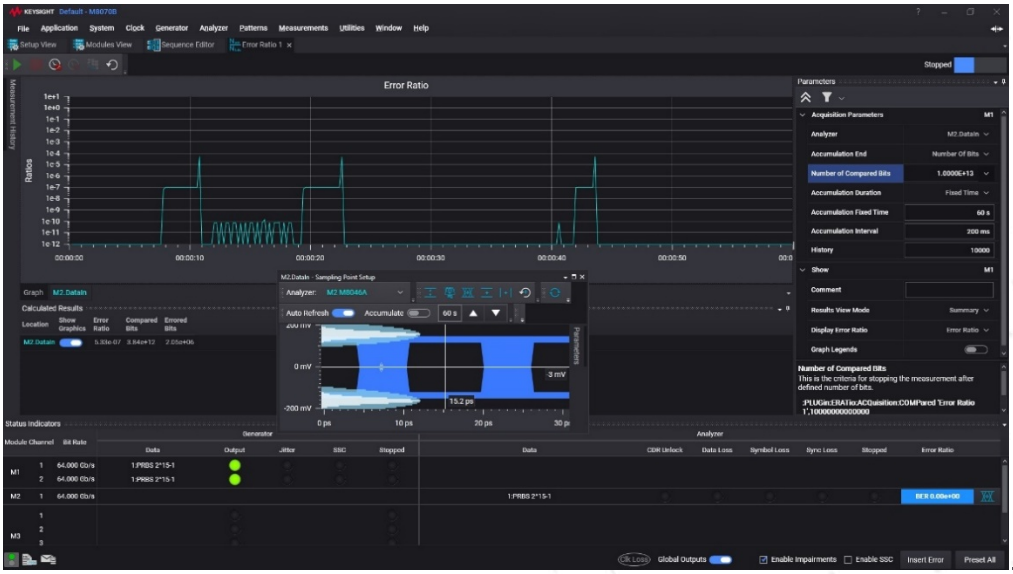
APPLICATION NOTE

BER Measurement

with Real-Time Oscilloscope Integrated in M8070B Software



BER Measurement beyond 64 Gbd

Solution enabling the BER measurement beyond 64 Gbd with flexible equalization

KEYSIGHT TECHNOLOGIES

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Summary

This application note describes how to make BER (bit error ratio) measurements using a real-time oscilloscope, when integrated into M8070B BERT system software. The configuration can include a BERT pattern generator or AWG. The real-time oscilloscope can be used to measure BER to higher data rates than traditional BERT error detectors. The basic differences between this method and the traditional BER measurement approach using the M8040A high performance BERT are explained, where both use the same M8045A pattern generator (PG) to generate the pattern stream. The hardware and software configurations of the setup using the real-time oscilloscope as pattern capture front-end are described. Subsequently topics such as the measurement details of BER including variation of BER under different data rates, time required to complete the measurement, and input sensitivity of real-time scope are discussed. Finally, the differences between the BERT and real-time oscilloscope-based approaches are explained in detail.

Prerequisites

The following requirements must be met for the successful integration of the real-time oscilloscope with the M8070B software.

- Supported oscilloscope models: refer to appendix A:
- Oscilloscope Infiniium firmware version:
  - 06.10.00614 or higher for Infiniium Z-series
  - 10.00.03804 or higher for UXR series
- Following licenses are required on the oscilloscope
  - N5384A Serial Data Analysis (SDA) (now included as a part of baseline application for UXR)
  - N8827A PAM4 Measurement (PM4)
  - N5461A Equalization (DEQ)

M8070B software revision: 6.5 or higher with M8070ADVB a license installed.

For demonstration purpose, the following instruments are recommended as pattern generators

- M8045A pattern generator from M8040A high-performance BERT
- M8194/5/6A arbitrary waveform generator

Hardware

Direct loopback configuration

Direct loopback configuration between the pattern generator (PG) and the oscilloscope were used with no Device Under Test (DUT) in the data path. The oscilloscope input is directly connected to the pattern generator output.

The setup consists of:

- one of the real-time oscilloscope models like the DSAZ634A, 63 GHz Z-series Infiniium oscilloscope (alternatively UXR series real-time oscilloscope can be used)
- an M8045A pattern generator (PG) from the M8040A BERT-series instruments. (alternatively, M8194/5/6A Arbitrary Waveform Generator (AWG) can be used),
- cables and adapters to connect the oscilloscope to the pattern generator.

The differential inputs of channel 1 of the M8045A PG and its remote head M8057A/B or the AWG M8194/5/6A are connected to the inputs of the real-time oscilloscope. RealEdge inputs are used for Z-series and normal channel inputs are used for UXR series oscillocopes.The use of proper cables is extremely important for signal quality especially at higher data rates. It is recommended to use a combination of M8045A-801 1.85 mm cables, 11900B female-to-female adapters, and M8046A-802 2.4 mm 0.85 m matched cable pair for the connection between the remote head and the real-time oscilloscope.

Optionally, for the AWG connection, the M8194-61605 matched cable pair can be used.

Both oscilloscope and AXIe chassis, in which the M8045A PG or M8194/5/6A AWG is housed, must be connected to the controlling PC with the M8070B software (version 6.5 or higher) installed on it, using USB or LAN.

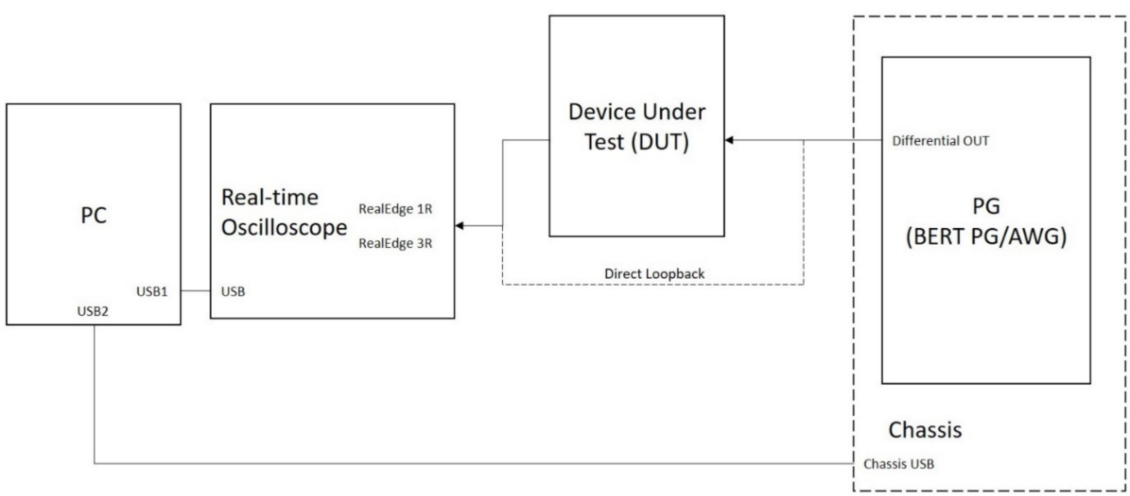


Figure 1. Basic connection setup: Real-time oscilloscope controlled from M8070B software

Software

Initial configuration

A one-time installation must be performed to configure the software prior to initial use. The complete instructions with all details can be found in the M8070ADVB user guide.

- Once the real-time scope is connected to the PC, from the Keysight Connection Expert, open the *Connection Expert* and check whether the oscilloscope with its details is shown.
- If connected, it should be displayed. (Refer to Figure 2.)
- Click on oscilloscope model number icon on the left side, the details of the scope will be shown on the right side.
- Change the visa aliases set to this instrument to one of the following: RTS_PROXY, RTS_PROXY_1, RTS_PROXY_2, RTS_PROXY_3 or RTS_PROXY_4.

Now the instrument is ready to be integrated into the M8070B software. This is shown in figure 2.

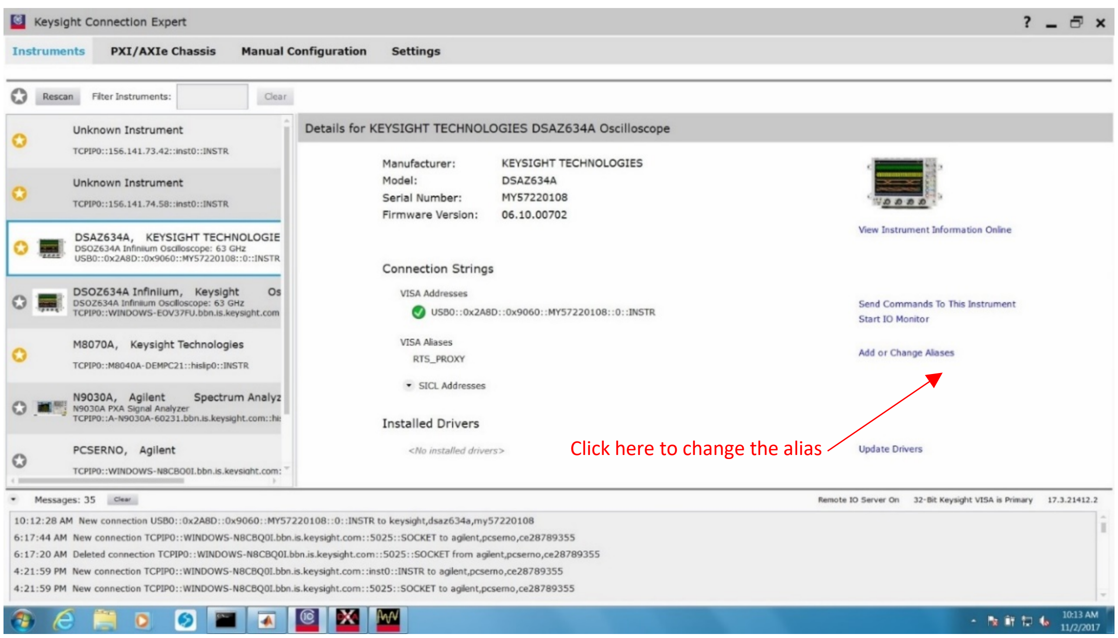


Figure 2. Keysight Connection Expert showing on the left the DSAZ. Change VISA Alias as described above.

Operational setup

The M070B user interface is modified in such a way that during the measurement of BER, the user doesn’t need to access the oscilloscope’s user interface. All the necessary controls are included in the M8070B software.

- Once hardware connections are made, power up the AXIe chassis and oscilloscope.
- Both instruments will require a warm-up time to be functional.
- When they are ready to be used, the M8070B software can be launched.

- During the initialization process, the software will configure both M8045A PG or respective AWG and the real-time oscilloscope.

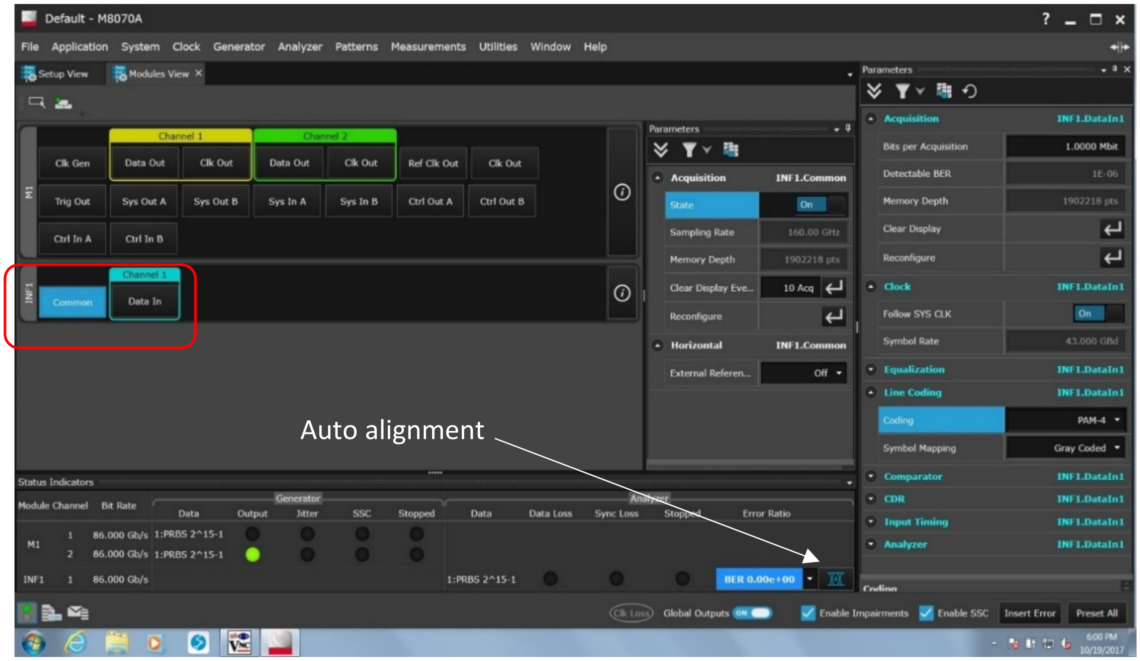


Figure 3. In Modules View *INF1* indicates the integrated Infiniium Z-series oscilloscope

- INF1 is shown as a separate module, treating the oscilloscope like an M8000A series module (such as M8045A PG or M8046A ED or M8194/5/6A AWG).

Setting the oscilloscope measurement parameters

It is assumed that the PG parameters are already set. These include the channel selection, data rate, pattern, line coding and output voltage. For achieving zero BER, the data rate, pattern type, and line coding must be kept same for the oscilloscope.

Figure 3 shows the controls which are divided under two tabs: *Common and Data In*. The *Common* tab sets the general-purpose measurement parameters. As shown in figure 3 the *Common* tab includes sub-tabs such as *Acquisition* and *Horizontal*.

- The Acquisition controls acquisition related parameters such as the sampling rate, memory depth and can also reconfigure the oscilloscope through the reconfigure option.
- The Horizontal has an option of activating or deactivating the external reference clock input if any such reference is applied to the oscilloscope.

The *Data In* tab controls the parameters related to the input of the oscilloscope. It has sub-tabs such as *Acquisition, Clock, Equalization, Line Coding, Comparator* and *CDR* (clock data recovery).

Auto-alignment

An important feature of the M8070B software is the auto-alignment function (refer to figure 3 beside the BER display). The real-time oscilloscope standalone GUI has auto set threshold and auto set equalizer tap controls, but these two are independent from the auto-alignment feature of the M8070B BERT software. In M8070B, auto-alignment searches for the widest eye-opening with its voltage threshold and sampling point (delay) being stepped over the eye. The auto-alignment feature of the M8070B software with real-time scope being integrated in it, optimizes the sampling threshold, delay and equalizer. During this process, the eye opening is automatically found by adjusting the delay and voltage threshold values for the lowest possible BER measurement.

If equalization is performed on the incoming data, then auto–alignment is highly recommended as this will:

- Optimize for the un-equalized signal to find the widest eye opening.
- Optimize the equalization process with the given set of parameters (such as taps and pre-taps).
- Optimize the equalized signal to identify the widest eye opening.

The option of individual auto-alignments is provided in *Comparator* and *Equalization* sub-tabs to optimize the eye-opening (delay and threshold) or equalization individually.

Changing measurement parameters

Prior to starting the measurement or when changing any of the above measurement parameters (such as data rate, type of line coding etc.), auto-alignment must be performed.

BER Measurement

Using M8040A BERT

A traditional BERT sends a known pattern of bits and checks the bits that are received in real-time against the expected bit pattern, counting the errors. The clock for the error detector is provided either by the pattern generator, by the DUT or by a clock recovery.

Using real-time oscilloscope stand-alone

In this method, for the BER (Bit Error Ratio) and SER (Symbol Error Ratio) measurements for PAM4 and NRZ signals, clock recovery, and at least two error-free copies of an identical repeating bit pattern in the acquisition memory are required. Typically, a PRBS test pattern is used. The oscilloscope stores these copies into its memory, compares the subsequently measured bit patterns with those saved patterns and determines the BER. The capture memory limits the length of the pattern.

The BER measurements are provided in two ways:

- BER per acquisition which gives the BER for every acquisition of the incoming bit pattern
- Cumulative BER which gives the combined BER of all the acquisitions until and including the current one.

Using real-time oscilloscope controlled by M8070B

This approach uses the M8070B software to control the real-time oscilloscope. In this case the real-time oscilloscope is used only to capture the signal and to convert it into symbols (as a digitizer). The comparison with the expected pattern is handled by the M8070B software.

The main advantages of this approach compared to the case where the oscilloscope is used as a standalone error detector are:

1. Comparison against an expected pattern and not against the stored pattern as the stored pattern may have systematic errors already. The stand-alone oscilloscope can never establish the reference pattern if the link has poor BER performance because the reference pattern is not error free.

2. It can work for longer PRBS patterns (for example, PRBS 2^{31} or QPRBS31)

It also leverages all measurement capabilities in M8070B e.g. jitter tolerance measurement and parameter sweep Key settings to measure BER. As the real-time oscilloscope is used to capture the data, the BER measurement can also be of two types which are BER per acquisition and cumulative BER.

BER measurement with real-time oscilloscope using M8070B software

The settings, measurements and the setup descriptions provided in this section apply specifically to the setup with the M8045A Pattern Generator and the DSAZ634A, 63 GHz real-time oscilloscope.

Following M8070B launch, here is the procedure to enable BER measurement using the real-time oscilloscope:

Step 1 - Pattern Generator (PG) settings

Under the *M8045A PG* section of the M8070B software:

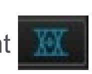
- Set the pattern to PAM4 (for this example)
- Adjust the data rate to 26 GBaud
- Set the pattern to PRBS 2^{15}-1
- Set the input signal amplitude to 300 mVpp
- Finally, turn on the output amplifiers.

To detect the PAM4 signals, the oscilloscope is to be configured to match the PG in terms of clock and type of line coding.

Step 2 - Real-time oscilloscope settings: edit via M8070B user interface

- Reconfigure the oscilloscope (clicking on the reconfigure option under acquisition tab) to refresh the settings
- Set the parameters such as the clock frequency (in this case 26 GHz by default), line coding (PAM4), acquisition depth (128000 bits), loop bandwidth divisor to 5000 (under CDR section of Data In tab. For NRZ signals it should be set to 1667).
- Select the necessary expected pattern (in this case PRBS 2^^{15}-1) from the sequence editor and ensure it is the same as that of the PG
- Turn on the global outputs (to turn on all PG outputs)
- Set the oscilloscope's acquisition state to ON under the Common tab of the oscilloscope in the M8070B software.

Step 3 - Auto alignment:

- Perform the auto-alignment by clicking on auto alignment  as shown in figure 3.

Once completed the BER 0 is visible at the bottom right corner of the M8070B front screen.

Need for equalization

Most PAM4 and some NRZ links working at very high speed (above 45 GBaud) do not run error free by design. If a loopback is configured either with an ED or with the real-time oscilloscope, then the BER may not be zero due to the channel loss in the loopback path. To reduce this problem, one can introduce either de-emphasis on the transmit side or equalization on the receive side. De-emphasis is introduced at the PG/AWG outputs and equalization is introduced by either the ED or the real-time scope. The main purpose of equalization is to compensate for the loss caused by the transmission channel. Equalization techniques provide a way to reopen closed eyes at the receiver. The equalization types provided by the real-time oscilloscope are FFE (feed forward equalization), DFE (decision feedback equalization) and CTLE (continuous time linear equalization).

The M8070B software (when integrating a real-time oscilloscope) supports adjustable FFE and a CTLE, which can be set under the Data In tab. Under FFE, it also has the option of auto-set for the FFE equalizer taps. This is identical to setting the FFE equalizer on a real-time oscilloscope.

For FFE, using the default settings (FFE with 5 taps and 1 pre-tap) is recommended. After setting the equalizer settings, turning on the equalization and by redoing the auto-alignment a wide open eye should be visible on the oscilloscope screen.Utilizing this equalization feature, it should be possible to achieve a BER of 0 for data rates up to 58 GBaud.

The Keysight UXR series oscilloscope supports bandwidth options up to 110 GHz. BER measurements can be made up to 100 GBaud and beyond (for both NRZ and PAM4 line coding), when used with a suitable arbitrary waveform generator such as the M8194A.

Figure 4 depicts the eye diagram with and without using the equalization (9 tap FFE with 3 pre-taps) with 63 GHz Z-series oscilloscope at 56 GBaud of data rate where there is clearly a signal quality improvement after using equalization.

Manually setting the taps of the equation

It is also possible to manually set the taps of equalization however by increasing the number of taps, the measurement speed decreases considerably. By default, the equalizer is set to FFE 5 taps and 1 pre-tap.

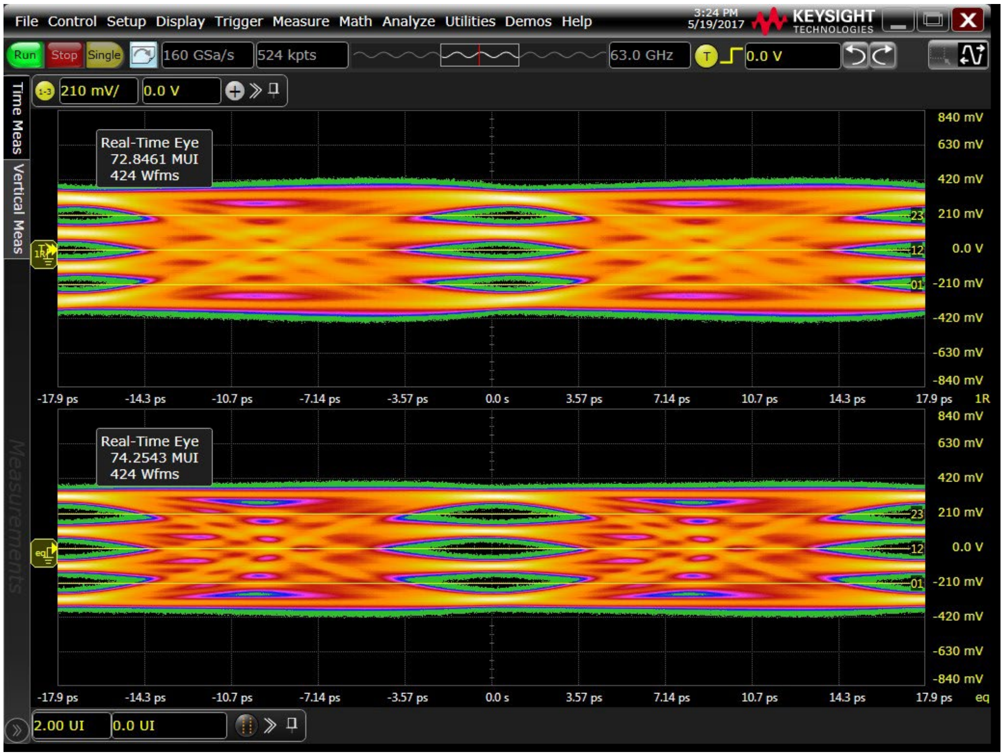


Figure 4. Eye diagram at 56 GBaud without equalization (upper) and with equalization (lower)

As stated earlier, the equalization option under the *Data In* of the M8070B includes FFE and CTLE with the option of applying either one or the other. By manually controlling the oscilloscope it is possible to apply DFE and combinations of FFE, DFE or CTLE. The procedure is explained in Appendix B.

The M8194A AWG generates data rates of up to 100 GBaud and beyond. An adjustment of the equalizer settings is required at these rates. In addition, the generator signal must be adjusted using the alpha factor under the AWG parameters. The alpha factor or the roll-off factor is a factor of raised cosine pulse shaping filter. It can vary between 0 and 1. In the frequency domain, it reduces the excess bandwidth of the filter. With 0 it reduces the bandwidth to Nyquest frequency whereas with 1 it allows the full bandwidth usage. At 100 GBaud, the alpha factor is adjusted in between 0.1 and 0.2 for compensating ISI (Inter Symbol Interference).The adjusted 100 GBaud PAM4 (200 Gbps) eye and corresponding alpha factor settings are depicted in Figures 5 and 6 respectively.

AWGs M8194/5/6A

The AWGs M8194/5/6A can also be used as a pattern generator instead of the M8045A PG.

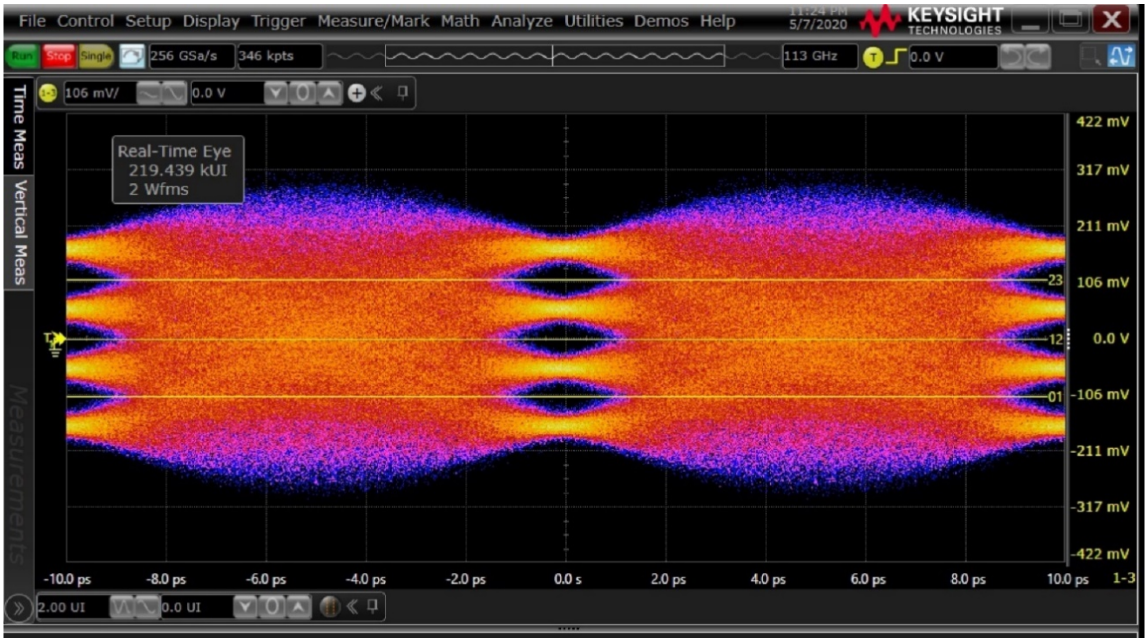


Figure 5. 100 GBaud PAM4 equalized eye generated with M8194A AWG

The corresponding settings in the M8070B are shown below:

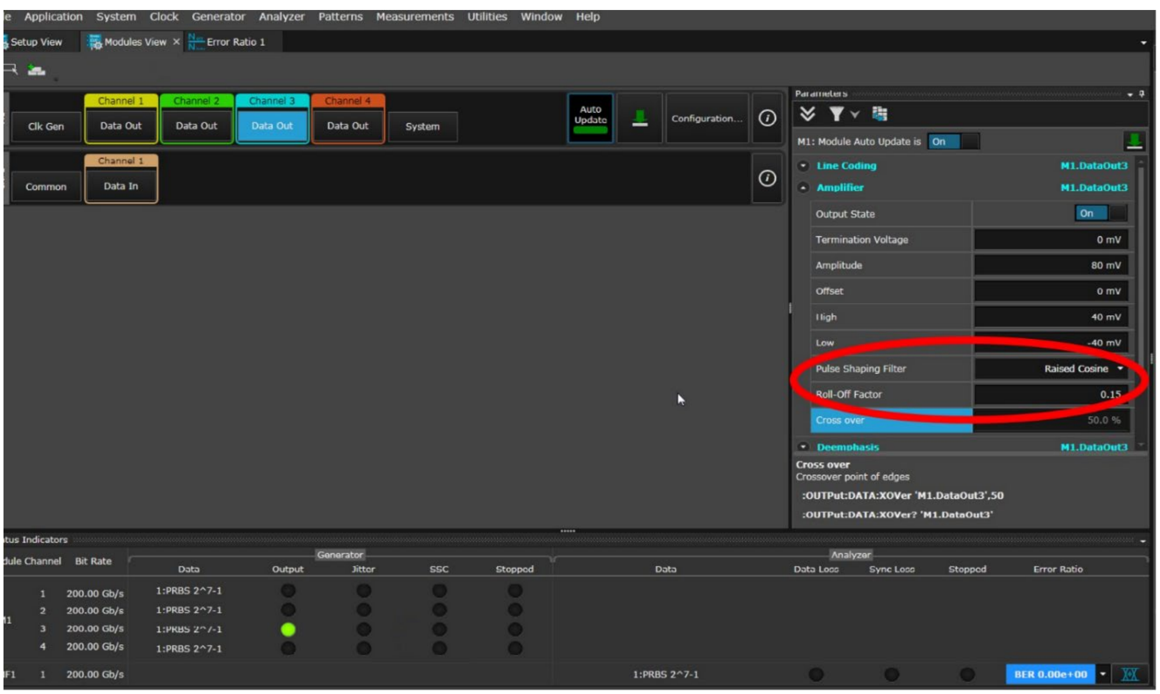


Figure 6. The M8194A parameter adjustment in M8070B at 100 GBaud

Measuring cumulative BER

BER is the number of errors divided by the number of compared bits. In order to confirm that a DUT achieves the target BER with the required confidence level (CF), a huge number of bits or symbols must be compared (depends on the target BER threshold). When using a BERT error detector every single bit or symbol is compared. In the case of a real-time oscilloscope, the acquisition happens with a given acquisition memory depth. When the number of bits/symbols to be compared exceeds the acquisition memory, multiple acquisitions must be made. Errors occurring between the acquisition phases are not recognized for the BER measurement.

The BER measurement in M8070B for real-time oscilloscope based integration approach, can either be BER per acquisition (which is indicated by the blue BER icon on M8070B) or cumulative BER. For cumulative BER, there are various BER test cases supported as described below.

Three detail BER measurement approaches

The three approaches to create the detailed BER measurement: running for the full duration, pass/fail and for a given number of bits. All these options are available under the *Accumulation End sub*-tab.

- Full duration BER measurement: the measurement is run, and a graph will be plotted for the specified amount of time (accumulation duration).
- Pass/fail measurement: the target BER is specified and the BER measurement will continue until the specified confidence level is reached for the specified target BER. There is a statistical relationship between the confidence level achieved, and the number of bits compared (roughly 95% confidence level with target BER 1E-6 requires 3 million bits to be checked). As the number of compared bits increases, the confidence level also increases until an error is encountered.
  - If an error is encountered, the confidence level decreases, but the measurement will still continue.
  - If the number of errors encountered are so high that the specified confidence level can never be reached (or in other words that the measured BER is greater than target BER), then the measurement is declared as a fail. This typically happens when the confidence level keeps on decreasing as the measurement progresses.
  - This type of BER measurement can also be made in a limited time, by specifying accumulation duration. In which case if the required confidence level is not reached in the specified time interval, then this measurement is also declared as fail.
- In the third type of BER measurement, the specified number of bits are compared and a BER is shown.

Pass/fail BER measurement

To initiate the target BER measurement, the selection of the *BER measurement* from the *Measurement* menu is required. Once activated it opens a new window showing the detailed BER measurement parameters.

To set the target BER, select the *Accumulation End sub*-tab under *Acquisition Parameters* and select its type as *pass/fail.* Set the necessary parameters, such as a target confidence level (95% in this case) and a target BER (1E-8 in this case).

The BER is now set to complete the measurement with the specified parameters. The target BER measurement window is shown in figure 7. The accumulation interval is fixed to 200 milliseconds.

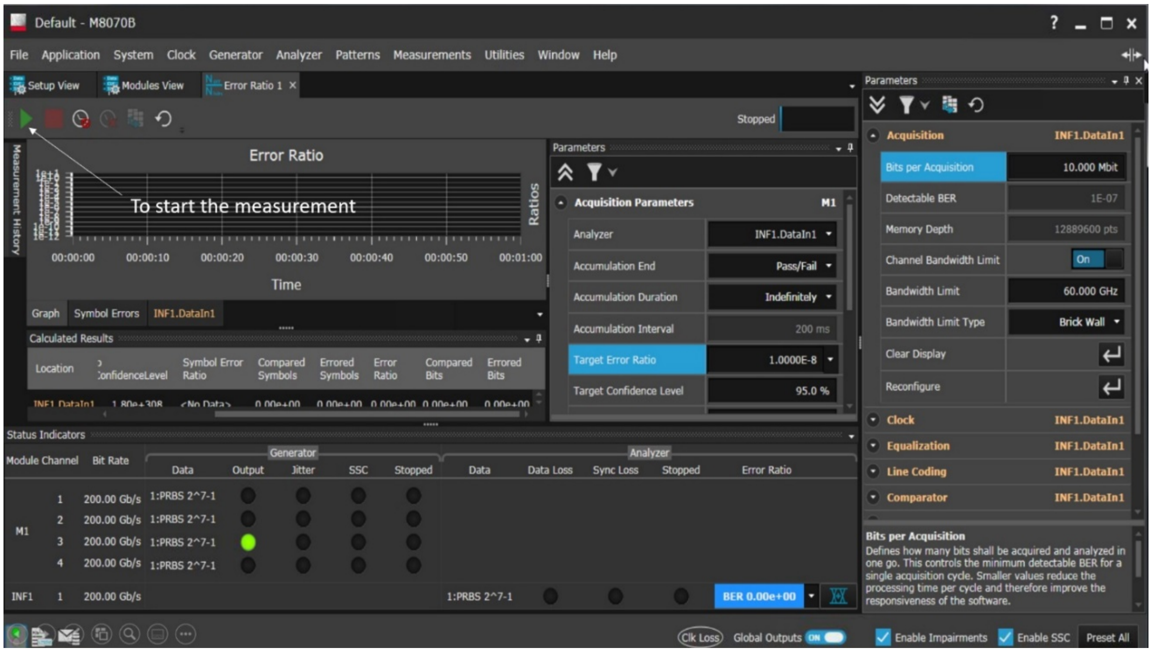


Figure 7: Target BER measurement with 1.E-8 as target BER at 95% confidence.

To start the test, click on the green arrow on the top left corner (See Figure 7). Once the test is started, the oscilloscope will digitize the incoming data signal and the M8070B begins checking the received bits, visible in the *compared bits* and *errored bits'* sections of the results. At the interval of 200 milliseconds (each accumulation interval), the oscilloscope updates the compared bits and the confidence level, indicating the increase in number of compared bits as well as the confidence level. This will continue until the oscilloscope reaches a 95% confidence and the result will be shown. If any error is encountered within this time frame, the confidence level will be decreased as explained above. It is also possible to increase the measurement window of the target BER by setting it even lower (<1E-8). However, the lower the target BER the greater number of bits must be checked, which increases the measurement time. This is inversely proportional to the target BER threshold, eventually making the BER measurement very time consuming for very low target BER thresholds (<1E-8).

Direct Loopback BER measurement

The direct loopback BER measurements, i.e. per acquisition as well as detailed BER measurements, are successful without using equalization up to 50 GBaud (45 GBaud in case of a real DUT) only. For baudrates above, transmitter de-emphasis or receiver equalization should be applied to ensure the BER is maintained at 0. Again, the direct loopback from a PG or AWG is typically the best case and the BER value may be higher with the real DUT in place. Hence it is advised to incorporate the equalization feature at higher data rates whenever required. The default equalization parameters are FFE with 5 taps and 1 pre-tap. At symbol rates above 56 GBaud , this default equalization is not sufficient, and the equalization must be increased. For example, setting it to 9 taps and 3 pre-taps. Incorporation of equalization ensures that the system BER is maintained at 0 until 58 GBaud. However, increasing the equalization level, the oscilloscope requires more time to create the equalized digitized signal (applying equalization on the received signal and then digitizing it) resulting in a considerable increase in the measurement duration.

To ensure sure that the BER is being measured correctly, it can be cross-checked by using the error insertion capability, available in the M8045A (PG). Figure 8 shows the error insertion window in the M8070B software interface for the M8045A PG module.

Error insertion

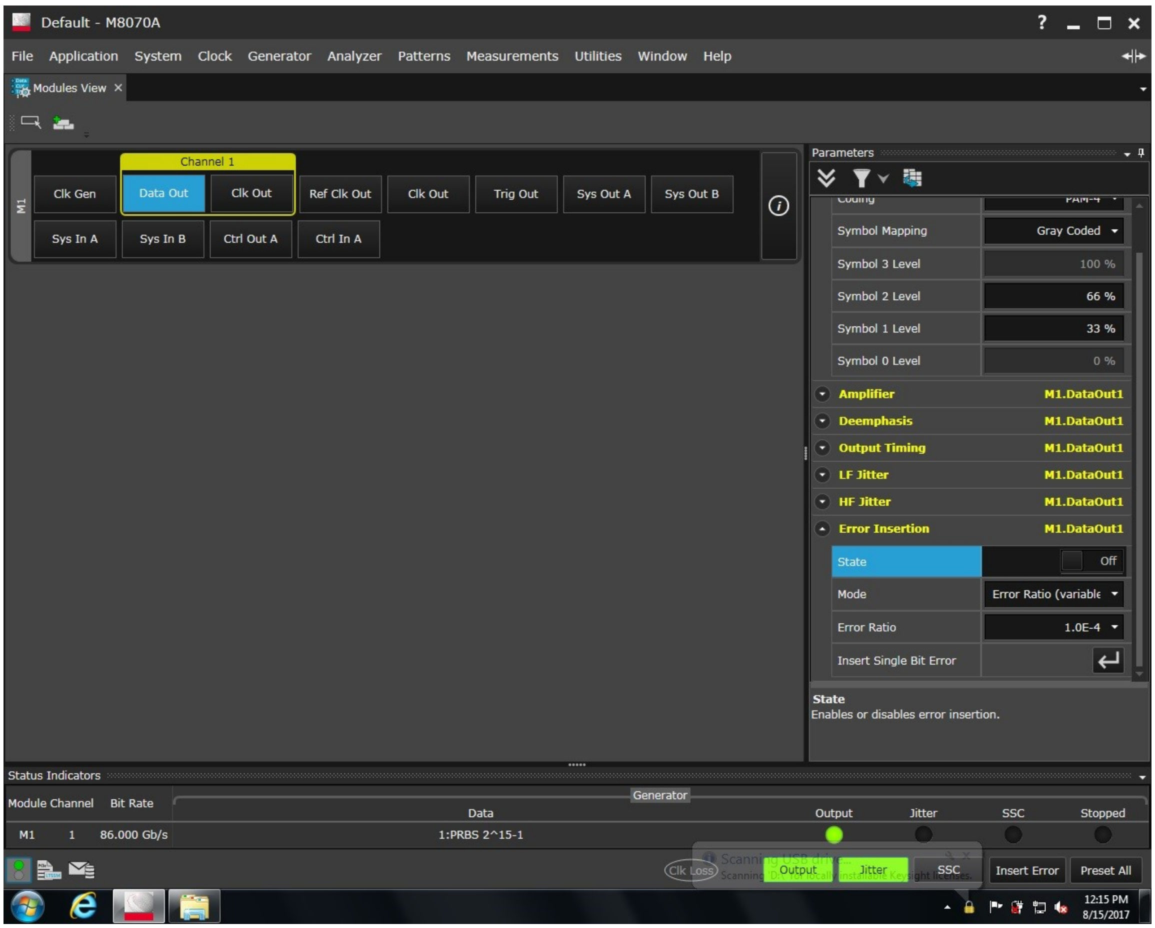


Figure 8. Error insertion window in M8070B software for PG module

Under the Error Insertion parameters of the M8045A PG, mode of error insertion can be selected. When selecting an error ratio mode with a value of 1E-4 and turning on the error insertion, the acquisition BER (BER at the bottom right corner of the M8070B screen) as shown in the figure 8, also shows a BER in the order of 1E-4, indicating that it is encountering errors. By turning the error insertion off, the BER shifts back to 0 again, confirming that it follows the error insertion. This shows that the M8070B software detects errors accurately and can reliably be used for BER measurement. This error insertion approach can be used for PAM4 and NRZ line coding.

It should be noted that if for a particular case if the BER is 1E-6, inserting an error at the rate which is less than 1E-6, will be overlooked and will not be detected by the system. For example, by selecting an error insertion ratio of 1E-8 (< 1E-6) the M8070B software will not detect it. To enable detection of error ratios of the order below 1E-6, the BER must be maintained below the required error insertion ratio.

Input sensitivity

The sensitivity of the real-time oscilloscope is the minimum peak to peak amplitude of an input signal that the oscilloscope can detect.

All above BER measurements are achieved at an input amplitude of 300 mVpp and the amplitude kept constant even though the data rates were changed. Sensitivity measurements on the oscilloscope are made with specific target BER. Sensitivity measurements referenced hereafter are valid for a target BER of 1E-6. For PAM4 line coding, the oscilloscope shows excellent sensitivity as low as 50mVpp up to 45 GBaud, (single ended and without any error or jitter inserted and without equalization applied). Beyond 45 GBaud the sensitivity requirements are categorized based on the applied equalization.

When excluding equalization, the oscilloscope sensitivity requirements increase with an increase in data rate. For Z-series 63 GHz rereal-time oscilloscope, at 50 GBaud, the oscilloscope requires 63 mVpp input amplitude to detect the input data signal properly. At 56 GBaud 150 mVpp is required, and at 58 GBaud it requires 250 mVpp. Continuing to 60 GBaud, it shows sensitivity requirements of 250 mVpp and thereafter shows some fluctuations such as at 61 GBaud about 450 mVpp and at 62 GBaud 350 mVpp.

Applying equalization (9 tap FFE), up to 56 GBaud, the required sensitivity is as low as 50 mVpp and increases thereafter. At 58 GBaud 63 mVpp is required and then increasing sharply to 350 mVpp and 450 mVpp at 60 and 61 GBaud. With equalization, sensitivity requirements generally increase with an increase in data rate and the equalization improves the performance by maintaining the low sensitivity values at higher data rates until 58 GBaud. Summarization available in Figure 9.

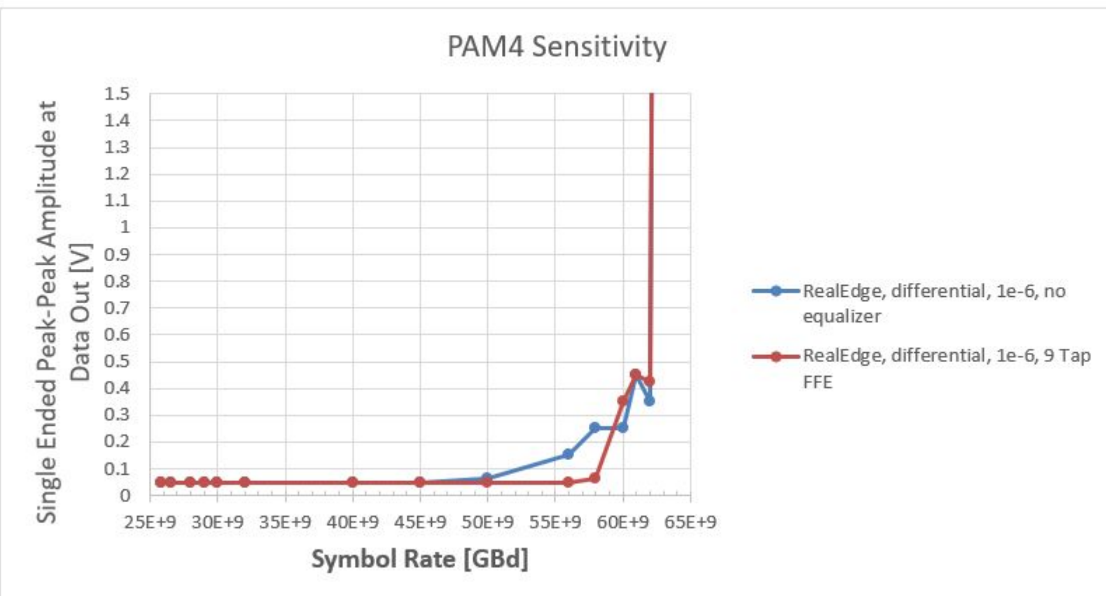


Figure 9. Sensitivity of real-time oscilloscope DSAZ634A with and without equalizer

For different target BER such as 1E-7 or even 1E-8 an increase of the amplitude at lower data rates is required. For example, at 55 GBaud the minimum amplitude of 63 mVpp at target BER of 1E-8 needs to be maintained followed by a sharp increase to 463 mVpp at 56 GBaud.

In the case of the NRZ, sensitivity is as low as 50 mVpp (single ended peak to peak) is possible of up to 58 GBaud (with over-programming up to 64 GBaud).

The comments made above are applicable exclusively for 63 GHz Z series oscilloscopes. However, with the UXR series oscilloscopes, measurements beyond 100 GBaud are all possible. The pattern generator should have adequate capacity to generate the signals. Equalization is required for data rates of 100 GBaud and beyond.

Using UXR1102A (110 GHz, 2 channel UXR) with M8194A as pattern generator, at 100 GBaud PAM4 BER measurement, sensitivity as low as 80 mV (for target BER 1E-8) and 76 mV (for target BER 1E-7) is achievable.

Jitter tolerance testing

Basics of jitter tolerance testing with M8070B software utilizing the BERT real-time oscilloscope

Jitter

This is the deviation from true periodicity of a presumably periodic signal, often in relation to a reference clock signal (*). In simple terms, it is the variation in the data transition instant (1 to 0 or 0 to 1) with respect to its expected position. Excessive jitter should be avoided because it leads to the eye closure leading to errors in the data stream increasing the BER.

There are various types of jitter classified as per the pattern, such as random jitter and deterministic jitter. Deterministic jitter is additionally classified as periodic, data dependent (which is furthermore classified as duty cycle distortion and inter symbol interference) and bounded uncorrelated jitter. A few examples of sources causing jitter are thermal noise (random jitter), cross talk (bounded uncorrelated jitter), long or short bits (inter symbol interference) etc. The total jitter is the summation of all the individual jitter contributing to data impairments.

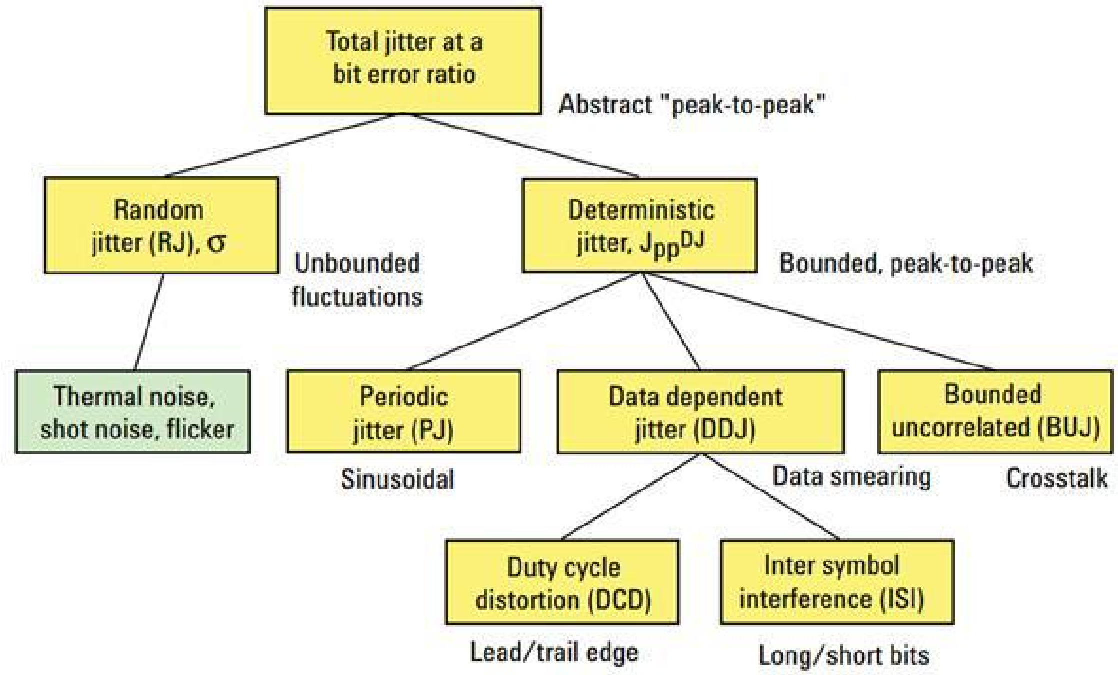


Figure 10. Classification of jitter

Jitter tolerance

Knowledge of system jitter tolerance provides key insights into the digital design circuitry. Each receiver is designed to accept a certain amount of jitter. Jitter tolerance is the ability of the receiver to tolerate, or to deal with the jitter on the received signal to successfully receive the pattern symbols and interpret them.

For the most part, the receiver standards define a specific tolerance of the amount of jitter across a certain jitter modulation range.

Sinusoidal jitter

Sinusoidal jitter is introduced into the data stream to carry out the jitter tolerance measurement and is a periodic jitter in which the jitter function follows a sinusoidal curve. Thus, the variation of the transition event with respect to its ideal position will be sinusoidal. Figure 11 depicts the jittered NRZ signal seen on the Infiniium sampling oscilloscope DCA-X at 28 GBaud. From the histogram, the two peaks at the end resembling the sine function are visible. In this example, 1 MHz of low frequency sinusoidal jitter with 700 mUI of amplitude was injected using M8045A PG.

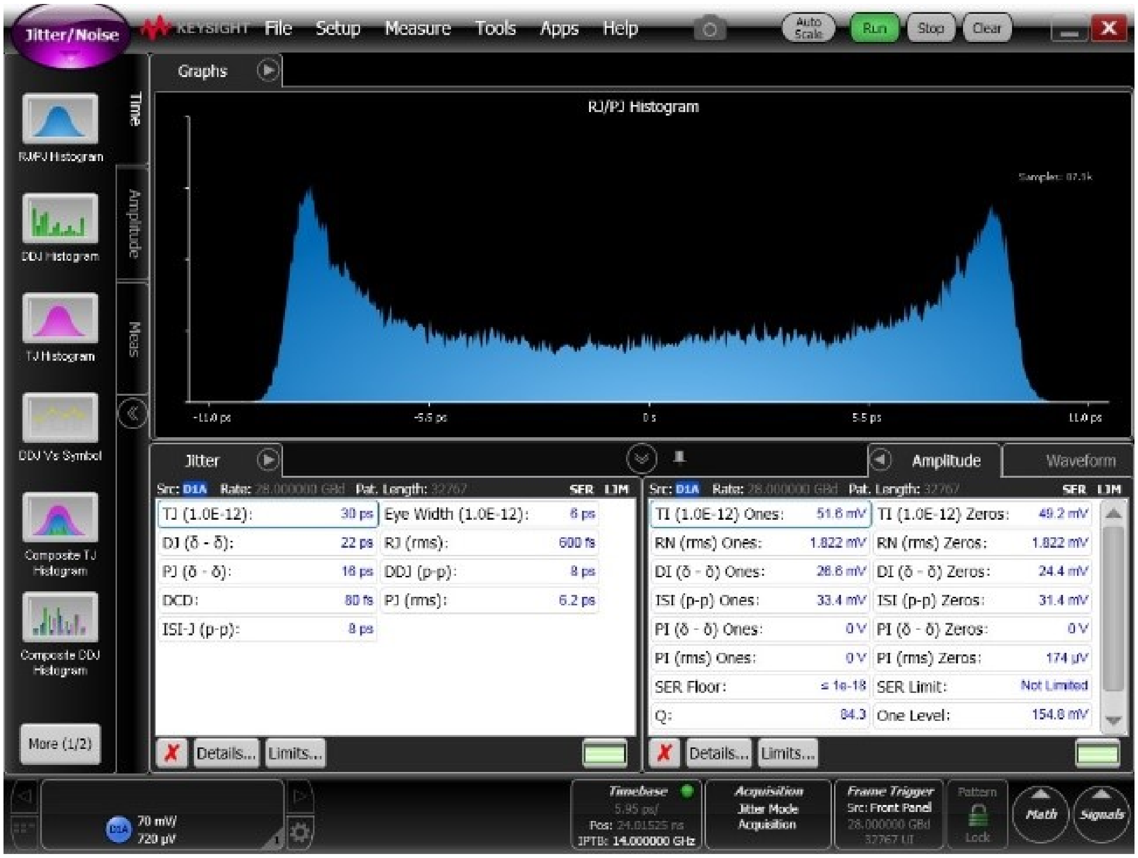


Figure 11. Sinusoidal jitter as seen on infiniium DCA-X

Basic jitter tolerance testing approach

The basic approach of testing jitter tolerance includes injection of sinusoidal jitter into the pattern generated by the pattern generator and measuring the BER via a loopback path. The target BER can be selected for a jitter tolerance measurement. The BER measurement is carried out for various jitter amplitudes and at different jitter modulation frequencies. The test begins with the injection of sinusoidal jitter of a particular frequency, (start frequency) and the jitter amplitude is varied, (either increased or decreased depending upon the algorithm selected), until the BER exceeds the target BER set and then the measurement shifts to the next jitter modulation frequency value, (either higher or lower frequency depending upon the algorithm selected). In this way, a jitter frequency vs jitter amplitude graph is plotted which is the outcome of jitter tolerance test. Automated sweep of the jitter amplitude and the jitter modulation frequency helps to minimize the duration of a jitter tolerance measurement.

Jitter tolerance test window in M8070B is as shown below (M8070ADVB plugin is required).

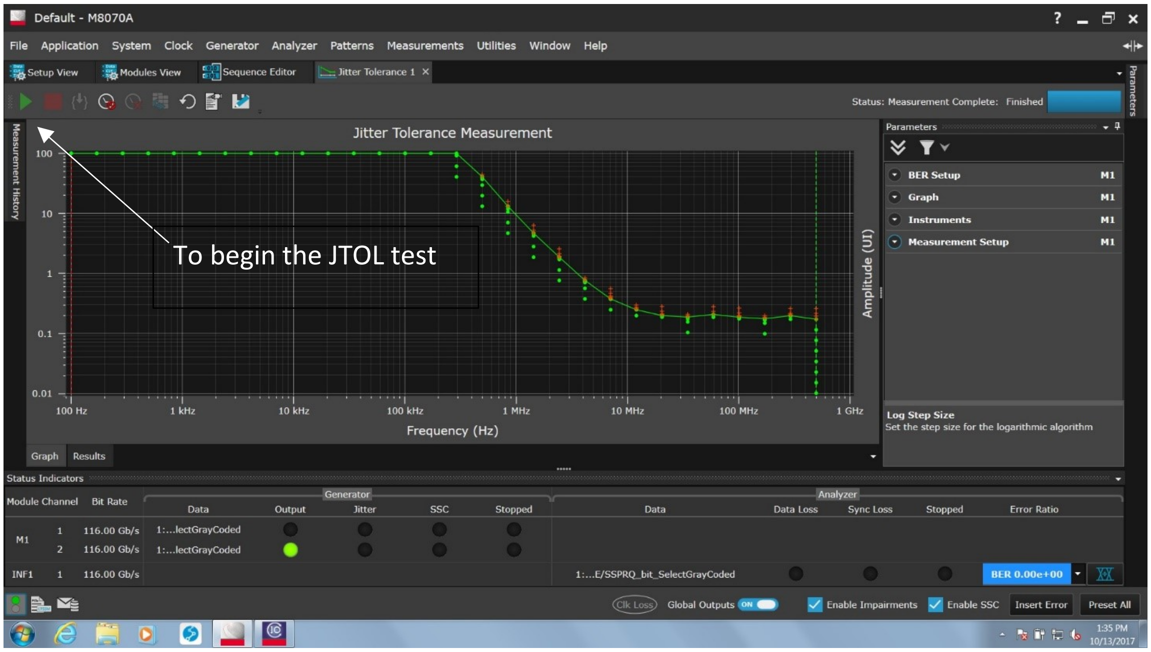


Figure 12. Jitter tolerance measurement window

Figure 12 shows the parameters on the right side that can be set such as BER setup, Graph, Instruments and Measurement Setup.

BER Setup: The sub-tabs include

- **Target BER**: Sets the desired target BER
- **Confidence Level**: It decides the reliability of BER measurement. An increase of the confidence level, results in an appropriate insrease of the number of bits to be compared for target BER set. Higher confidence levels require more data to be measured, subsequently increasing the duration of the measurement.
- **Frequency Relax Time:** Time duration for which the measurement will pause prior to hopping to the next jitter frequency
- **Amplitude Relax Time**: Time duration for which the measurement will pause prior hopping to next jitter amplitude at the same frequency

Graph tab: Consists of sub-tabs which are associated with displaying the jitter tolerance results in a graphical manner. It has four sub-tabs; *Template Limits*: *Points, Compliance Limits and Show All Points*. The sub-tabs are self-explanatory.

Instruments tab: Discerns the devices involved in the measurement. It has two sub-tabs which are *Generator* and *Analyzer*. For the generator when M8045A PG is used, two options are available to select either *channel 1* or *channel 2.* Settings can be adjusted via this tab.

Measurement setup tab: This is the most important tab and it sets all the necessary parameters required to configure JTOL test. The subtabs are:

Start and stop frequencies: Indicate the start and stop of frequencies of the jitter tolerance measurement. Depending upon algorithm, selections are either, high to low or low to high frequency types of measurements possible.

Number of points: It is the number of frequency hops that the measurement will take when it is running from start to stop jitter frequencies.

Mode: Two modes are possible: *characterization* or *compliance.* In *compliance*, the jitter tolerance will only be up to the point of compliance limits, while in *characterization*, the test will be performed as per the mentioned specifications.

Compliance Margin: Given only in compliance mode, it indicates the acceptable limits of the system performance (results).

Algorithm: Indicates the algorithm selected for stepping the jitter amplitude in the jitter tolerance test. Few examples of algorithm are up logarithmic, down logarithmic, up linear, down linear, adaptive binary etc. In up linear, the amplitudes start from very low value (0.01 UI) and increase until a very high value for which the resultant BER is more than the target BER. The increment in amplitude is linear.

Binary Step Size: Used for an adaptive binary type of algorithm, it indicates the amplitude step value when hopping from one amplitude to the next.

Linear Step Size: Used for linear algorithms where it indicates the amplitude step value when hopping from one amplitude to the next.

Log Step Size: Used for logarithmic algorithms where it indicates the logarithmic step value in percentage when hopping from one amplitude to the next.

CDR LBW Auto: When turned *ON*, jitter tolerance measurement takes into consideration the CDR LBW (clock data recovery loop bandwidth) curve of the DUT. This option is by default ON.

Jitter tolerance test using BERT and real-time oscilloscope when controlled from M8070B

An automated jitter tolerance measurement is possible with the M8070B system software for the M8000 series. Starting from the software version 4.0, it can also be used with a real-time oscilloscope together with a pattern generator, such as M8045A.

M8040A high performance BERT is well equipped to carry out the jitter tolerance measurement. Setting all the necessary parameters as mentioned in the previous sections, and start the test by clicking on the green arrow in the top left corner as shown in Figure 12. The target BER value which is set to 1E-9 by default. This can be alternated as required. However, the real-time oscilloscope, using a value of 1E-6 or more (1E-5, 1E-4 etc.) is recommended, otherwise the measurement is time consuming. The time taken for the measurement depends upon the time required to complete the individual BER measurements. BERT being very quick, jitter tolerance measurement targeted at 1E-9 BER takes a few minutes to complete. The jitter tolerance measurement test duration is dependent on, the number of points, the algorithm selected, the selected mode which decides the number of points to be tested. Keeping these parameters constant, the measurement time is directly impacted by the individual target BER measurement which is then affected by various factors in the case of the real-time oscilloscope when controlled via the M8070B (as discussed in earlier sections).

AWG as PG doesn't support the real-time oscilloscope-based jitter tolerence testing

The AWG as PG doesn't support the real-time oscilloscope-based Error Detector (RED) based jitter tolerance measurement. A standalone real-time oscilloscope cannot perform a jitter tolerance measurement.

If the target BER is kept very high such as 1E-3 or 1E-4, the measurement duration is limited by the acquisition time. However, keeping the target BER very low such as the default target BER of JTOL test measurement 1E-9, the testing becomes impractical for the real-time oscilloscope due to the time taken to complete the measurement. Refer to figure 13 as a reference to the time taken to complete the measurement at different target BERs. All the lower target BER values (<1E-6) are not practical.

The adaptive binary algorithm is recommended to be used for jitter tolerance testing when the real-time oscilloscope is controlled via the M8070B, as it saves on the measurement time considerably. Typically, this algorithm starts from the highest measurement jitter frequency to the lowest measurement jitter frequency. For the highest jitter frequency, the UI amplitude will be gradually increased as per the binary step size given until it encounters first failure. Once confirmed, for the subsequent frequencies, this particular amplitude is taken as a reference point and from this point, next UI amplitude is then in return checked for compliance. This process continues, and the graph is plotted. JTOL measurement testing graphs for the real-time oscilloscope, when controlled via the M8070B for different target BERs are as shown in Figure 13.

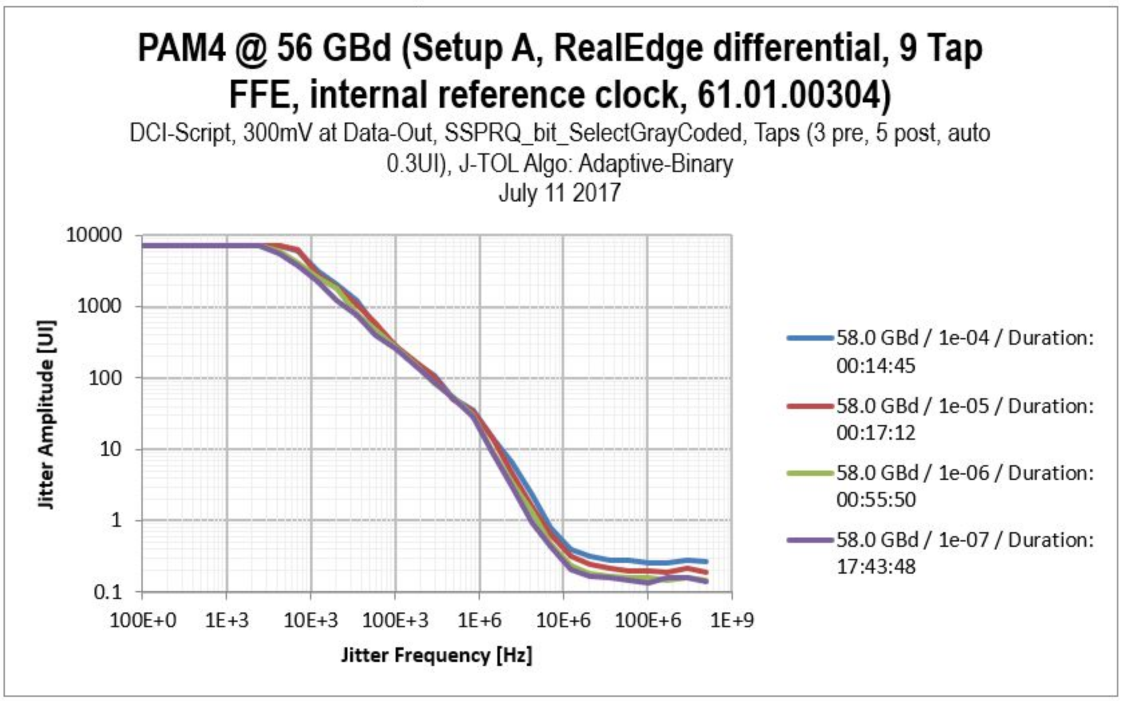


Figure 13. Jitter tolerance measurement curves at different target BER when real-time oscilloscope is integrated in M8070B

Detailed comparison between BER measurement using BERT and real-time scope

Three BER measurement approaches are discussed in this application note.

- Using the traditional M8040A high-performance BERT: comparing directly the received bits against the expected ones.
- Standalone oscilloscope based BER measurement which initially needs two error free copies of the pattern in its acquisition memory comparing all the received patterns against the stored patterns to generate the BER measurement.
- The real-time oscilloscope when controlled from the M8070B software: bit comparison and BER calculation against an expected pattern are accomplished via the M8070B software and digitizing the received signal is handled by the real-time oscilloscope. The advantage of using the real-time oscilloscope for error detection purposes, is the ability of viewing the waveform used for the loopback, permitting both the verification of the equalization and the various parameters of the waveform used.

Measurement time

In the case where the real-time oscilloscope is controlled from the M8070B, measurement time is a critical factor. BERTs such as the M8040A correctly and accurately measure BER in real-time and the measurement is fast (completed in few milliseconds). Even with the change in the data rate, the corresponding change in the measurement time is very less or insignificant (but it is not totally independent of the change in the data rate; e.g. it takes 30 times longer to capture and compare 10^{15} bits at 2 Gbps than at 60 Gbps).

Controlling the real-time oscilloscope via the M8070B, the oscilloscope captures and digitizes the incoming signal. As previously referenced, the target BER is set at 1E-6 for Z-series real-time oscilloscope. By decreasing the target BER threshold, the real-time oscilloscope must digitize a multitude of bits to satisfy the required target BER threshold to an ascertained confidence level (to 95% in this example). The BER measurements at 32 GBaud and PAM4 at 128000 bits acquisition depth (UI) for Z-series 63 GHz real-time oscilloscope is exampled in table 1. In this case no equalization is used in the realtime oscilloscope. The measurement duration is shown in hours: minutes: seconds.

Target BER	Confidence level	Duration (hrs:min:sec)	Compared Bits	Confidence at target BER
1e-4	95%	00:00:02	2.62e5	99.9999…%
1e-5	95%	00:00:05	5.24e5	99.46%
1e-6	95%	00:00:29	3.15e6	95.69%
1e-7	95%	00:04:42	3.01e7	95.05%
1e-8	95%	00:46:54	3.00e8	95.01%

Table 1: BER measurement times (without using equalization) at 32 GBaudGBaud (applies for DSAZ634A controlled by the M8070B).

As visible in Table 1, by decreasing the target BER threshold, the measurement duration increases. Comparing target BERs 1E-7 and 1E-8, the duration is 5 minutes and 47 minutes, respectively at a 95% confidence level. The significant increase in measurement time makes it impractical for the use in a typical test lab environmenet for characterization and validation of designs. When using equalization in the real-time oscillosocope, the measurement duration increases even further.

Table 2 illustrates that when using equalization in the real-time oscilloscope the measurement time increases significantly. Even at target BER of 1E-7, the measurement time takes up to or over an hour to complete. Moreover, if the extent of equalization is increased to using 9 taps instead of 5 taps, the measurement duration is further increased.

Target BER	Confidence level	Duration	Compared Bits	Confidence at target BER
1e-4	95%	00:00:39	2.62e5	99.9999…%
1e-5	95%	00:01:19	5.24e5	99.46%
1e-6	95%	00:07:53	4.14e6	95.68%
1e-7	95%	01:15:03	3.01e7	95.08%
1e-8	95%	-12:30:30	-3e8	-95%

Table 2: BER with 5 tap FFE at 32 Gbaud (measured with DSAZ634A controlled by M8070B)

The symbol rate of a received pattern additionally impacts the measurement duration when using a real-time oscilloscope.

The ratio between symbol rate and sample rate defines how many samples are taken per UI. The symbol and sample quantities are related by the following equation:

$$N(samples) = \frac{Sample\ Rate}{\text{Symbol rate}} * N(Symbols)$$

Where: N(Samples) = Number of samples

N(Symbols) = Number of symbols

Using the Real Edge inputs of the Infiniium Z series oscilloscope, the sample rate is fixed to 160 GSa/sec i.e. 160 GHz. For a specified target BER, as previously referenced, the oscilloscope must digitize a fixed number of symbols for a specified confidence level. By decreasing the symbol rate, the oscilloscope needs more time to reach the specified number of symbols to ensure the target BER and confidence level. But as the sample rate is a constant for the oscilloscope, it will take an additional number of samples over the increased time interval. The higher number of samples requires greater memory depth, which increases the processing time. Therefore, lower symbol rates take longer to process for the same number of symbols (decided by target BER), effectively leading to an increase in the measurement duration. For symbol rates below 14 GBaud the measurement duration increases significantly, so that the attractiveness of the real-time oscilloscope for making BER measurements in typical validation labs is marginal and therefore not supported.

The acquisition depth of an oscilloscope also affects the measurement time. By increasing the acquisition depth, more bits are captured in one acquisition indicating that fewer acquisitions will be required to reach the target bit threshold and the measurement time will be reduced. However, for higher acquisition depths, processing and update times will be increased.

The type of line coding used is also responsible of the effect on the measurement time. At the constant data rate, the time required to reach the target threshold is set by the target BER at the specified confidence level (normally specified at 95%). In case of the PAM4 type of line coding, at the constant data rate, the time required to reach the target threshold is half in comparison to the NRZ line coding. This is due to one NRZ symbol, has one bit, whereas PAM4 has two bits making it twice as fast as NRZ line coding.

In the case of UXR series oscilloscope, following are the results at 100 GBaud PAM4 measurement with acquisition depth of 1 million bits for UXR1102A (110 GHz, 2 channel oscilloscope). With 1 million bits in one acquisition, total number of bits for both 1E-4 and 1E-5 are reached in one acquisition indicating that the duration for these two target BER would be same.

Target BER	Confidence level	Duration (hh:mm:ss)
1e-4	95%	00:00:02
1e-5	95%	00:00:02
1e-6	95%	00:00:06
1e-7	95%	00:01:05
1e-8	95%	00:16:47

Table 3: BER measurement data for UXR1102A

Update rate and measurement time:

The update rate is an additional aspect associated with the measurement time. It is the rate at which the acquired symbols are uploaded by M8070B and directly depends on the individual acquisitions. For example, one update with one million bits takes less time than ten updates with 10^5 bits.

In effect, lower update rates have less measurement time, however because of an increased acquisition depth the measurement on the oscilloscope's screen appears as if halted. The update rate is affected by the acquisition depth, symbol rates, equalization and the line coding. An increase in acquisition depth decreases the update rate. The lower symbol rates require longer to process as per the dependence of the measurement time on the change in the data rate. The update rate also gets reduced, if equalization is introduced. The PAM4 line coding is twice as fast as the NRZ in terms of the update rate.

The update rate dependencies assigned to the extracted values are illustrated in figure 14.

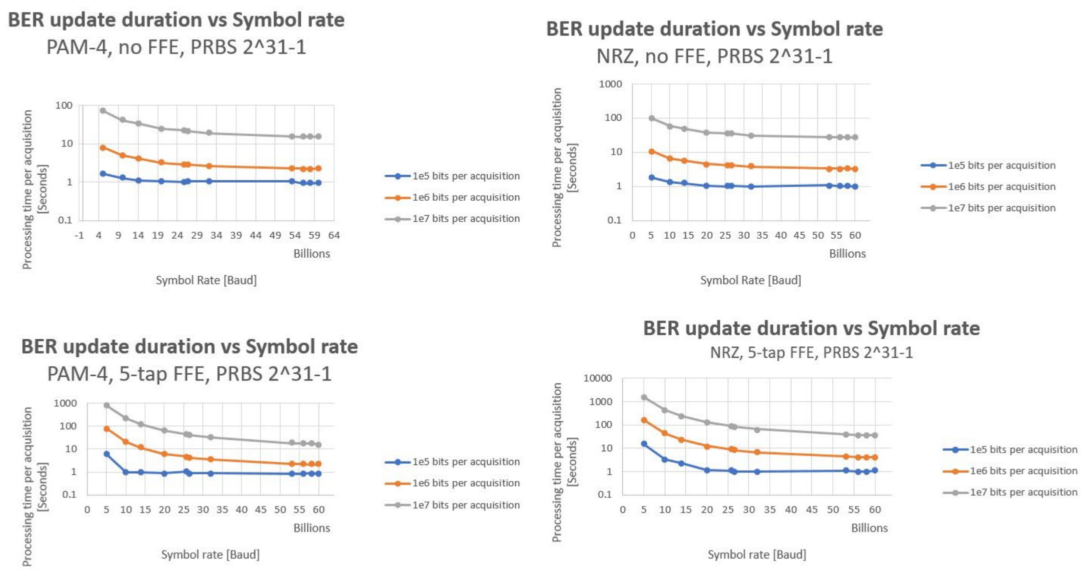


Figure 14. Update rate dependencies

Performance of BER testing

BERT instrumentation is specifically designed for BER testing, delivering real-time, true and fully sampled measurements (against an expected pattern in real-time comparison and 100% of bits compared). Each received bit is compared against the expected bit without any gaps in the acquisition interval.

Using the real-time oscilloscope as a standalone error detector, as an oscilloscope has no expected pattern memory, the only way to do a BER measurement is, to use captured pattern strings as reference. The other key difference as compared to the M8070B based real-time oscilloscope integration approach, is that the oscilloscope acquisition memory limits the amount of samples.

When controlled by the M8070B, the oscilloscope just captures and digitizes the received signal. The signal is captured in acquisitions by the oscilloscope and sent to the M8070B software where it is compared against an expected pattern and the BER measurement result is provided. The BER testing is affected by the time gap between the successive acquisitions, during which the oscilloscope is blind, and measurements cannot be accomplished. The measurement reliability is dependent on an increase of the acquisition depth of the oscilloscope to store more bits for subsequent comparisons. By increasing the acquisition depth to a very high value (such as 2 Mbits), it is possible to collect all the required bits in a single shot (depending on the pattern length) and the measurement can be generated directly. However, for the lower target BER threshold an increase of the number of bits will be required to run the measurement, that can’t be finished in a single shot acquisition. As referenced earlier, an increase in acquisition depth results, in increased processing time and low update rate and the appearance of the oscilloscope seems like halted the measurement. (for higher acquisition depths such as 10 Mbits for Zseries 63 GHz oscilloscope,1 acquisition takes almost 34 seconds). It is recommended to keep the acquisition intervals short for a very low target BER threshold.

Taking the above clarification into consideration, the conclusion is that the real-time oscilloscope when controlled from the M8070B software can generate a BER measurement at the required confidence level, however, there remains an effect from the dead time between the subsequent acquisitions.

The ability to compare against an expected pattern rather than a captured reference pattern eliminates the risk to overlook any systematic bit errors.

The M8070B control of the real-time oscilloscope will detect the errors which are randomly distributed. The probability of not detecting errors only exists when errors are occurring in the dead time when the oscilloscope is blind, and this phenomenon being always repeated exactly in the dead time interval. This probability is very low.

Achievable symbol rates

The currently available error detector options at the time of publishing of the BERT M8040A system supports symbol rates up to 64 GBaud for NRZ line coding and 58 GBaud for PAM4.

When the real-time oscilloscope is used as BER tester controlled from the M8070B software, then error-free loopback up to approximately 58 GBaud (for both NRZ and PAM4 line coding) is possible using the M8045A as a pattern generator and 63 GHz, Z-series real-time oscilloscope.

The real-time oscilloscope can be used also above 58GBaud when using models with adequate bandwidth such as UXR series oscilloscopes. In that case we recommend to use an AWG such a M8194A or M8199A instead of the M8040A as a pattern generator. When approaching symbol rates of 100 GBaud and beyond equalization techniques would be needed on the transmiter as well as on the receiver side.

For NRZ line coding, the data rates up to 58 GBaud are supported without using the equalization (over-programming can support data rates up to 64 GBaud).

Again, this only applies to the direct loopback case, with certain cables. The distortions introduced by the real DUT when it is inserted in the loopback path can change the limits substantially.

Sensitivity

The input sensitivity of M8046A error detector is

- For both NRZ, 2 to 64 GBaud 12% input range + 40 mV eye height
- For PAM4 for 2 to 32 GBaud 12% of input range + 40 mV and for 32 GBaud to 53.2 GBaud 12% input range + 15 mV eye height per eye

The Z-series 63 GHz real-time oscilloscope has sensitivity of 50 mVpp single ended for PAM4-line coding up to 50 GBaud excluding equalization (only with direct loopback and without a DUT) and up to 56 GBaud with 9 tap FFE. This 50 mV value (from the sensitivity diagram, refer to figure 9) is the data out peak to peak amplitude. The inner eye seen by the oscilloscope digitizer is at least three times smaller. With 9-tap FFE incorporated, it can perform down to 63 mV until 58 GBaud which is the recommended data rate limit. In principle the real-time oscilloscope has a better performance (and sensitivity) in terms of input data signal amplitude as compared to a traditional BERT.

For NRZ line coding as well, the real-time oscilloscope has a higher performance as it functions well with the requirements as low as 50 mVpp (single ended peak to peak) until 58 GBaud data rates.

With the UXR series oscilloscopes, the data rates beyond 58 GBaud and sensitivity as low as 20 mVpp is possible.

Equalization

M8040A BERT: 16 tap FFE based equalization is provided. Users can choose a preset or to use the self-optimizing equalizer function.

The real-time oscilloscope has additional equalization adjustability. Based on the number of taps and pre-taps, the real-time oscilloscope can calculate the coefficients required for the FFE and DFE equalizers. For CTLE a variety of options based on either manual pole-zero frequencies or based on presets defined for PCIe, USB and other standards, are available.

The current version of the M8070B can control the oscialloscope's FFE or CTLE parameters. However, if additional equalizer settings, such such as DFE or a combination of equalizers are required, then the oscilloscope can be manually controlled for this purpose (Appendix B).

Conclusion

Summarizing the comparisons, the real-time oscilloscope offers advantages in terms of achievable data rates, sensitivity and equalization. Whereas the BER measurement time duration is lengthened, and the measurement duration is affected by various factors such as equalization, target BER, symbol rate and acquisition depth.

Summarizing the Different Error Analysis Approaches

Real-time oscilloscope standalone	Real-time oscilloscope integrated into the M8070B	BERT Error analyzer (ED)
No true error information • Reported BER/SER can be 0 even for the case that all bits are incorrect	True error information	True error information without having guard bands (dead zones) in between the acquisitions
BER and SER for PAM4 signals only	BER and SER for both NRZ and PAM4 signals	BER and SER for both NRZ and PAM4 signals
No detailed error information • only mean, min, max and standard deviation of BER	Detailed error information • Counted/erroneous 0/1 bits received/ compared/ erroneous symbols	Detailed error information • Counted/erroneous 0/1 bits received/compared/erroneous symbols
Burst error analysis: no	Yes via M8070EDAB error distribution analysis	Yes via M8070EDAB. Plus ability to generate a trigger signal on a burst error condition
Data rates supported • Beyond 14-100 GBaud with equalization	Data rates supported • Beyond 14-100 GBaud with equalization	Data rates supported • NRZ: Up to 2-64 GBaud • PAM4 Up to 2-58 GBaud
Sensitivity • Can sense signals as low as 20 mVpp (single ended peak to peak) for PAM4 (inner eye seen is at least 3 times smaller)	Sensitivity • Can sense signals as low as 20 mVpp (single ended peak to peak) for both NRZ and PAM4 (inner eye seen is at least 3 times smaller in case of PAM4)	Sensitivity • For both NRZ 2 to 64 GBaud 12% input range + 40 mV eye height For PAM4 for 2 to 32 GBaud 12% of input range + 40 mV and for 32 GBaud to 53.2 GBaud 12% input range + 15 mV eye height per eye
Measurement Time • It is affected by factors such as equalization, symbol rate and acquisition depth	Measurement Time • It is affected by factors such as equalization, target BER, symbol rate, type of line coding, update rate and acquisition depth	Measurement Time • Although the measurement time is not independent of the symbol rate, measurements are the fatsest possible. (i.e. milliseconds to generate and display) as that of the real-time oscilloscope
Only BER per acquisition and cumulative are given	Supports advance measurements such as accumulated BER, jitter tolerance	Supports advance measurements such as accumulated BER, jitter tolerance
Error counting on software equalized signal which gives a lot of adjustability	Error counting on software equalized signal which gives a lot of adjustability	Software equalization is included but it's not as flexible as the real-time oscilloscope
Ability to view equalized loopback eye	Ability to view equalized loopback eye	Histogram view only

Appendix A

Infiniium Q and Z series oscilloscope models:

DSOZ634A, DSAZ634A, DSOX96204Q, DSAX96204Q, DSAZ594A, DSOZ594A

Infiniium UXR models:

UXR1102A and UXR1104A, UXR1002A and UXR1004A, UXR0802A and UXR0804A, UXR0702A and UXR0704A, UXR0702AP and UXR0704AP, UXR0592A and UXR0594A, UXR0502A and UXR0504A, UXR1104A, UXR1004A, UXR0804A, UXR0704A, UXR0704A, UXR0594A, UXR0594A, UXR0504A, UXR0404A, UXR1102A, UXR1002A, UXR0802A, UXR0702A, UXR0702A, UXR0592A, UXR0592A, UXR0502A, UXR0402A, UXR0134A, UXR0164A, UXR0204A, UXR0254A, UXR0334A, UXR0304A

Appendix B

For controlling the scope equalizer manually, the following steps should be followed:

1. Verify the physical connections of the setup
2. Set the parameters as required in the oscilloscope's Common and Data In tab in M8070B.
3. Turn on the Equalization function in M8070B, which will initiate the M8070B software to receive the data from the equalizer.

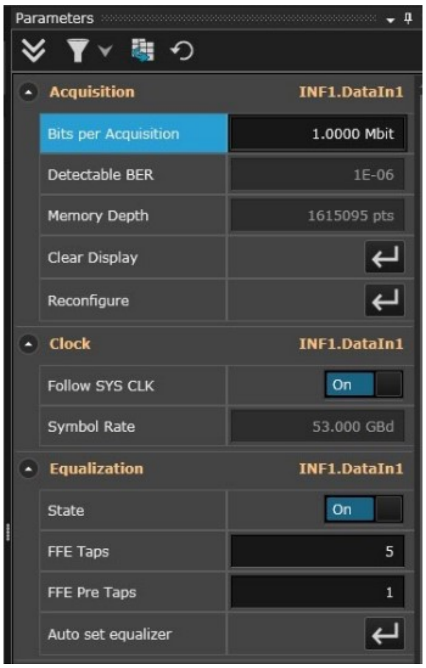


Figure 15. Equalization menu for real-time oscilloscope integrated into the M807B

4. Perform the auto-alignment (next to the BER icon as shown below) from M8070B to achieve the optimization in the sampling point, level thresholds and delay setups.

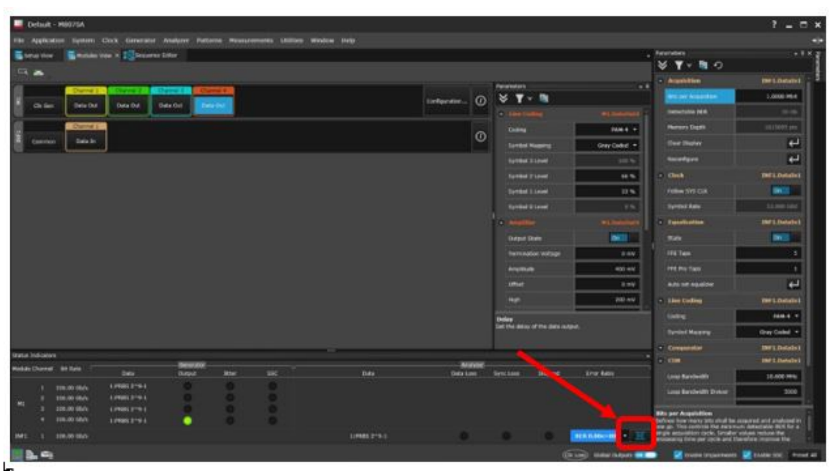


Figure 16. Total auto alignment button in the M8070B

5. Turn off the acquisition from M8070B's *Common tab* to control the real-time oscilloscope.

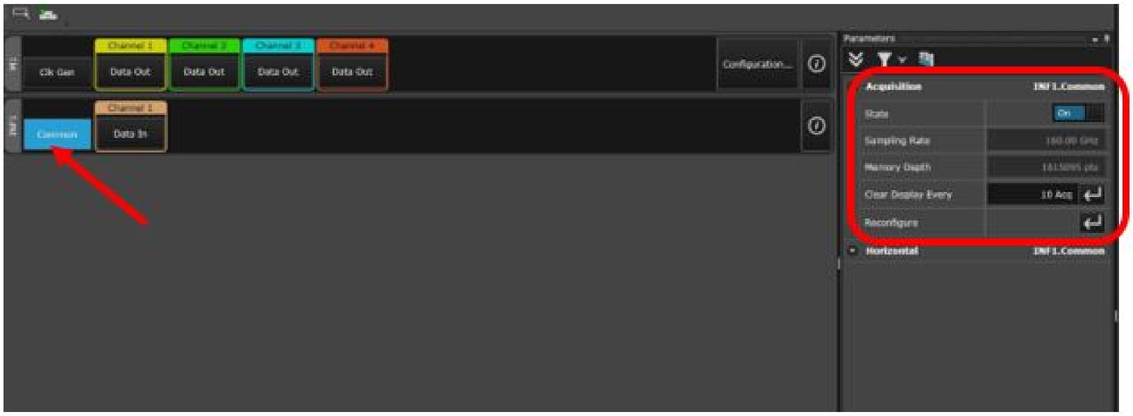


Figure 17. Acquisition tab in the M870B software for real-time oscilloscope integration

6. Now enable the GUI of the real-time oscilloscope, as the acquisition is turned off in M8070B, it will not control the oscilloscope remotely and the changes into the oscilloscope's equalizer can be made as required manually. The screenshot of the oscilloscope looks as shown below when it is integrated into the M8070B.

Figure 18. Oscilloscope GUI when remotely controlled from the M8070B

7. Please note that when controlling the oscilloscope manually to adjust the equalizer settings, do not touch the clock, Equalization and total auto-alignment options, (as shown in the figure below), on the M8070B software because if done so then the changes that were manually made on the equalizer in the oscilloscope are reset. Also note that the changes made on the real-time oscilloscope manually will not be reflected on the M8070B software interface.

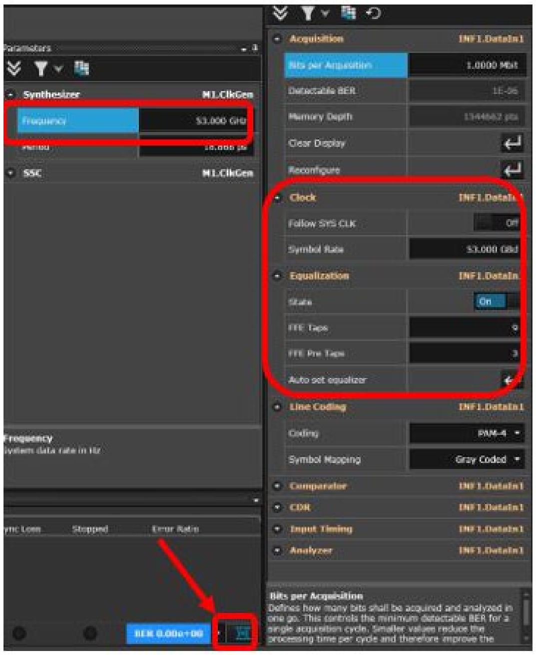


Figure 19. Locations of clock, equalization and auto-alignment options in the M8070B

8. Get the scope in Run mode by pressing on the Run button.

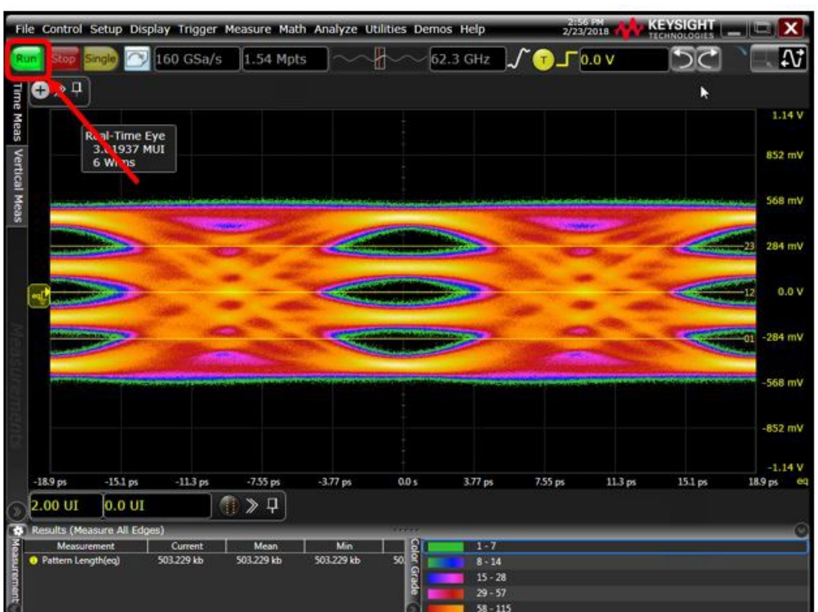


Figure 20.. Real-time oscilloscope in Run mode

9. Apply the equalization manually by changing the equalization parameters by clicking on the oscilloscope's 'Analyze' menu.
10. Adjust the equalizer through the real-time oscilloscope manually by changing the equalization options as required.
11. Once done turn on the acquisition from M8070B to start measuring the BER.

Avoid an override of the manual equalizer settings

To avoid an override of the manual equalizer settings, nothing should be controlled from the M8070B software in regards to the clock, equalization and the total auto-alignment. If a change to any of the parameters is required, then step 2 to 11 should be repeated for the newly set parameter (either clock or data or auto-alignment). If a change in parameters other than those mentioned above is desirable, that may be achieved even when the oscilloscope is controlled manually

Reference

(*) Wolaver, Dan H. (1991). Phase-Locked Loop Circuit Design. Prentice Hall. p. 211
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Literature

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