Application Note

Anritsu Advancing beyond

# PAM4 Bit Error Rate Measurement

Signal Quality Analyzer-R MP1900A Series
PAM4 BERT MU196020A/MU196040B

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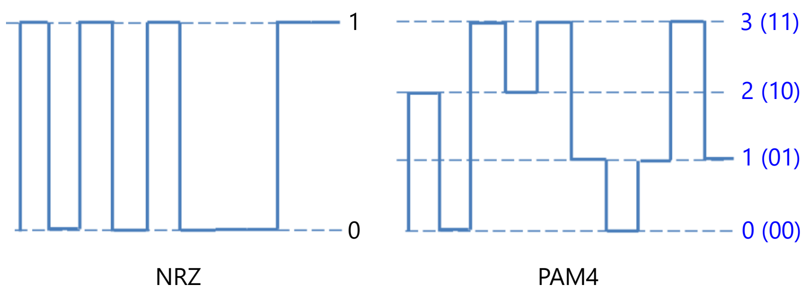
# 1 Introduction

Data centers supporting 5G communications and high-speed data-communications networks for cloud computing are progressing with introduction of 400 GbE communications standards that use the PAM4 transmission format. Unlike the previous NRZ format, which transfers 1-bit of data as two values of 0 and 1 per unit time, PAM4 transfers 2 bits of data as four values of 00, 01, 10, and 11 per unit time, to achieve twice the transmission capacity.




When evaluating communications quality, with NRZ, the change between 1↔0 is detected and displayed as bit errors, but with PAM4, there are multiple possible error cases between the four values of 0 (00), 1 (01), 2 (10), and 3 (11), requiring evaluation of PAM4 symbol errors in addition to conventional bit errors.

This Application Note summarizes PAM4 signal bit errors and PAM4 symbol errors, as well as explains PAM4 error measurement solutions using the Signal Quality Analyzer-R MP1900A series.

# 2 Outline of PAM4 Signal Bit Errors and PAM4 Symbol Errors

## 2.1 Bit Errors and PAM4 Symbol Errors

As described above, the NRZ and PAM4 formats transfer different amounts of data per unit time. As a consequence, PAM4 has 12 error-case permutations compared to 2 for NRZ. The following table outlines the data expressed by NRZ and PAM4 signals.

Table 2.1-1 Outline of NRZ and PAM4 Signals

| | NRZ | PAM4 |
|---|---|---|
| Pulse Level Value | 2 | 4 |
| Bit Count (/Unit Time) | 1 | 2 |
| Bit Definition (/Unit Time) | 0, 1 | 00, 01, 10, 11 |
| Transmission Errors | 2 cases | 12 cases |

When transmission errors occur in a bit stream at the Tx side, the error cases detected at the Rx side are as follows:

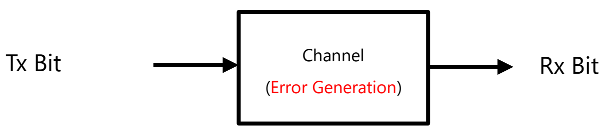



Table 2.1-2 NRZ Error Cases

| Tx Bit | → | Rx Bit | Bit Error Count |
|---|---|---|---|
| 0 | Transmission | 1 | 1 |
| 1 | Error | 0 | 1 |

Table 2.1-3 PAM4 Error Cases

| Tx Bits | | Rx Bits | Bit Error Count | PAM4 Symbol Error Count |
|---|---|---|---|---|
| 00 | → Transmission Error | 01 | 1 | 1 |
| | | 10 | 1 | 1 |
| | | 11 | 2 | 1 |
| 01 | | 00 | 1 | 1 |
| | | 10 | 2 | 1 |
| | | 11 | 1 | 1 |
| 10 | | 00 | 1 | 1 |
| | | 01 | 2 | 1 |
| | | 11 | 1 | 1 |
| 11 | | 00 | 2 | 1 |
| | | 01 | 1 | 1 |
| | | 10 | 1 | 1 |

With PAM4 expressing the signal as four values using a 2-bit stream, when an error causes a level change between 1 (01)↔2 (10), and 0 (00)↔3 (11) as shown above, the bit error count detected at the Rx side is 2 bits. Additionally, instead of bit errors, PAM4 uses PAM4 symbol errors as the index for evaluating the error count per unit time. All the error cases shown in the above example of transmission errors are detected as one PAM4 symbol error.

As with conventional NRZ, the receiver test for the 400GAUI-8 C2C (Annex 120D) and 400GAUI-8 C2M (Annex 120E) interfaces used by PAM4 and standardized by IEEE802.3 specifies measuring the BER (Bit Error Rate) by detecting the bit errors. As explained above, PAM4 has multiple error cases; moreover, since there are both 1-bit and 2-bit error cases, debugging and specifying the causes of errors is not simply a case of conventional bit error counts and BER evaluation, but instead requires using the PAM4 SER (Symbol Error Ratio) by detecting PAM4 symbol errors, and evaluating in which bit an error occurred.

## 2.2 About Gray-code

As shown in the error cases in section 2.1, with PAM4, either 1-bit or 2-bit errors are detected depending on the value change. In contrast, errors where adjacent 1 (01)↔2 (10) values are changed are not handled as 2-bit errors but instead use the Gray-code encoding method for handling as a 1-bit error. For PAM4 expressing data with 2 bits, errors at changes in adjacent values caused by channel loss, etc., can be evaluated as 1-bit errors by outputting a Gray-coded signal with 10 as 3 (11) and 11 as 2 (10) at the Tx side, which is Gray-decoded at the Rx side with 2 (10) as 11 and 3 (11) as 10.

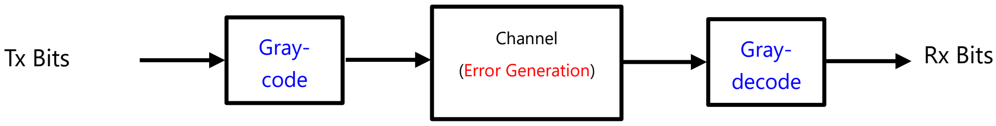



Table 2.2-1 PAM4 Error Cases with Added Gray-code/Gray-decode

| Tx Bits | → Gray-code | | Channel Output | Bit Error Count | → Gray-decode | Bit Error Count |
|---|---|---|---|---|---|---|
| 00 | 00 | Channel | 00 | 0 | 00 | 0 |
| | | | 01 | 1 | 01 | 1 |
| | | | 10 | 1 | 11 | 2 |
| | | | 11 | 2 | 10 | 1 |
| 01 | 01 | | 00 | 1 | 00 | 1 |
| | | | 01 | 0 | 01 | 0 |
| | | | 10 | 2 | 11 | 1 |
| | | | 11 | 1 | 10 | 2 |
| 10 | 11 | | 00 | 2 | 00 | 1 |
| | | | 01 | 1 | 01 | 2 |
| | | | 10 | 1 | 11 | 1 |
| | | | 11 | 0 | 10 | 0 |
| 11 | 10 | | 00 | 1 | 00 | 2 |
| | | | 01 | 2 | 01 | 1 |
| | | | 10 | 0 | 11 | 0 |
| | | | 11 | 1 | 10 | 1 |

# 3 PAM4 Signal Measurement Solution using MP1900A PAM4 BERT

## 3.1 BER Measurement, PAM4 SER Measurement, Capture Function

The Jitter Tolerance test for 400GAUI-8 C2C and 400GAUI-8 C2M interfaces specified by IEEE 400 GbE uses a test signal source with added jitter stress and an error detector to confirm that bit errors occurring at the DUT receiver are less than the standard value.

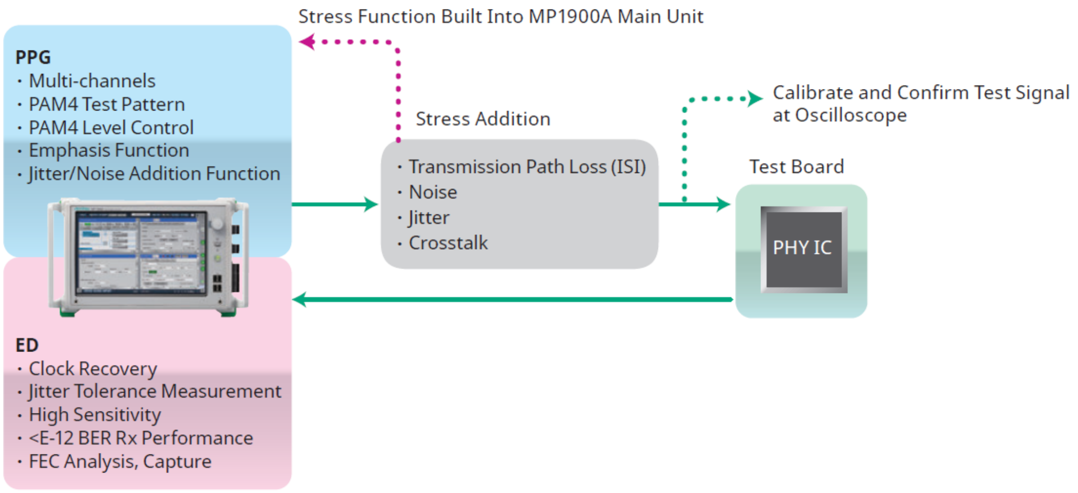



Fig. 3.1-1 Outline of Jitter Tolerance Measurement using PAM4 BERT

The MP1900A series PAM4 ED MU196040B can confirm all 12 error cases occurring in measured PAM4 signals at one screen. As a result, confirming errors occurring between which levels can play a role in troubleshooting error causes. Moreover, in addition to detailed BER and PAM4 SER measurements, measuring both the MSB and LSB supports verification of both physical errors in the channel as well as logical errors.

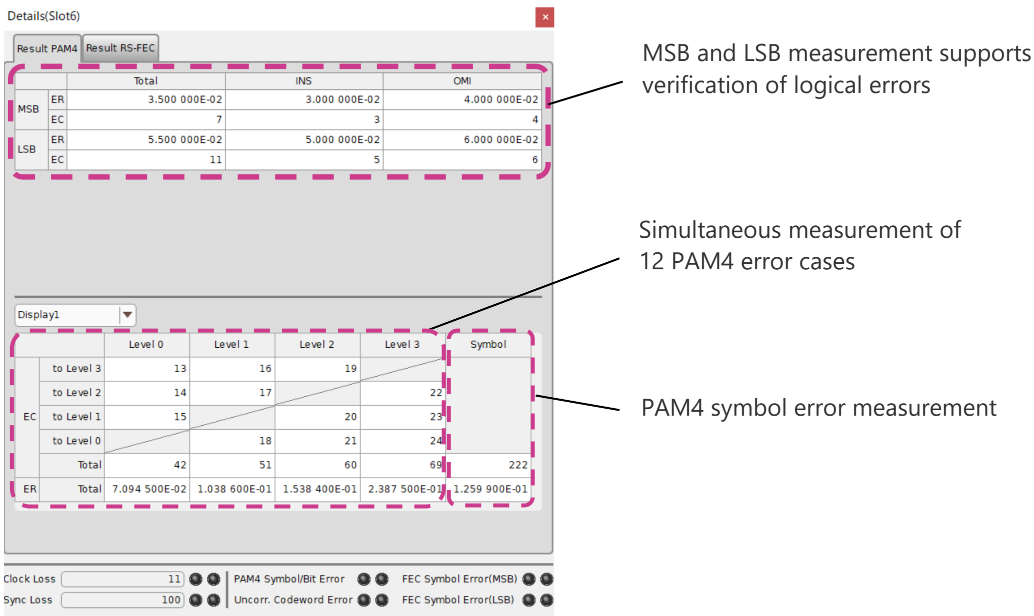



Fig. 3.1-2 PAM4 Error Measurement Screen Example

Additionally, capturing input signals at the detected error timing can confirm each error bit graphically. Using the capture function for detailed inspection supports analysis and debugging of error cases.

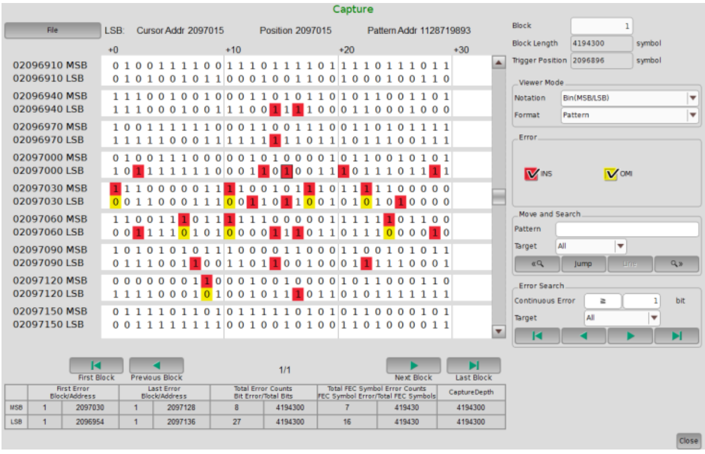



Fig 3.1-3　Capture Measurement Screen Example

## 3.2 Gray-code Function, and Gray-decode and FEC Analysis

In addition to supporting the test patterns required by PAM4 transmissions, the MP1900A series PAM4 PPG MU196020A also supports the Gray-code function. Moreover, by using the PAM4 ED MU196040B FEC analysis function, jitter tolerance measurements based on FEC correction ability is supported. For FEC evaluation, refer to the "100/200/400 GbE FEC Testing with MP1900A" Application Note.)

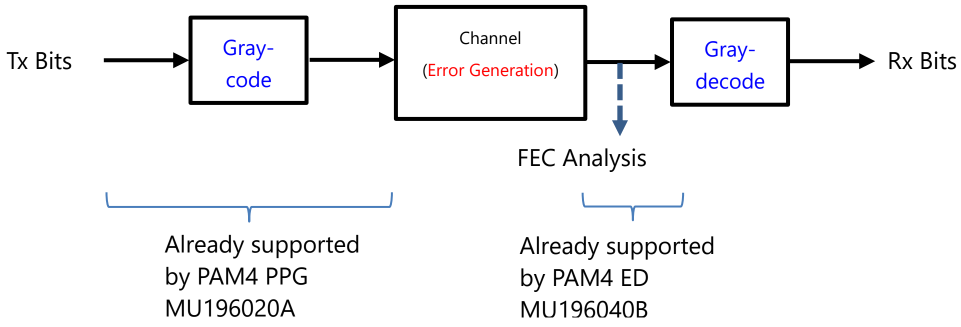



Table 3.2-1 PAM4 Error Cases

| | → Gray-code | | Channel Output | Bit Error Count | → Gray-decode | Bit Error Count |
|---|---|---|---|---|---|---|
| 00 | 00 | Channel | 00 | 0 | 00 | 0 |
| | | | 01 | 1 | 01 | 1 |
| | | | 10 | 1 | 11 | 2 |
| | | | 11 | 2 | 10 | 1 |
| 01 | 01 | | 00 | 1 | 00 | 1 |
| | | | 01 | 0 | 01 | 0 |
| | | | 10 | 2 | 11 | 1 |
| | | | 11 | 1 | 10 | 2 |
| 10 | 11 | | 00 | 2 | 00 | 1 |
| | | | 01 | 1 | 01 | 2 |
| | | | 10 | 1 | 11 | 1 |
| | | | 11 | 0 | 10 | 0 |
| 11 | 10 | | 00 | 1 | 00 | 2 |
| | | | 01 | 2 | 01 | 1 |
| | | | 10 | 0 | 11 | 0 |
| | | | 11 | 1 | 10 | 1 |

However, as explained in item 2.2, for channel or DUT-passage bit errors, differences can occur in bit-error counts and FEC analysis results in comparison to measurement results after Gray-decode counting of changes in adjacent values as a 1-bit error for error cases with a change between 1 (01)↔2 (10) counted as 2-bit errors. As a result, it is important to consider differences in error-bit counts according to error case when comparing bit error and FEC analysis results before and after Gray-decode.

# 4 Conclusions

At evaluation of communications quality and devices using PAM4 signals, PAM4 SER measurements and detailed bit-error inspection are required in addition to conventional BER measurements. Detailed error measurements using the Signal Quality Analyzer-R MP1900A series PAM4 signal BER, PAM4 SER measurement, and capture functions support efficient design verification and debugging. In addition, bit-error measurement and FEC analysis functions support measurement based on FEC correction ability.

Anritsu works to understand future trends in the communications world to provide timely solutions helping customers and contributing to business development.

Reference: IEEE 802.3

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