APPLICATION NOTE

Error Analysis of PAM4 Signals

Introduction

Increasing demands for a connected world with instant data access continues to drive Ethernet, 64G fiber channel, CEI-56G and other next generation data center networking links. With data rates continuously increasing, emerging data center standards like OIF, CEI, and IEEE 802.3 Ethernet are moving to PAM4 (pulse amplitude modulation with four levels) multilevel signaling formats. The next step in the continuing need for increased network bandwidth in data centers is 400 Gb/s links. Multilevel signaling formats such as PAM4 are enabling technology to implement 400G. The switch from NRZ (non-returned to zero) to PAM4 is revolutionary, rather than evolutionary from 100G, presenting many new concepts and design challenges. The design and systems characterization of transmission using PAM4 and NRZ signals is challenging at high data rates. The scope of this application note is to provide the detailed insights into PAM4 signal generation and analysis techniques; only error analysis techniques and not TDECQ. Before getting into the details, let's first have a look at the basic definitions.

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Basic Definitions

NRZ signal: This is a type of line coding used to represent the bits 0 and 1. Positive voltage represents logical 1s, and the equivalent negative voltage represents 0s.

PAM4 signal: This is a type of line coding which uses a pulse amplitude modulation technique. PAM4 signals have four voltage levels wherein each amplitude level corresponds to the logical bits 00, 01, 10, and 11. In other words, each symbol of PAM4 coding consists of 2 bits which correspond to one voltage level which is amplitude.

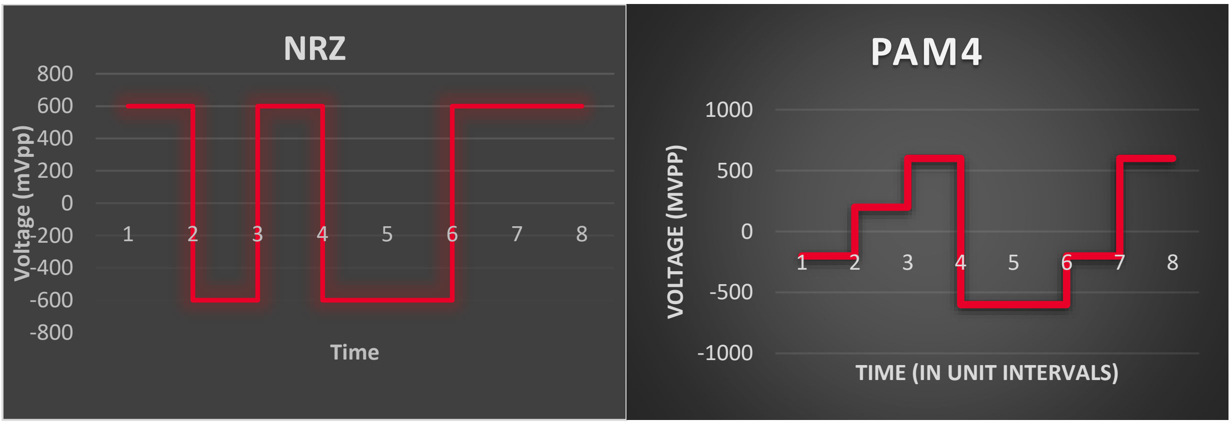


Figure 1: NRZ and PAM4 signals

Gray code: The Gray code, or reflected binary code, is the coding pattern where successive symbols differ by one binary bit. In the case of PAM4, 00,01,10 and 11 are the binary bit sequences to represent levels 0, 1, 2, and 3 shown in Table 1. The Gray code representation for the same symbols would be 00, 01, 11, and 10 for the levels 0, 1, 2, and 3.

Symbol	Binary Code	Gray Code
0	00	00
1	01	01
2	10	11
3	11	10

Table 1: Binary code and Gray code

PAM4 encoding is also created using a Gray coding pattern because it facilitates error correction. The Gray coding adheres to IEEE and OIF standards.

With the introduction of bits and symbols, it is worth mentioning the difference between bits per second and Baud. The bits per the second unit is used to denote the total number of bits (1s or 0s) transmitted per second. Baud is used to denote the number of symbols transmitted per second. In the case of an NRZ signal, the symbols are the same as that of the bits; Baud and bps (bits per second) mean the same. However, in the case of PAM4, they are different.

PAM4 has 2 bits per symbol. Therefore, some symbols transmitted per second (Baud) is half as that of the number of bits transmitted per second. In the case of PAM4, if the symbol rate is 28 Gbaud, then it means there are 56 Gigabits transmitted per second.

Need for PAM4

NRZ signals are widely used in digital communication links for data rates below 20-25 Gbaud. However, with increasing demand for higher transmission bandwidth, the channel loss of the transmission medium gets increasingly challenging. As an example, Figure 2 shows the channel loss of a short reach interface, as defined by CEI-56G VSR channel.

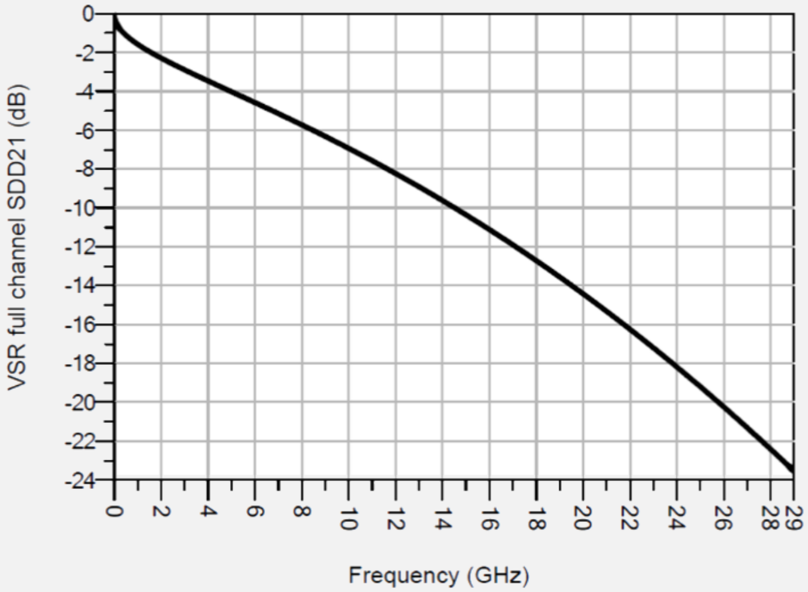


Figure 1: CEI-56G VSR channel characteristics [1]

As the frequency increases, the channel insertion loss also increases.

This response resembles the behavior of a low-pass filter. In fact, the channel acts as a low-pass filter and doesn’t allow higher frequencies to pass through, delimiting the usable channel bandwidth. According to the Shannon Hartley theorem:

$$C = 2*B*\log_2(M)$$

C = Channel capacity or maximum data rate achievable in bits per second.
B = Bandwidth of the channel in Hertz.
M = Number of signal levels.

This formula implies that to increase the data rate or channel capacity either the channel bandwidth (B) or the number of signal levels (M) must be increased.

Increasing the usable channel bandwidth (B) can be achieved by a physical improvement. However, this option may prove very expensive and imply a complete change of the existing installation. Instead of changing the channel, changes can be performed by de-emphasis (at the transmitting end) and equalization (at the receiving end). This compensates for channel loss and improves the channel response - a small and noise-limited improvement.

For larger improvements of the channel response a method that increases the number of signal levels M, is the right choice.

For example, at 56 Gbps, the bandwidth required for an NRZ (M=2) signal is 28 GHz, but for PAM4 (M=4), the bandwidth required would be 14 GHz - a frequency range where there is less attenuation. At constant bandwidth this means that by increasing M the data rate can be increased. Additionally, you can introduce de-emphasis and equalization to compensate for the losses and improve the signal quality.

PAM4 Error Analysis

The integrity of a serial data link is generally specified by the bit error rate (BER). Note that the term here is ‘rate’ and not ‘ratio’. Bit errors are measured per unit time. Most of the bit errors in real systems are the result of random noise and occur at random times as opposed to an evenly distributed rate [2].

Systems that employ decision feedback equalizers (DFE) may generate burst errors which are not randomly distributed.

The BER is an estimate assessed by taking the ratio of the number of errored bits to the number of transmitted bits. To characterize the randomness of bit errors in real systems, the more convenient way is to explain BER as the bit error *ratio* at the output of the receiver which is a statistical measurement. The BER is a measure of the receiver’s quality. In practice, BER measurements are important for characterization testing, also because standard consortia define BER compliance requirements. Analyzing specific errors on only 0s or 1s is useful for troubleshooting problems in the receiver or elsewhere in the link.

The BER measurement is a statistical process, and the measured BER only approaches the actual BER as the number of bits tested approaches infinity. Fortunately, the BER is tested with a predefined threshold; which is the target BER. The number of bits required to reach the predefined threshold i.e. target BER depends on the required confidence level. The confidence level is the probability which ascertains the system’s true BER with the specified BER which is the target BER. The confidence level does not reach 100 percent as this would require an infinite number of bits which are not measurable. For most applications, a typical confidence level of 95 percent is sufficient. Different confidence levels lead to different measurement times. For more details, refer to this guide on how to measure BER.

Bit Error Ratio

The bit error ratio (BER) is the ratio of the total number of errored bits to the total number of transmitted bits. In mathematical form, the BER is given by,

$$\text{BER} = \frac{Number\ of\ errored\ bits}{Total\ number\ of\ bits\ transmitted}$$

A Bit Error Ratio Tester (BERT) typically gives the BER measurement as:

$x * 10^{-y}$
$x \in R$ (set of rational numbers)
$y \in N$ (set of natural numbers)

Example: A BER of 5.6 * 10-6 represents
56 bit errors out of 10 million compared bits. Sometimes instead of using powers of 10, the letter ‘E’ is used. The above expression is now: 5.6E-6.

SER (Symbol Error Ratio)

The SER is also a statistical measurement illustrating the ratio of the total number of errored symbols to the total number of transmitted symbols. This measurement differs from BER as BER gives the performance in terms of bit errors, whereas SER gives the performance in terms of symbol errors.

$$\text{SER} = \frac{\mathit{Number\ of\ errored\ symbols}}{\mathit{Total\ number\ of\ symbols\ transmitted}}$$

Depending upon the type of digital modulation, bits and symbols differ from one another. For example, in the case of NRZ signal, bits and symbols are the same. Therefore, BER and SER are the same. However, in the case of digital modulation schemes other than NRZ, BER and SER are not the same.

Importance of SER in PAM4 Context

In this application note, the term SER corresponds to the PAM4 signaling, and not to be confused with the SER requirements stated to forward error correction (FEC) in the IEEE standard.

In PAM4, each symbol represents 2 bits. However, when an error occurs, one symbol error could be either 1-bit error or a 2-bit error.

Depending on the error, the BER and SER can be the same, or the BER can be half of the SER when each symbol error is only a 1-bit error.

One of the popular ways of generating PAM4 includes its generation using two binary weighted NRZ streams which involves combining them using power combiner to generate PAM4 signal (discussed later). In this approach however, problems with one of the NRZ transmitters such as slew rate, incorrect voltage level, and skew could result in errors that only appear on specific transitions (symbol errors) in the PAM4 output. Diagnosing the cause of these situations is possible through error analysis on specific transition types.

To characterize the PAM4 system, a full understanding of BER and SER is necessary since SER plays a vital role in characterizing PAM4 signals. As PAM4 has four symbols, there are a total of five possible SER measurements. Four are the individual SER measurements, and one is the total SER measurement as explained above. When one PAM4 symbol encounters an error, it is also essential to know which symbol is in error (0, 1, 2, or 3). Depending upon this information, symbol 0/1/2/3 error ratios are possible.

Knowing these SERs, the user can identify which PAM4 symbol is in error, or how often a specific symbol is encountering an error. This detailed SER analysis is helpful for complete characterization of the PAM4 system. The formulas for total PAM4 SER and individual PAM4 symbol SERs are:

$$\text{SER (total)} = \frac{\mathit{Total\ number\ of\ errored\ symbols}}{\mathit{Total\ number\ of\ symbols\ transmitted}}$$

$$\text{Symbol 0/1/2/3 error ratio} = \frac{\mathit{Total\ number\ of\ errored}\ 0s\ or\ 1s\ or\ 2s\ or\ 3s}{\mathit{Total\ number\ of}\ 0s\ or\ 1s\ or\ 2s\ or\ 3s\ \mathit{transmitted}}$$

BERT System

To check the BER and SER, a bit error ratio test (BERT) system is used. The BERT system consists of a pattern generator (PG), an error detector (ED), and a clock. The PG generates a known pattern of bits or symbols which passes through DUT and loops back into the ED through the DUT. The ED compares the received pattern against the expected pattern to calculate the BER Figure 3 shows the basic test configuration using BERT. As the test data sent to the receiver input is impaired, the loopback path must be clean which means that the DUT must have a suitable transmitter for loopback and a short trace or cable connection to the BERT ED.

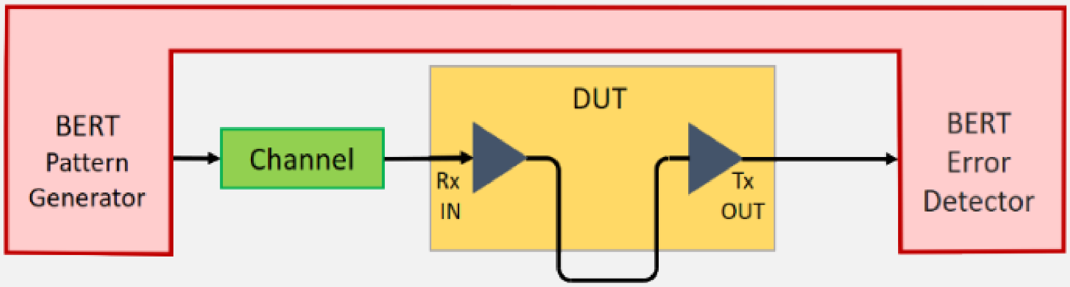


Figure 3: Basic test configuration using a BERT

General attributes of BERTs

- Operate at the full data rate of the test signal.
- All data test in real time.
- The test is continuous.
- The error detector is not a sampling system. It counts all the bits and errored bits in real time, at the data rate - unlike a scope, which acquires data, then processes it.
- It is essential to verify low BER targets such as BER < 10-12.
- PG outputs and ED inputs are electrical: External instrument grade E/O, a tunable laser with modulator and O/E converters are needed to test optical modules.
- The PG has user-controlled error injection:
  - Usually manual (single error), or settable at a high BER (for example 10^2 to 10^{-6}).
  - Useful to verify loopback configuration, or to check the DUT's internal error counters

Generating PAM4 Signals

There are two approaches used to generate PAM4 signals. The first approach relies on the generation of PAM4 signals using two NRZ pattern signals. The second approach is to generate a PAM4 pattern directly. We'll discuss both approaches.

PAM4 Generation Using Two NRZ Channels

Two NRZ patterns with different amplitudes are required to generate a four-level signal for PAM4. These two NRZ patterns act as a least significant bit (LSB) and a most significant bit (MSB) pattern and are added together to form a PAM4 signal. The logical states corresponding to each NRZ pattern are 0 or 1. Considering two NRZ streams, the logical states are 00, 01, 10 or 11.

As an example, in Figure 4, the MSB and LSB NRZ patterns are represented using different amplitudes: -400 mVpp to 400 mVpp MSB and -200 mVpp to 200 mVpp LSB.

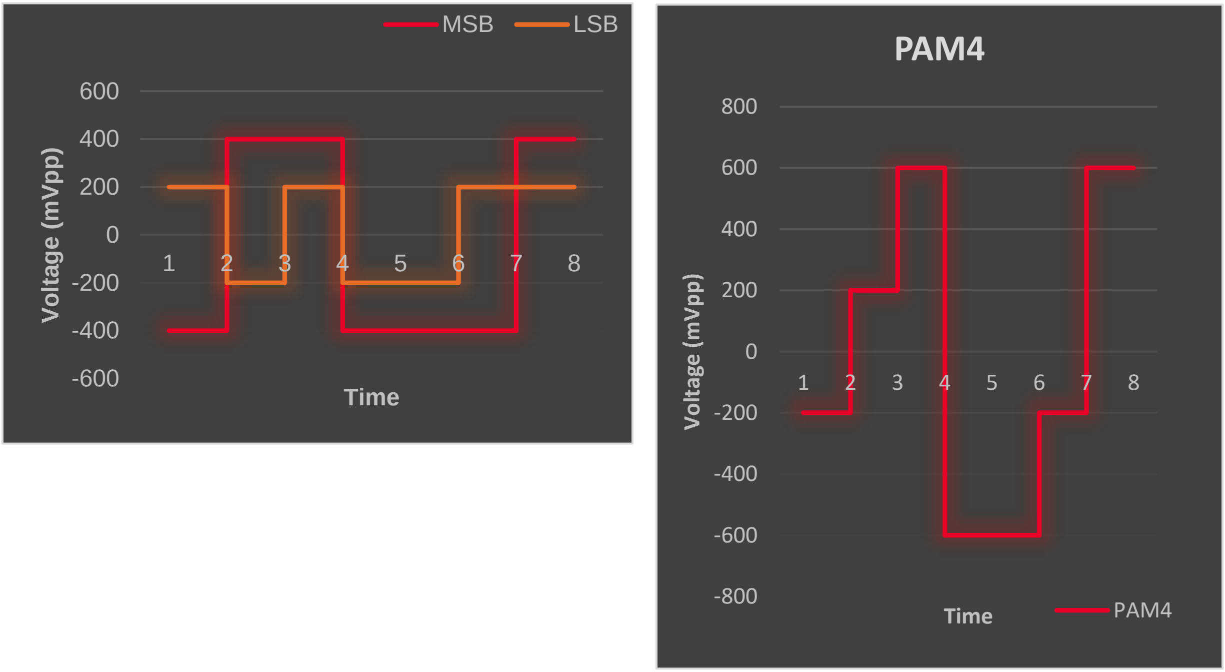


Figure 4: PAM4 generation using two NRZ channels

The values mentioned in Figure 4 are examples. The different amplitudes are achieved by adding a 6 dB attenuator in the LSB NRZ channel as shown in Figure 5. Add a delay equal to the attenuation path in the output representing the MSB, and the two signals are summed together using an RF power divider. In practice, two attenuators are often used; a 10 dB and a 3 dB. The attenuation in both the paths reduces the effect of reflections from a mismatch in the transmission lines, which cause problems in PAM4 systems. The 10-dB attenuator is used in the LSB output, as 9 dB attenuators are not commonly available. Correct the 1 dB error with the amplitude controls in the pattern generator outputs [3]. Figure 5 displays the simplified block diagram.

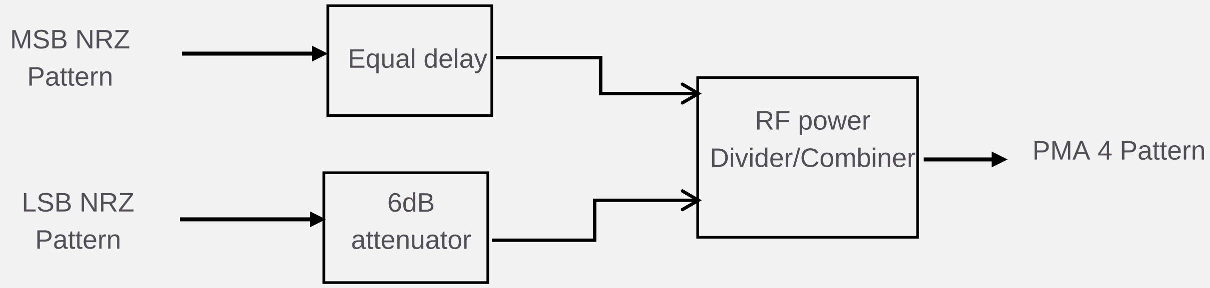


Figure 5: PAM4 generation using two NRZ channels

Although the approach looks simple and straightforward, there are certain limitations associated with it.

Challenges of PAM4 Generation Using Two NRZ Channels

- Inflexibility: The height of an individual eye cannot be varied independently. The amplitudes of both the NRZ channels are varied to change the eye heights. However, this is not helpful to adjust the heights of all three eyes individually.
- Skewing: Ensure the NRZ channels combined are perfectly phase aligned with each other and with the clock. A small difference in the individual NRZ phases results in a decreased eye-opening which directly affects quality. This issue is prominent with the injected jitter.
- De-emphasis: Introducing de-emphasis to compensate for channel loss is a challenge. De-emphasis needs to be applied on each NRZ channel to get the de-emphasis at the output.
- External accessories make the signal quality worse and reduce the available amplitude range.

Using a native PAM4 generation approach can eliminate these issues. Apart from removing the inflexibility and the skewing issues, there isn’t a necessity to use the devices. However, for PAM4 generation using two NRZ channels, an attenuator and a power divider are a required for eliminating the irregularities in the channel path.

Keysight’s M8040A BERT PG uses native PAM4 generation and generates PAM4 signals with varying levels Figure 6 shows the eye diagram of the PAM4 signal generated with a M8040A on a DCA-M sampling scope.

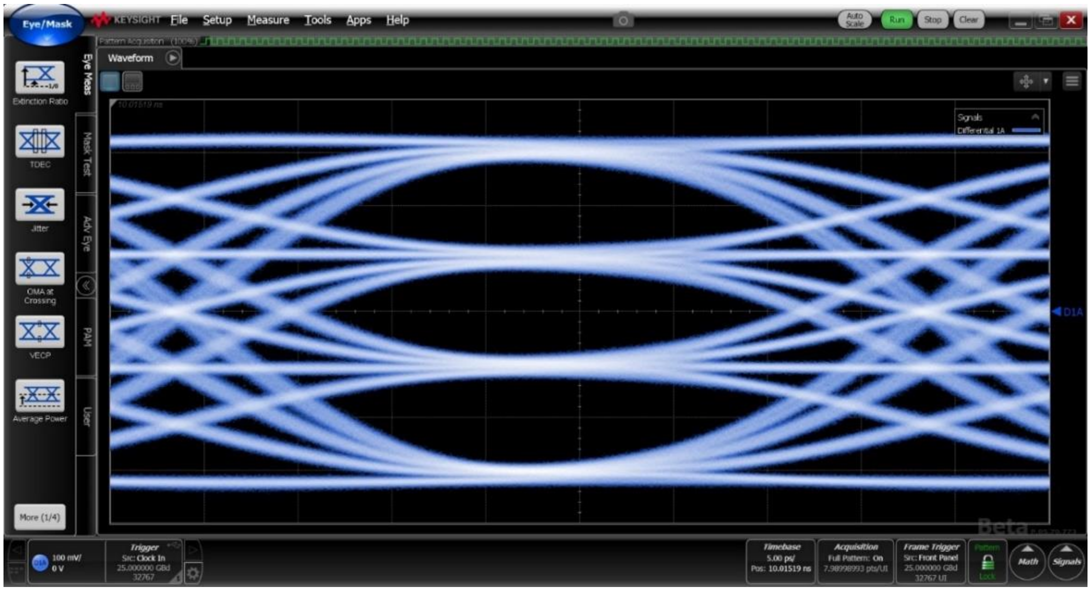


Figure 6: Differential PAM4 signal as seen on DCA sampling scope.

Error Detection Techniques

The ED receives the pattern, compares it against expected pattern and calculates the BER. The expected pattern is either an algorithmically generated pattern such as PRBS, or a *memory-based* pattern. To create a valid BER measurement, the ED needs to know the data rate to synchronize with the incoming pattern and adjust the sampling delay point. Moreover, it needs to know the amplitude level to make the accurate decision through sampling threshold.

The quality of an ED is determined by:

- Real-time error analysis.
- The various expected patterns that it can support: PRBS, SPQR, PRBS31Q, or memory-based patterns.
- The data rates supported.
- The input amplitude levels supported; the sensitivity of an ED.
- Full sampling which means sampling of each unit interval (UI).
- True BER measurement; the comparison against the expected pattern.
- Intrinsic jitter.
- Equalization; an eye-opening capability.
- Ability to detect PAM4.
- Measurement capabilities, such as jitter tolerance, BERT scan, total jitter measurement, Q factor which is moving the threshold level with fine precision.
- Parameter sweep.

How an ED works:

- The BERT system has an ED which is not a sampled system. It samples the bits and errored bits in real time and at the data rate specified. It has an expected pattern that is either memory-based or algorithmically generated; such as a PRBS pattern. It compares this pattern against the received pattern and creates real-time BER calculations.

Operation of an NRZ ED

If the incoming signal is an NRZ pattern, a single threshold voltage is sufficient to detect the incoming signal. The threshold voltage sets at 0 volts which is the midpoint of the two NRZ transition instants. If the sampled voltage is above the threshold, it is interpreted as logic 1, and if it is below the threshold voltage, it is consider as logic 0.

The sampling threshold must be at the midpoint of the NRZ eye so at the sampling instant there isn’t any ambiguity in deciding the incoming signal level. Depending upon the sampling threshold and the sampling point delay (sampling instant, or delay instant) the decision is 1 or 0 for NRZ. The incoming pattern is compared against the expected pattern to calculate the BER. The BER measurement is performed in real-time because the expected bit is available for the comparison at that instant.

Figure 7 displays the quality of NRZ ED. The quality is determined by its resolution and its precision in adjusting the sampling point regarding sampling delay and threshold level to find the center of the eye opening

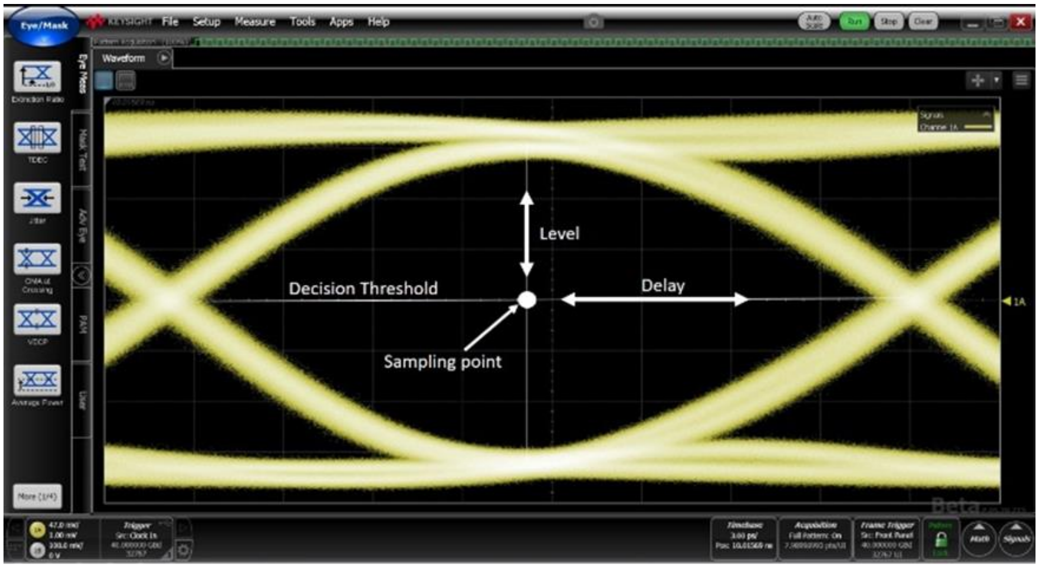


Figure 7: NRZ ED sampling point.

An NRZ signal is fully characterized in real-time by an NRZ ED which supports the properties mentioned above. Let's see how the ED is used for analyzing PAM4 signals.

PAM4 Error Analysis

Using an NRZ ED for PAM4

There are different approaches for detection of PAM4 BER using NRZ ED. Out of these different approaches, three are prominent.

1. The sampling point using a one-channel NRZ ED is varied over each eye. Calculate the BER for the single eye and use that information to obtain the PAM4 signal. This approach uses only one NRZ ED. The major drawback of this method is that a portion of the data is missing; only one eye is visible.

2. The PAM4 signal demultiplexes by encoding into two NRZ channels. The BER of both channels is used to give the total BER of the input PAM4 signal as shown in Figure 8.

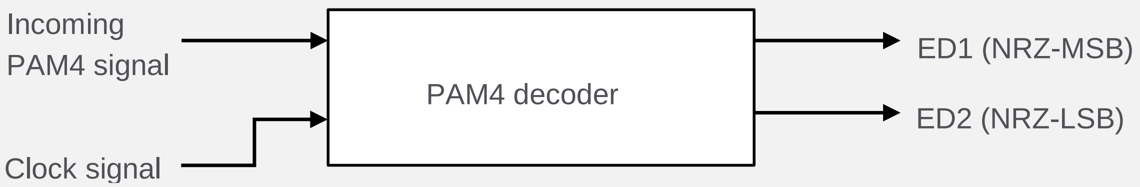


Figure 8: PAM4 decoding into two NRZ streams

3. The incoming PAM4 signal is divided into three signals using two power dividers, and each connected to an NRZ ED. The PAM4 BER is generated for each eye simultaneously. However, it's not an SER. An advantage of this approach is that the eyes are horizontally skewed; the sampling point delay is varied. However, the specific disadvantage is the additional use of power dividers that reduce the signal amplitude.

NRZ ED Challenges

These approaches using an NRZ ED have associated challenges:

- In the second approach, the clocking of the demultiplexer is an issue if the clock signal has jitter, or if the DUT has its clock recovery where it retimes the clock.
- In the third approach, when the PAM4 signal is divided using a power divider, the signal diminishes to a minimal value which causes the SNR to go low. The PAM4 signal reduces to a low value and may reach to the detection limits (sensitivity) of the error detector and may be misinterpreted; 0 instead of 1.
- The addition of any component into the signal path incorporates losses and adds to the delays and signal distortions.
- Double counting issue: This problem applies to the symbol error rate. Error detectors which use three separate slicers to monitor each eye are susceptible to this issue. For example, if the expected value of the PAM4 symbol is 0 (00 binary), and the analog input signal is in between a 2 and 3, the slicer monitoring the lower and center eye will both output a high signal. If an additional logic is not used to mask the second slicer output, two symbol errors are counted for this single bad symbol as shown in Figure 9.

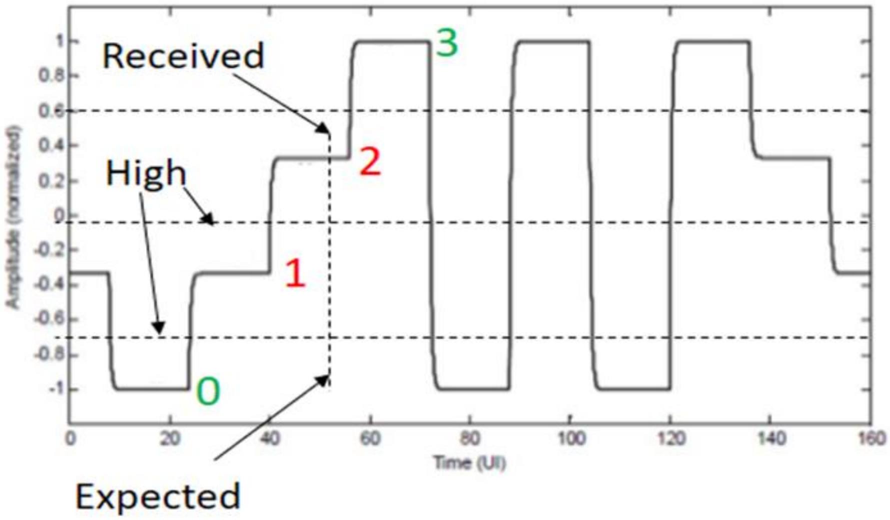


Figure 9: Double counting problem

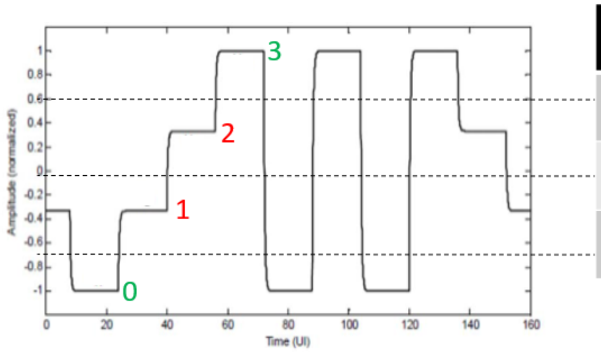
The error detection system requires additional logic which uses a mask code to prevent the double counting. The mask code is stored in the pattern memory along with the expected pattern. This masking only works if all the three ED channels are bit-synchronized. The software in the pattern editor encodes the pattern in advance to create the proper mask codes. The particular logic in the ED masks the outputs of multiple slicers depending on the value of the expected symbol code.

For the above example, the expectation is 0. The output of the slicers monitoring the middle and the upper eyes would are masked, and only the lower eye slicer is used to feed the error counter. This technique works and can only operate with the memory-based patterns per the mask code information stored in the pattern.

This would not work for long PRBS patterns such as PRBS31Q which is the most common test pattern used for receiver compliance test in the 400G class standards.

Direct PAM4 Analysis

Real time and direct PAM4 analysis are implemented to overcome the challenges mentioned above. This can be achieved if in the three signal eyes all three thresholds of the incoming PAM4 signal are sampled simultaneously.



Detecting	1	0
Threshold V_{upp}	= 3	= 0 or 1 or 2?
Threshold V_{mid}	= 2 or 3?	= 0 or 1?
Threshold V_{low}	= 1 or 2 or 3?	= 0

Figure 10: PAM4 voltage thresholds

Figure 10 shows the PAM4 signal with its threshold voltages. At any instant of time other than the transition instants, the incoming PAM4 sequence will either represent the voltage levels 0, 1,2, or 3. By sampling the three voltage thresholds simultaneously, the logical 1 or logical 0 states of the individual voltage thresholds correspond to the PAM4 symbol and corresponding Gray code. It is then successfully decoded in real time using the look-up table. Table 2 summarizes the operation.

PAM4 level	Vupp	Vmid	Vlow	Gray Code	
3	1	1	1	1	0
2	0	1	1	1	1
1	0	0	1	0	1
0	0	0	0	0	0

Table 2: PAM4 decoding table

Example: If the sampled threshold voltages are: V_{upp}=0, V_{mid}=1, and V_{low}=1, then the incoming symbol is PAM4 level 2 symbol.

The direct PAM4 symbol reception is complete. It is then compared against the expected PAM4 symbol to calculate the BER and SER measurements.

It is also possible to detect the PAM4 signals with varying eye heights. The slicer (sampler) threshold is set according to the expected PAM4 signal.

Advantages of Direct PAM4 Detection

Although the BER or SER of PAM4 signals is measured by various methods as discussed, there are advantages of a direct PAM4 detection over the other approaches:

- Real-time PAM4 analysis: Direct PAM4 detection is performed in real time and post-processing is not involved. This is a significant advantage because it allows to measure the long PRBS patterns which exceed the depth of the capture memory (for example QPRBS31) and it minimizes the measurement time for low target BERs of 10^{-12} or less because the SERs and BER counters update in real time.
- Use of a lookup table removes the possibility of double counting and removes the need for masking and corresponding limitation of memory-based patterns.
- Supports Gray coded patterns which are recommended by standards.
- Detailed error analysis: The detailed error analysis of received symbols is possible including the individual symbol error ratio measurements for symbols 0, 1, 2, and 3. This feature is essential, and the detailed SER analysis is only possible if the comparison is made in real time and against the PAM4 expected pattern. This detailed analysis is a powerful troubleshooting tool which helps us to consider the possible cause of the error.
- Detection of eyes with different eye heights: This feature enables the user to detect a PAM4 signal of varying eye heights per his requirements. You can achieve this by setting the sampling point threshold according to the expected PAM4 signal.
- De-skew calibration is not required as there is only one single ED.

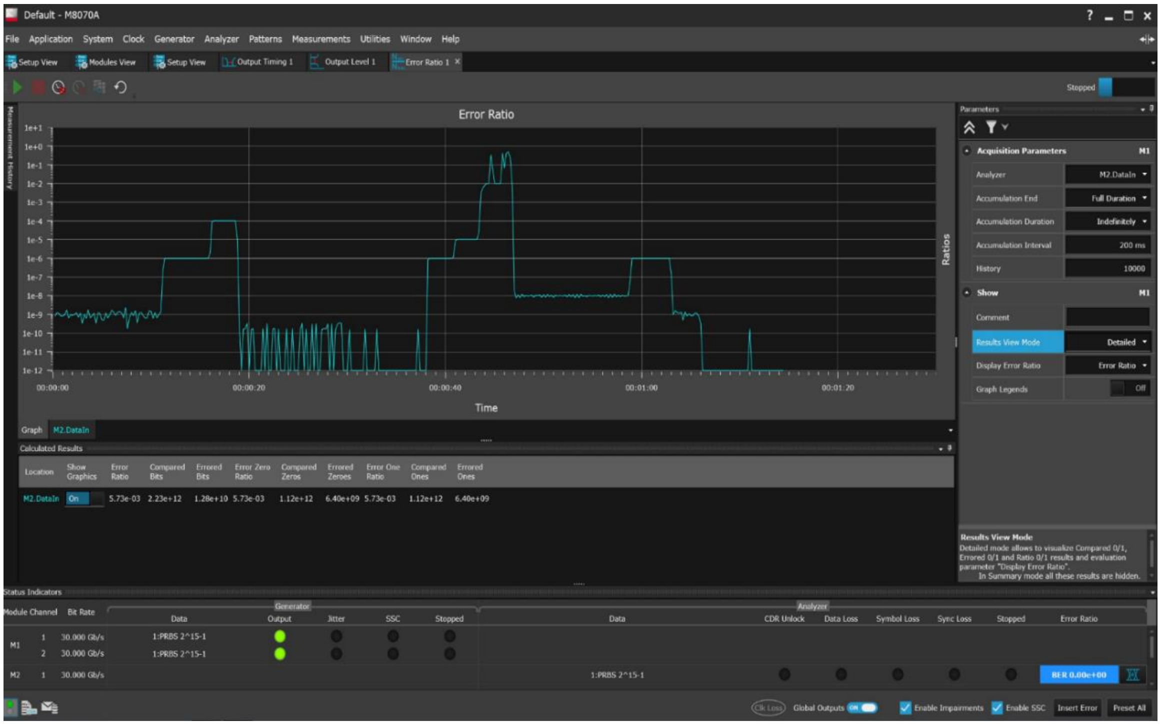
Error Ratio Analysis Using M8040A

Keysight’s M8040A is a highly integrated BERT for physical layer characterization and

compliance testing. With support for PAM4 and NRZ signals and symbol rates up to 64 Gbaud (corresponds to 128 Gbit/s), it covers all emerging 400/200 GbE and CEI-56G standards. The M8040A BERT´s true error analysis provides repeatable and accurate results; optimizing the performance margins of your devices.

It consists of the M8045A pattern generator module and M8046A error detector module. It offers a broad spectrum of measurements to facilitate the error ratio analysis. The key features of M8040A high-performance BERT are:

- True and real-time analysis of both NRZ and PAM4 signals
- High integration with jitter, de-emphasis and equalization capabilities Also supports a wide range of patterns such as algorithmic PRBS, QPRBS and memory-based patterns including pattern sequencer with loops and error injection capabilities
- Scalable and upgradable
- The M8070A system software controls the M8040A BERT. Figure 11 shows the M8070A user interface with error ratio measurement.



Acquisition Parameters M1

Analyzer	M2.DataIn
Accumulation End	Full Duration
Accumulation Duration	Indefinitely
Accumulation Interval	200 ms
History	10000

Show M1

Comment	
Results View Mode	Detailed
Display Error Ratio	Error Ratio
Graph Legends	Off

Results View Mode
Detailed mode allows to visualize Compared 0/1, Errored 0/1 and Ratio 0/1 results and evaluation parameter "Display Error Ratio".
In Summary mode all these results are hidden.

Calculated Results

Location	Show Graphics	Error Ratio	Compared Bits	Errored Bits	Error Zero Ratio	Compared Zeros	Errored Zeroes	Error One Ratio	Compared Ones	Errored Ones
M2.DataIn	On	5.73e-03	2.23e+12	1.28e+10	5.73e-03	1.12e+12	6.40e+09	5.73e-03	1.12e+12	6.40e+09

Status Indicators

Module	Channel	Bit Rate	Generator Data	Generator Output	Generator Jitter	Generator SSC	Generator Stopped	Analyzer Data	Analyzer CDR Unlock	Analyzer Data Loss	Analyzer Symbol Loss	Analyzer Sync Loss	Analyzer Stopped	Analyzer Error Ratio
M1	1	30.000 Gb/s	1:PRBS 2^15-1	●	●	●	●							
	2	30.000 Gb/s	1:PRBS 2^15-1	●	●	●	●							
M2	1	30.000 Gb/s						1:PRBS 2^15-1	●	●	●	●	●	BER 0.00e+00

Figure 21: M8070A detailed BER test interface

Introduction to M8040A

The real advantage of Keysight's M8040A high-performance BERT is visible in PAM4 generation and analysis. The M8040A provides detailed BER and SER analysis for PAM4 signals. The M8040A high-performance BERT is divided into two main parts which are M8045A PG and M8046A ED.

M8045A PG provides data rates up to 64 Gbaud; and supports both NRZ and PAM4 line codes. It also supports a broad range of patters such as PRBS, QPRBS, SSPR as well as memory-based patterns. M8045A PG connects with the M8057A remote head module. This remote head reduces the cable length required and sets the PG output as close as possible to the DUT. The main advantage of M8045A PG is the PAM4 linearity which is the ability to adjust the individual eye heights through M8070A software interface and produce the PAM4 eyes as per individual requirements. The linearity feature makes M8045A PG unique.

M8046A ED provides real-time analysis of PAM4 and NRZ signals.

Key capabilities of the error analyzer module M8046A include:

- One differential channel per analyzer module
- Symbol rates up to 30 Gbaud for PAM4, and up to 64 Gb/s for NRZ
- Native PAM4 decoding
- Built-in equalization to re-open closed eyes at the analyzer input
- Selectable expected patterns like QPRBS31, pattern memory, pattern sequencing, masking, Gray coding and custom PAM4 symbol mapping
- Clock recovery for PAM4 and NRZ signals
- DUT control interface allows access to built-error counters from the M8070A software

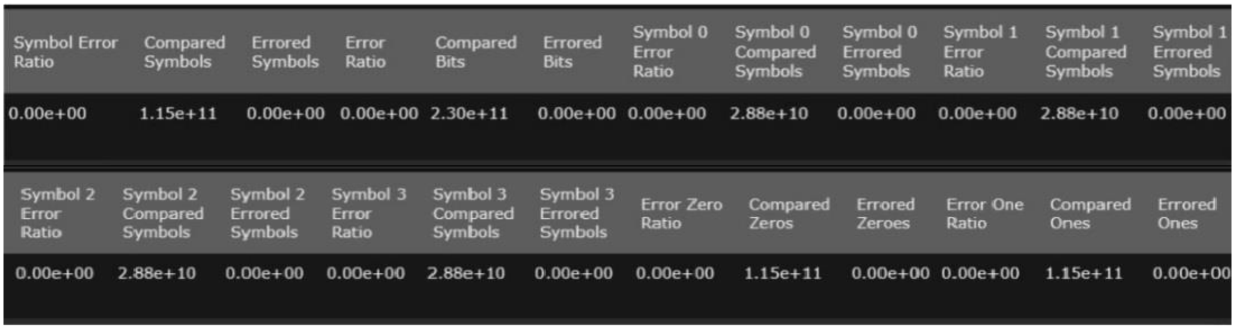
Figure 3 shows the M8040A high-performance BERT system with the M8045A PG, M8046A ED, and M8057A remote head.

Figure 32: M8040A BERT system with M8045A PG, M8046A ED, and M8057A remote head

PAM4 Analysis Using M8040A BERT

To characterize the PAM4 system effectively, direct PAM4 detection is important. As explained above, in the case of PAM4, SER is an important measurement. M8046A ED enables you to characterize the received PAM4 data in real-time completely. The incoming PAM4 signal is analyzed by M8040A ED in real time with the direct PAM4 detection sampling all three thresholds simultaneously. It uses one sampling delay point that samples all three thresholds at a time. All the advantages about the direct PAM4 detection apply to the M8040A high-performance BERT. The M8040A provides the BER and SER measurements and also provides a detailed error analysis such as all five PAM4 SER measurements; four for individual PAM4 symbols and one total SER measurement considering all the symbols, number of errors encountered for each of the symbols from symbol 0 to symbol 3, the total number of compared bits and the total number of compared symbols. All the possible BER and SER measurements for PAM4 signals generate from the M8040A.

In the case of BER, the measurements of the total BER system, including the total number of compared bits, transmitted bits, errored zeros, errored 1s, BER for 0s and BER for 1s are shown. Figure 3 shows the detailed PAM4 error analysis as seen on M8070A software interface.



Symbol Error Ratio	Compared Symbols	Errored Symbols	Error Ratio	Compared Bits	Errored Bits	Symbol 0 Error Ratio	Symbol 0 Compared Symbols	Symbol 0 Errored Symbols	Symbol 1 Error Ratio	Symbol 1 Compared Symbols	Symbol 1 Errored Symbols
0.00e+00	1.15e+11	0.00e+00	0.00e+00	2.30e+11	0.00e+00	0.00e+00	2.88e+10	0.00e+00	0.00e+00	2.88e+10	0.00e+00

Symbol 2 Error Ratio	Symbol 2 Compared Symbols	Symbol 2 Errored Symbols	Symbol 3 Error Ratio	Symbol 3 Compared Symbols	Symbol 3 Errored Symbols	Error Zero Ratio	Compared Zeros	Errored Zeroes	Error One Ratio	Compared Ones	Errored Ones
0.00e+00	2.88e+10	0.00e+00	0.00e+00	2.88e+10	0.00e+00	0.00e+00	1.15e+11	0.00e+00	0.00e+00	1.15e+11	0.00e+00

Figure 13: PAM4 measurements as seen on M8070A software interface.

Summary

- PAM4 is a bandwidth efficient method of transmitting serial data requiring half the channel bandwidth of NRZ.
- To characterize the PAM4 system altogether, BER and SER play an essential role in characterizing, designing and debugging of links using PAM4 signaling. With the PAM4 signal, there are a total of five SER measurements possible. Four corresponding to individual symbols, and the remaining one being the total SER measurement.
- PAM4 signals can either be generated by combining the two NRZ signals or is generated directly. Combining two NRZ signals limits creates the ability to set each level independently, or to introduce de-emphasis, and requires delay/skew calibration. Direct generation approach doesn’t have these limitations.
- The typical BERT system has an ED which counts all the bits and errored bits in real time and at the data rate specified.
- Using an NRZ ED to perform the error analysis of PAM signals has certain limitations regarding increased hardware and lack of real-time analysis.
- Native PAM4 generation is the most efficient way of generating PAM4 signals without limitations. It also supports Gray coding and avoids double counting problem.
- Keysight’s M8040A high-performance BERT uses the direct PAM4 generation and detection approach. M8040A leverages the advantages listed above. The M8040A not only gives detailed error analysis regarding BER and SER including the SER for individual symbol values, but it also supports both long PRBS as well as memory-based patterns. Error ratios down to 10-15 can be measured even for long PRBS 231-1 or QPRBS31 patterns. This detailed error ratio analysis helps the user to characterize and troubleshoot his digital system.

References

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[3] 5992-0527EN – PAM4 design challenges and the implications on test

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