23 Gb/s.

## 5. Conclusion

Under-sampling is a valid method available to expand the usable range of the J-BERT's ED up to 28.4Gb/s when expected patterns are set-up as described. This is equivalent to using J-BERT for RX characterization over the whole band of data rates. Even the analysis of the RX's tolerance of F/2 jitter is possible, using the N4876A's F/2 jitter generation capability most advantageously. Furthermore, the BER-scan measurement can be used for TX characterization correcting the results as described.



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