Application Note

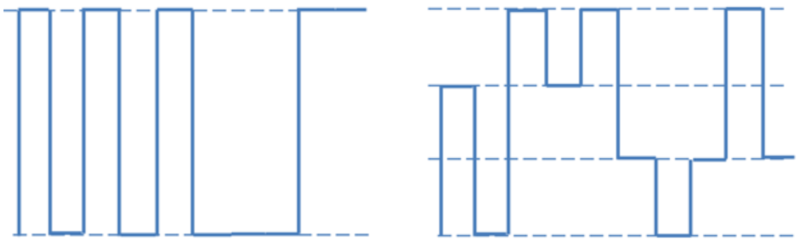
High-Speed PAM Signal Generation and BER Measurements

Signal Quality Analyzer-R MP1900A Series

Contents

1. Introduction

The next-generation 200 and 400-Gbits/s transmission methods defined by IEEE802.3bs and IEEE802.3cd increase the transmission capacity compared to the conventional NRZ method without increasing the symbol rate by implementing Pulse Amplitude Modulation (PAM) transmission technology.
In PAM4 signalling, instead of transferring 1 bit at one of two levels of 0 or 1 in one time slot as in NRZ signalling, two bits of data are transferred at four levels in one time slot. PAM has the merit of increasing the data transfer capacity without increasing the signal symbol rate, but conversely, since the voltage level of each signal in one time slot becomes smaller, it has the demerit of a poorer signal to noise ratio (SNR).
This Application Note explains generation of PAM signals with the above-described features as well as BER measurement methods.



NRZ: $2^1 = 2$ PAM4: $2^2 = 4$

Fig. 1.1 Signal Transmission Methods and Data Volumes

Table 1.1 lists the trend in transmission methods used by the latest 100G, 200G, and 400G standards. PAM4, which has been the main standard in recent years, has a transmission speed of 26.5625 Gbaud, but some 53.125 Gbaud PAM4 transmissions such as 400GBase-DR4, are being adopted for 400G

Table 1.1 Transmission Methods used by Each Standard

Optical Interface

Standard		Distance	Format	Baud Rate
400G	400G BASE-SR16	100 m	NRZ	26.6G
	400G BASE-DR4	**500 m**	**PAM4**	**53.1G**
	400G BASE-FR8	**2 km**	**PAM4**	**26.6G**
	400G BASE-LR8	**10 km**	**PAM4**	**26.6G**
200G	**200G BASE-SR4**	**100 m**	**PAM4**	**26.6G**
	200G BASE-DR4	**500 m**	**PAM4**	**26.6G**
	200G BASE-FR4	**2 km**	**PAM4**	**26.6G**
	200G BASE-LR4	**10 km**	**PAM4**	**26.6G**
100G	100G BASE-SR10	100/150 m	NRZ	10.3G
	100G BASE-SR2	**100 m**	**PAM4**	**26.6G**
	100G BASE-DR	**500 m**	**PAM4**	**53.1G**
	100G BASE-SR4	70/100 m	NRZ	25.8G
	100G SWDM	400 m	NRZ	25.8G
	100G PSM4	500 m	NRZ	25.8G
	CWDM4/CLR4	2 km	NRZ	25.8G
	100G BASE-LR4	10 km	NRZ	25.8G
	100G BASE-ER4	40 km	NRZ	25.8G
50G	**50G BASE-SR**	**100 m**	**PAM4**	**26.6G**
	50G BASE-FR	**2 km**	**PAM4**	**26.6G**
	50G BASE-LR	**10 km**	**PAM4**	**26.6G**
25G	25G BASE-SR	100 m	NRZ	25.8G
	25G BASE-FR	2 km	NRZ	25.8G
	25G BASE-LR	10 km	NRZ	25.8G

Electrical Interface

Standard IEEE802.3bs, OIF-CEI		**Format**	**Baud Rate**
400G	400GAUI-16	NRZ	26.6G
	400GAUI-8	**PAM4**	**26.6G**
200G	200GAUI-8	NRZ	26.6G
	200GAUI-4	**PAM4**	**26.6G**
100G	CAUI-10	NRZ	10.3G
	CAUI-4	NRZ	25.8G
50G	**50GAUI**	**PAM4**	**26.6G**
25G	25GAUI	NRZ	25.8G

Standard IEEE802.3by, IEEE802.3cd		Format	Baud Rate
200G	200G BASE-CR4	PAM4	26.6G
	200G BASE-KR4	PAM4	26.6G
100G	100G BASE-CR4	NRZ	25.8G
	100G BASE-KR4	NRZ	25.8G
	100G BASE-KP4	**PAM4**	**13.6G**
	100G BASE-CR2	**PAM4**	**26.6G**
	100G BASE-KR2	**PAM4**	**26.6G**
50G	**50G BASE-CR**	**PAM4**	**26.6G**
	50G BASE-KR	**PAM4**	**26.6G**

2. PAM Signal Generation

This section describes PAM4 signal generation methods as well as points to note at signal generation. As shown in Fig. 1.1, PAM4 transfers data for 4 values in one time slot. Consequently, PAM4 (2^2) signalling uses two Pulse Pattern Generators (PPG) as the data signal source. Figure 2.1 shows the setup for PAM4 signal generation. The basic setup uses a passive method in which the Data signal output from a multi-channel PPG is combined using a Passive Combiner. The Anritsu solution makes it easy to generate high-quality PAM4 signals, because it provides the multi-channel PPG, PAM4 Converter and waveform adjustment software.

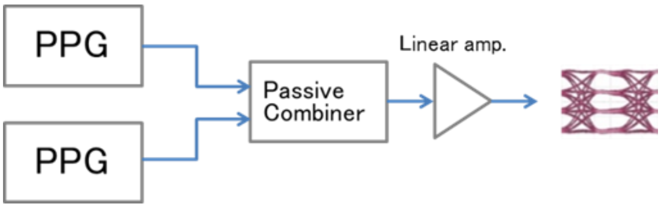


Fig. 2.1 Basic Setup for PAM Signal Generation using Passive Method

Fig. 2.2 Anritsu 32 Gbaud PAM4 Signal Generation Solution

In this setup, the multi-channel PPG requires:

(a) Function for varying data phase between channels with high accuracy
(b) High-quality waveforms (low Jitter, low waveform distortion, high-speed Rise and Fall times)

To reduce the PAM signal Jitter, the phase of the data between the multiple PPGs used to generate the PAM signal must have the exact same timing. From Table 1.1, the width of 1 bit at 26.6 Gbaud PAM4 signal transmission is 37.5 ps, corresponding to a short electrical length of about 7.9 mm, so a difference of just a few mm has a great impact on the waveform quality. Consequently, as described in item (a) above, the multi-channel PPG must have a function for precise adjustment of the data phase between channels.

In addition, as described in (b), obtaining a high-quality PAM signal requires that the PPG itself generates high-quality waveforms. If the PPG Jitter is large, the PAM signal Jitter will also be large, and if the waveform distortion is large, the SNR is degraded by the large signal baseline. Any delay in the rise and fall times has a direct impact on reduction of the phase margin and increased PAM signal Jitter and degraded SNR.

2.1. Controlling PAM Signal Linearity

The PAM signal linearity can be controlled using the 3Eye Independent Level Control function. Figure 2.1.1 shows the reference setup configuration for the TOSA evaluation solution, and costs can be cut because the external driver amplifier is eliminated by using this linearity control and high-amplitude control using the G0375A.

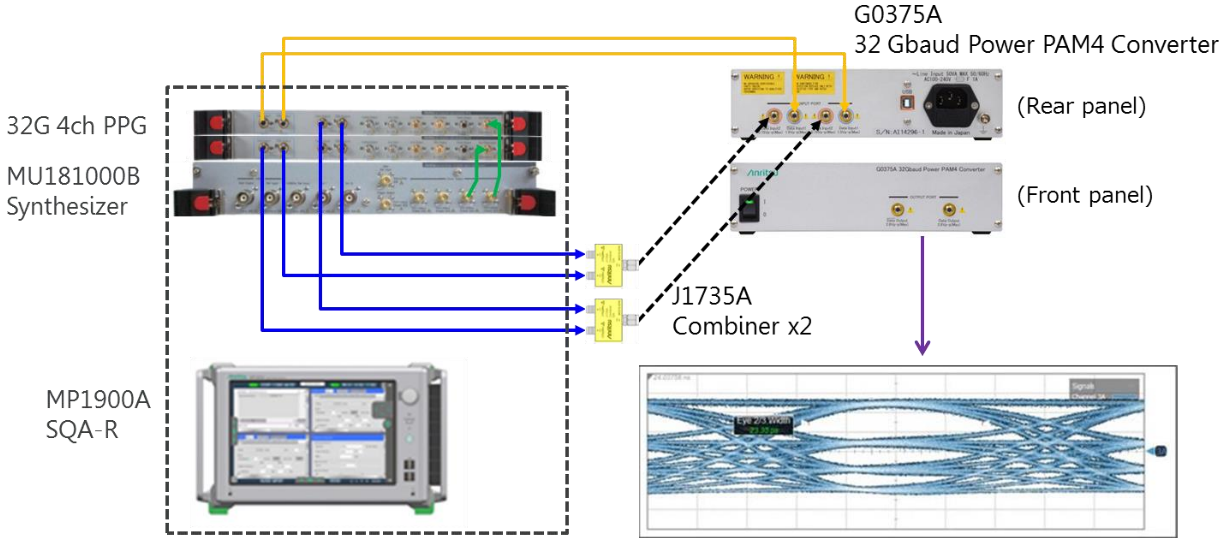


Fig. 2.1.1 Reference Setup Configuration for TOSA Evaluation Solution Using Linearity Control (EYE waveform is for image only)

2.2. PAM Signal Emphasis Function

With a built-in 21G/32G bit/s SI PPG (MU195020A) incorporating a 10Tap Emphasis function, the MP1900A supports more efficient design testing by simulating various devices and channels and outputting a high-reproducibility signal calibrated for loss after passage through the channel.

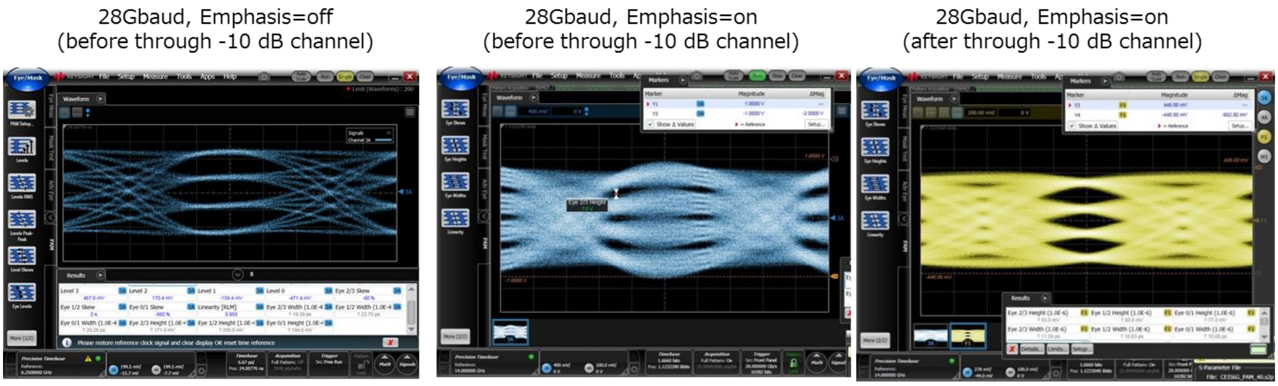


Fig. 2.2.1 PAM Signal Output Waveform at Emphasis Setting

2.3. 64 Gbaud PAM4 Jitter Addition

Anritsu has the G0374A 64 Gbaud PAM4 DAC supporting 53.1 Gbaud PAM4 transmissions required by 400GBase-DR4 for 400G transmissions.

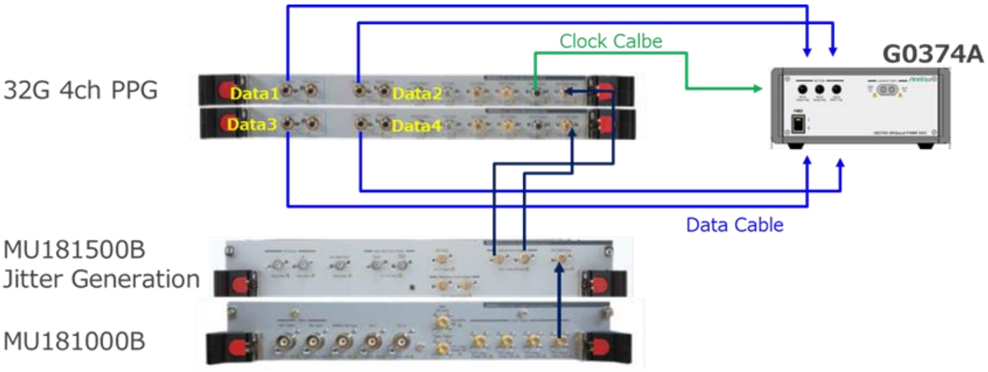


Fig. 2.3.1 Anritsu 64 Gbaud PAM4 Signal Generation Solution (with jitter addition)

Since both the 32 Gbaud Power PAM4 Converter (G0375A) and 64 Gbaud PAM4 DAC (G0374A) solutions have Jitter transparency, they support addition of Jitter to PAM4 signals and Jitter Tolerance tests.

3. PAM Signal BER Measurement

The MP1900A supports two PAM4 signal BER measurement methods: 1. Measurement of MSB and LSB-decoded NRZ signals using the PAM4 Decoder (G0376A 32 Gbaud PAM4 Decoder with CTLE), and 2. Measurement of each of the 3 Eyes of PAM4 signals without using the PAM4 Decoder.

As shown in Fig. 3.1, when using the PAM4 Decoder, each NRZ signal can be measured by the 2ch ED because the PAM4 signal MSB and LSB are decoded by the Decoder.

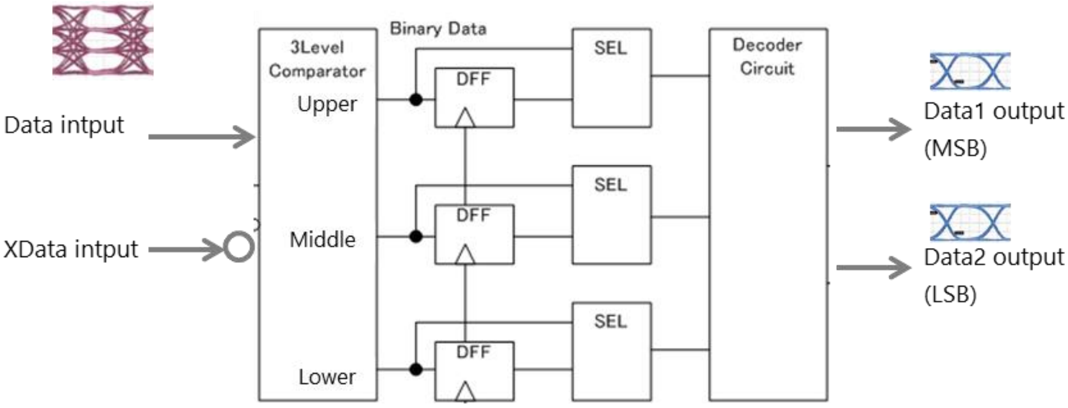


Fig. 3.1 PAM4 Decoder Block Diagram

BER measurement without using the PAM4 Decoder is explained next. Figure 3.2 shows the PAM4 signal generated from the PPG1 and PPG2 patterns. The horizontal parts of the waveform in the lower figure are called the Threshold, meaning the threshold voltage for evaluating the PAM4 amplitude. Since PAM4 uses four values, three threshold voltages are required to recognize each voltage.

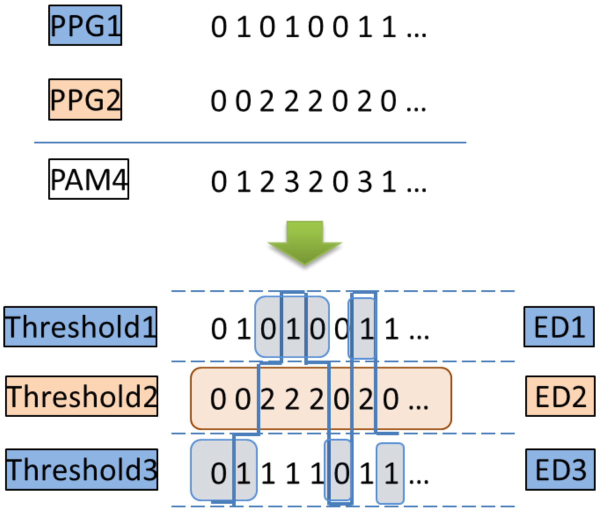


Fig. 3.2 PAM Signal and BER Measurement Threshold Relationship

The pattern for Threshold 2 is the same as the pattern of PPG2 generating the maximum amplitude at PAM generation. And the PPG1 pattern appears half in Threshold 1 and half in Threshold 3. The shaded blue parts in the waveform diagram are the PPG1 pattern. The PPG1 pattern appears at Threshold 3 when Threshold 2 = 0 (Low), and at Threshold 1 when Threshold 2 = 2 (High).
If the expected pattern at each Threshold is already known like this, the BER of the PAM signal can be measured by setting this pattern at the Error Detector (ED).
Since the data patterns for Threshold 1 and Threshold 3 are obtained by dividing the data pattern from one PPG into two, the measured BER is different from the true BER. The data pattern output from PPG1 is measured by two EDs corresponding to Threshold 1 and Threshold 3. If the PPG2 pattern mark ratio is assumed to be 1/2, the measurement target is 50% of each of the Threshold 1 pattern string and

Threshold 3 pattern string. Consequently, if the PPG1 measurement result is the simple sum of Threshold 1 and Threshold 3, there is a possibility of the Error Count being too large due to inclusion of errors outside the measurement target.

This section describes the three requirements for measuring instruments used to measure PAM BER.

1) PAM signal BER measurement presupposes prior knowledge of the patterns set at each ED. Consequently, the multiple PPGs generating the PAM signal require the ability to synchronize bit patterns rather than just synchronize the clock to change the cross point at the same timing. Anritsu's MP1900A Signal Quality Analyzer-R PPG can adjust each pattern generation position of the user programmable patterns generated from the PPG by ±128 bits and the PRBS pattern cycle can be shifted by either a ½ or ¼ period. As a result, if a PRBS23 pattern is set at two PPGs, adjusting each PPG pattern by a half cycle makes it possible to generate a correlation-free PAM4 signal. Moreover, since the PPG pattern is known, the pattern can also be set easily at the ED side.
2) The second condition is the ED input sensitivity. Assuming transmission of a PAM4 signal with a differential amplitude of 600 mVpp, the single-ended voltage identification range required by the ED is one-third of 300 mVpp, or 100 mVpp. Additionally, using Clock Recovery requires splitting the input into two using a Power Divider, etc. Since the amplitude after splitting by the Power Divider becomes 50 mVpp, an ED with a high input sensitivity is required.

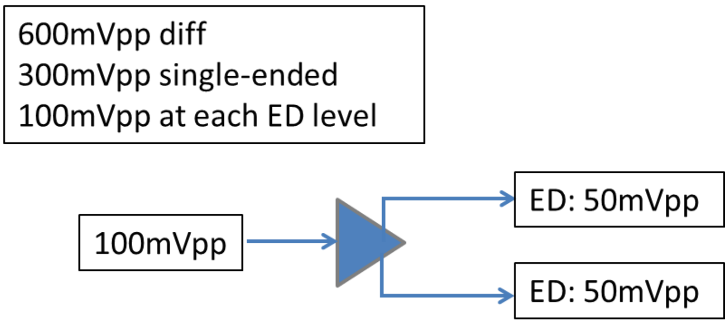


Fig. 3.3 Input Amplitude of Each ED

Consequently, the ED must have sufficient performance to measure a signal with an Eye Height of about 20 to 50 mV. The Anritsu ED MU18304xB series can measure signals with an Eye height of 10 mVpp (typ. @ 28.1 Gbps), while the MU195040A 21G/32G bit/s SI ED can measure signals with an Eye Height of 15 mVpp (typ. @ 28.1Gbps), offering the world's best input sensitivity and optimum measurement for these types of small-amplitude signals.

Moreover, although degraded SNR can reduce the amplitude of (or close) each Eye of a PAM4 signal, sometimes making measurement difficult, Anritsu's MP1900A Continuous Time Linear Equalizer (CTLE) function supports easy BER measurement by adjusting the Eye opening of PAM4 signals.

3) The final condition is the requirement for a measurement mask function to remove items that are not the target of measurements from the pattern to ensure accurate BER measurement as described earlier. Specifying the measurement target part for each 1 bit when setting the ED pattern assures more accurate BER measurements.

3.1. PAM Signal CTLE Function

Both the MU195040A and the 32 Gbaud PAM4 Decoder with CTLE (G0376A) MP1900A solutions support adjustment of the PAM4 Eye opening using the continuously variable CTLE Gain between –12 and 0 dB at a peak frequency of 14 GHz.

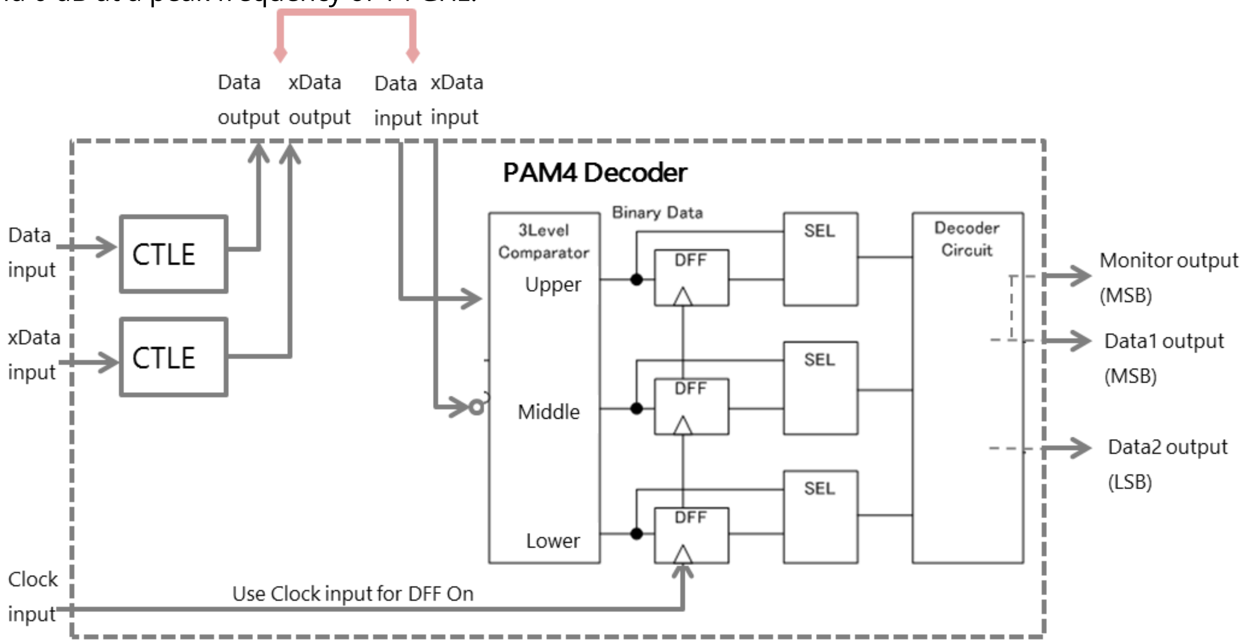


Fig. 3.1.1 Internal Block Diagram of G0376A 32 Gbaud PAM4 Decoder with CTLE

4. Anritsu Solutions for PAM Signal Generation and BER Measurement

This section describes generation of 32- and 64 Gbaud PAM4 signals and BER measurement using actual Anritsu solutions.

4.1. 32 Gbaud PAM4 Solution Using G0375A/G0376A

Figure 4.1.1 shows the TOSA/ROSA evaluation solution using the G0375A/G0376A.

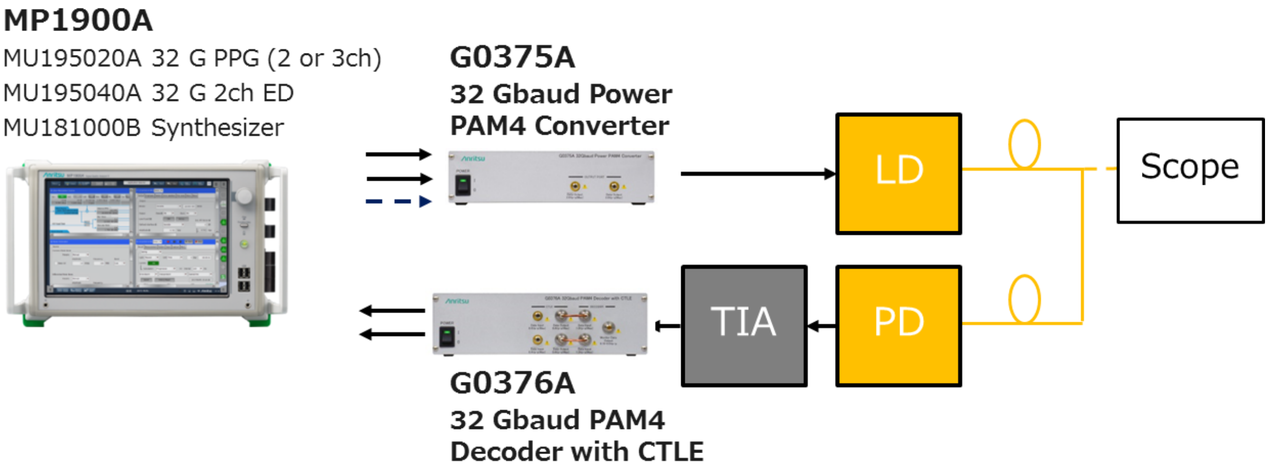


Fig. 4.1.1 32 Gbaud PAM4 Solution Using G0375A/G0376A

At the Tx side, the MSB and LSB signals output from the 2ch PPG are encoded by the G0375A PAM4 Converter and input to the DUT. In addition, using another 1ch PPG supports linearity control at the output PAM signal. See Fig. 2.1.1 for an example of the linearity control connection configuration.
At the Rx side, the bit error rate of all bits of the MSB and LSB signals decoded by the G0376A are measured in real time using the 2ch ED.
Refer to the MP1900A PAM4 Quick Guide "MP1900A 32 Gbaud PAM4 Solution" for details of the operation procedure using the MP1900A.
Figure 4.1.1 shows the equipment configuration used by this measurement solution. The cable connections to the DUT are not described in this configuration.

Table 4.1.1 Equipment Configuration for 32 Gbaud PAM Solution Using G0375A and G0376A

Model	Name	Qty	Remark
G0375A	32Gbaud Power PAM4 Converter	1	
G0376A	32Gbaud PAM4 Decoder with CTLE	1	
MP1900A	Signal Quality Analyzer-R	1	
MU181000B	12.5GHz 4port synthesizer	1	
MU195020A	21G/32G bit/s SI PPG	1	2 (Linearity control=on)
MU195040A	21G/32G bit/s SI ED	1	
J1735A	Combiner	2	for Linearity Control

4.2. 32 Gbaud PAM4 Solution Using G0375A/MU195040A

Figure 4.2.1 shows the Rx evaluation solution for 400GAUI-8/CEI-56G-VSR-PAM4 electrical interfaces using the G0375A/MU195040A.

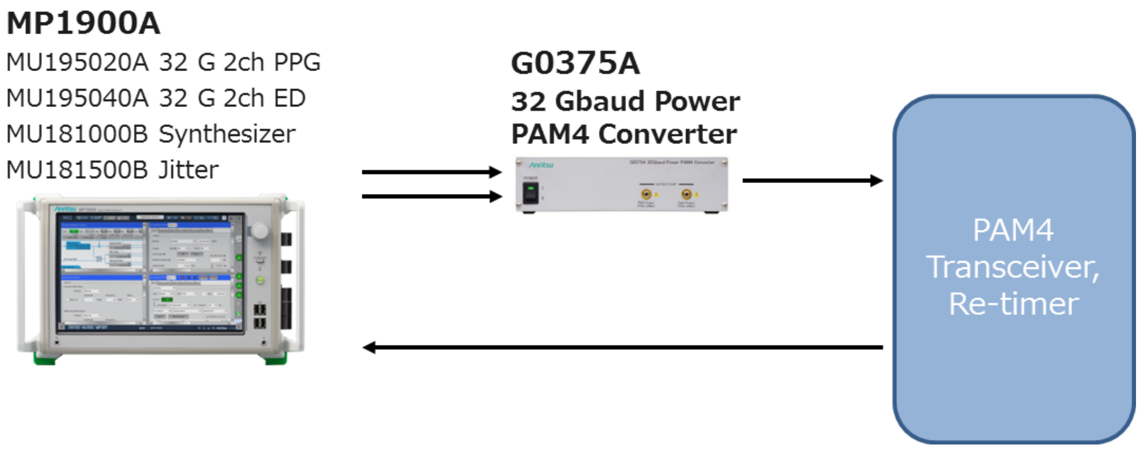


Fig. 4.2.1 32 Gbaud PAM4 Solution using G0375A/MU195040A

At the Tx side, like the solution described in section 4.1, the MSB and LSB signals output from the 2ch PPG are encoded by the G0375A PAM4 Converter and input to the DUT. Unlike the solution described in section 4.1, at the Rx side, each of the three Eyes is measured sequentially one-by-one. A 2ch ED is used instead of a 1ch ED when using Clock Recovery. The center PAM4 Eye threshold value is set as the 1ch Eye and BER measurement is performed at the 2ch Eye. In this case, at input of the PAM4 signal to the ED, the XData side is connected to the 1ch ED and the Data side is connected to the 2ch ED.
Table 4.2.1 lists the equipment configuration used by this solution. The cable connections to the DUT are not described in this configuration.

Table 4.2.1 Equipment Configuration for 32 Gbaud PAM4 Solution Using G0375A and MU195040A

Model	Name	Qty	Remark
G0375A	32Gbaud Power PAM4 Converter	1	
MP1900A	Signal Quality Analyzer-R	1	
MU181000B	12.5GHz 4port synthesizer	1	
MU181500B	Jitter Modulation Source	1	for jitter tolerance test
MU195020A	21G/32G bit/s SI PPG	1	
MU195040A	21G/32G bit/s SI ED	1	

Since each of the three Eyes is measured one-by-one sequentially at the Rx side, the setting method is explained here. As described in section 3, since the patterns at the ED side for Threshold 1 and Threshold 3 require changing from the usual PRBS pattern, instead of using a PRBS pattern, a User Programmable pattern is used.
As an example, this explains setting the two PPG patterns to PRBS7. Figure 4.2.2 shows the signal levels when the PAM4 PPG2 amplitude is twice that of PPG1. In this case, the signal is split into three for the three Thresholds measured by three EDs. Since Threshold 2 is the pattern of PPG2, in this case it is PRBS7. At Threshold 1, the bit where the PAM4 signal level is 3 is set as the “H” level, and the other bits are set as the “L” level. At Threshold 3, the bits where the PAM4 signal level is 0 are set as “L” level and the other bits as set as “H” level.

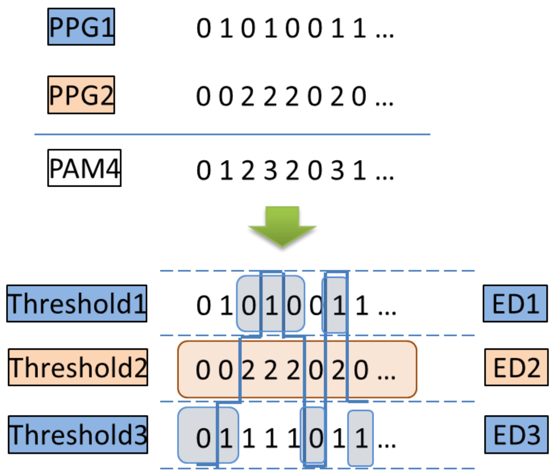


Fig. 4.2.2 PAM4 Signal ED Pattern

Since the patterns used for PAM4 testing are saved in the MP1900A, the saved User Programmable patterns can be loaded into ED1 for Threshold1 and into ED3 for Threshold3. As shown in Fig. 4.2.3, the loaded User Programmable patterns are already masked bits that should be excluded and can be used for accurate BER measurement.

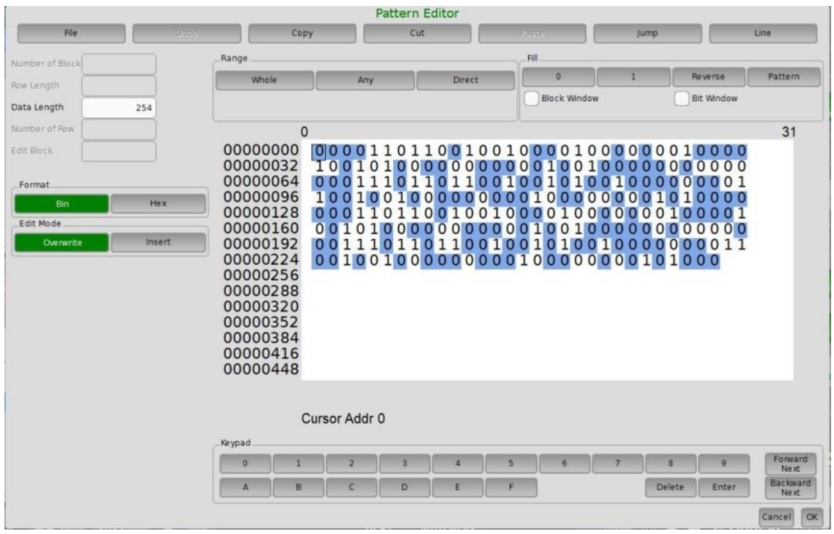


Fig. 4.2.3 Mask Setting at Pattern Editor

About the BER measurement result, the Top, Middle, and Bottom Eye is measured serially as shown in Fig. 4.2.4, and the Total BER measurement result is displayed. Since the BER is measured sequentially using a 1CH ED, the measurement result does not measure all bits without exception. It displays the BER essentials as a probability.

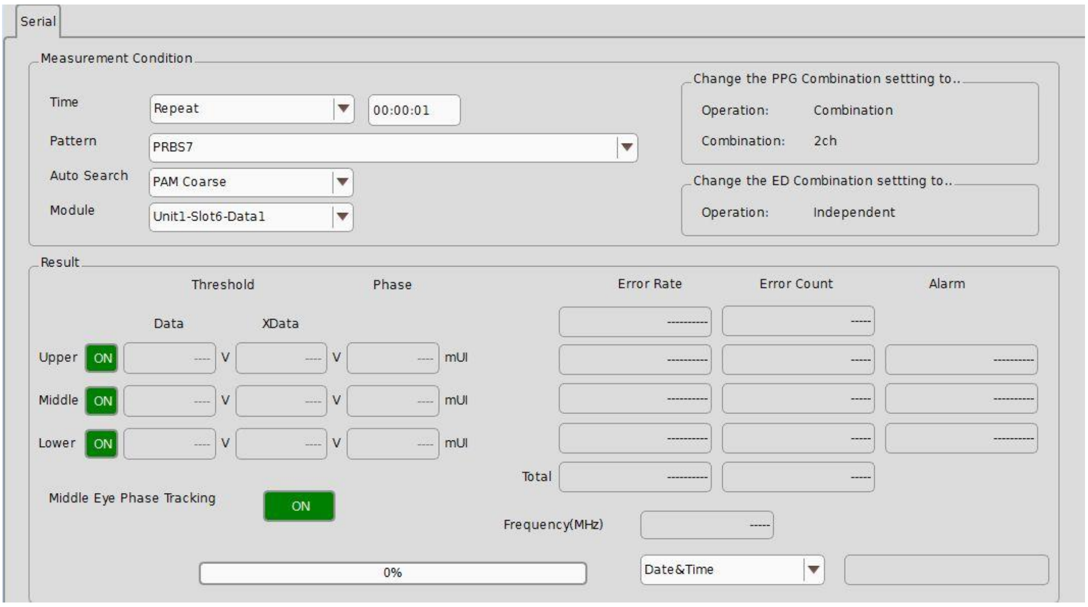


Fig. 4.2.4 Sequential PAM4 Measurement using 1CH ED

Refer to the MP1900A PAM4 Quick Guide "MP1900A 32 Gbaud PAM4 Solution" for details of the operation procedure using the MP1900A.

4.3. 64 Gbaud PAM4 Solution

A PAM4 signal up to 64 Gbaud can be generated by extending the MP1900A functions using the G0374A 64 Gbaud PAM4 DAC; the MP1800A supports 56 Gbaud PAM4 solutions including BER measurement. Refer to the MP1800A Application Note "High-Speed PAM Signal Generation and BER Measurements" for more details. Refer to section 4.2.

Figure 4.3.1 shows the setup for the 64 Gbaud PAM4 Solution. Two 32G 2CH PPG modules for the MP1900A connect four Data signals to the G0374A 64 Gbaud PAM4 DAC to generate PAM4 signals. The four J1612A cables connecting the PPG Data outputs and the G0374A Data inputs assure a skew difference of less than 3 ps. If cables with a large skew are used, the phase margin of the G0374A input section is reduced, which increases the possibility of errors at the G0374A Data output. Additionally, although cables handling high-frequency signals have specified skew and frequency characteristics at purchase, bending during use and impression of high mechanical pressure can cause subsequent changes in the cable rating, so handle cables carefully to assure specifications are satisfied.

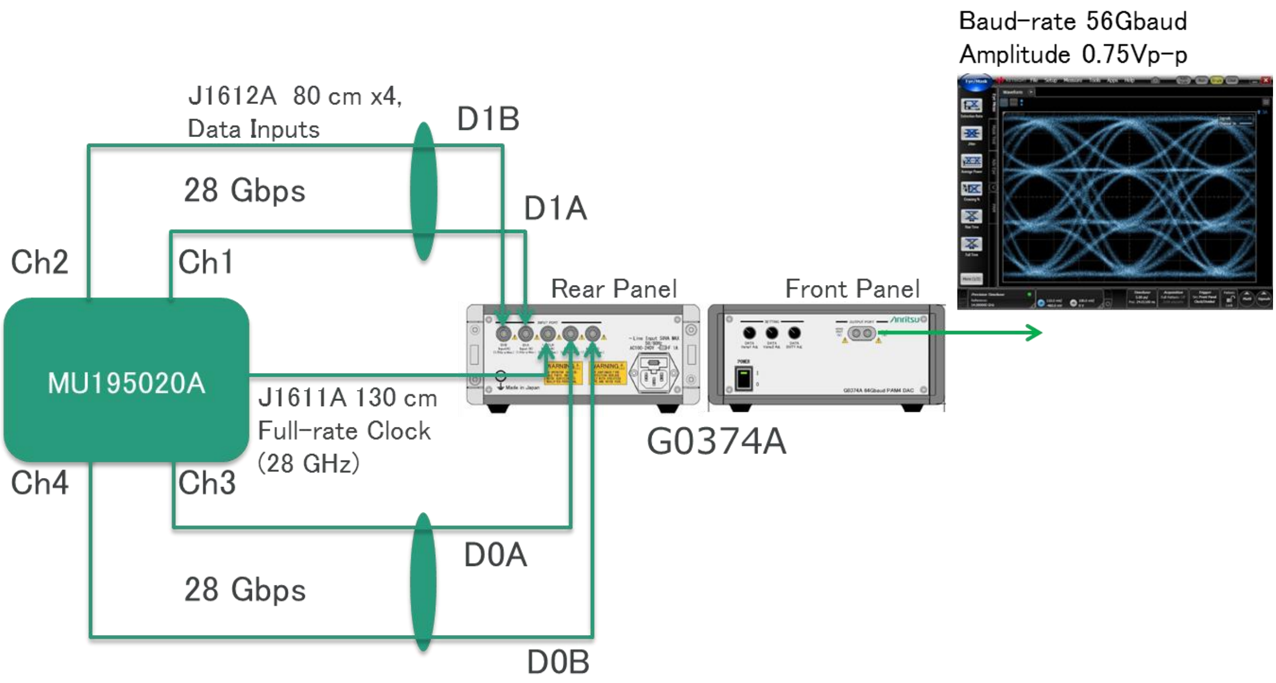


Fig. 4.3.1 Configuration for 64 Gbaud PAM4 Solution (56 Gbaud Output Waveform)

For the MP1900A PPG settings, select [64Gx2ch Combination] as shown in Fig. 4.3.2 and output the pattern for generating the 64 Gbaud PAM4 signals from the 32G 4ch PPG.

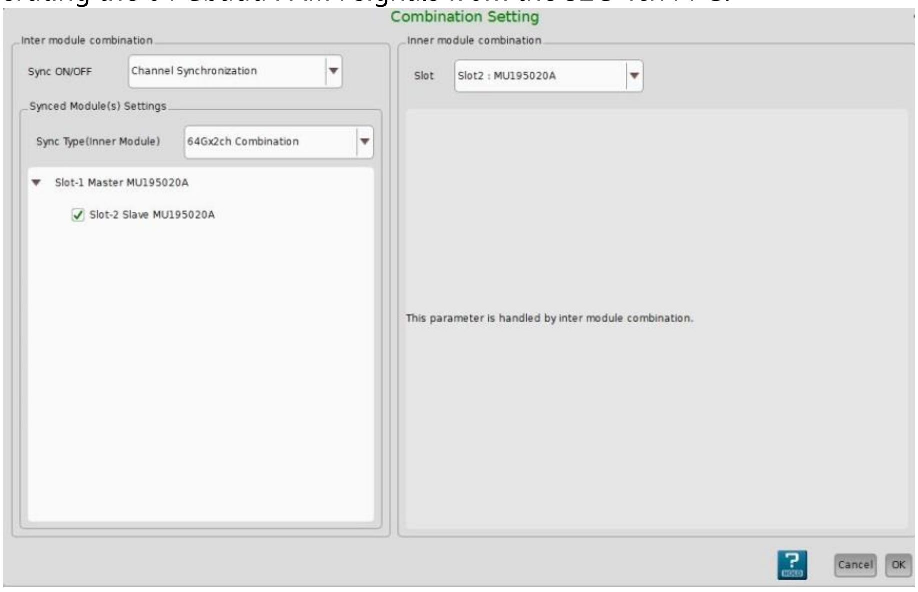


Fig. 4.3.2 PPG Combination Setting

In addition, the timing of the PPG and G0374A must be adjusted to generate 64 Gbaud PAM4 signals (Fig. 4.3.3). For details of the setting method including timing adjustment, refer to the MP1900A Quick Start Guide "64Gbaud PAM4 DAC G0374A".

Sample waveform before adjusting

Fig. 4.3.3　PAM4 Output Adjustment Example (56 Gbaud Output Waveform)

Table 4.3.1 lists the equipment used by the 64 Gbaud PAM4 solution. The cable connections to the DUT are not described in this configuration.

Table 4.3.1　Equipment Configuration for 64 Gbaud PAM4 Solution

Model	Name	Qty	Remark
MP1900A	Signal Quality Analyzer-R	1	
MU181000B	12.5GHz 4port synthesizer	1	
MU181500B	Jitter Modulation Source	1	for jitter tolerance test
MU195020A	21G/32G bit/s SI PPG	2	
G0374A	64Gbaud PAM4 DAC	1	

4.4　PAM Test Patterns

Table 4.4.1 lists and explains the PAM4 measurement patterns saved in the MP1900A.

Table 4.4.1 PAM4 Pattern Descriptions

Test Pattern	Details
PRBS13Q, PRBS31Q(*1), SSPRQ	PAM4 patterns defined by IEEE802.3bs, 802.3cd 200GbE, and 400GbE
QPRBS13-CEI	Patterns for Transmitter Output measurement and Receiver Input calibration defined by CEI-56G PAM4 standard
SSPR (Short Stress Pattern Random)	32,762-bit long pattern defined by CEI 3.1 standard; pattern length equivalent to PRBS15 and used as high-stress test pattern for PAM4 evaluation
JP03A	"0303..." pattern string used for Transmitter RJ evaluation
JP03B	62-symbol pattern composed of 15 contiguous "03" followed by 16 contiguous "30" for evaluating Transmitter Even-Odd Jitter
Square	"3333333300000000" pattern string for OMA evaluation of optical I/Fs (OMA: Optical Modulation Amplitude)
Transmitter Linearity Test Pattern	160-symbol pattern with following 10 PAM4 symbols each repeated as 16UI pattern {0, 1, 2, 3, 0, 3, 0, 3, 2, 1} The latest Linearity Test standard uses a PRBS13Q pattern.
Gray-xxxx	PAM4 signals express levels using 2-bit pairs but sometimes a 1-level change may be detected as a 2-bit change such as 01→10. To suppress this, a Gray code (00→00, 01→01, 10→11, 11→10) is used as the pattern at the Tx side.
PRBS	Pattern synthesized by PAM4 Converter using signals generated by two PPGs

(*1) Although there is no control at the Tx side, this can be selected only when using the G0376 at the

Rx side.

4.5. PAM Application Software

The PAM application software (Fig. 4.5.1 shows the software screen) for PAM signal settings, such as amplitude, offset, etc., can be downloaded from the following websites.

Japan: http://www.anritsu.com/ja-JP/test-measurement/support/downloads/software/dwl17288
USA: https://www.anritsu.com/en-us/test-measurement/support/downloads/software/dwl17288
Europe: https://www.anritsu.com/en-gb/test-measurement/support/downloads/software/dwl17288
ASIA: https://www.anritsu.com/en-au/test-measurement/support/downloads/software/dwl17288

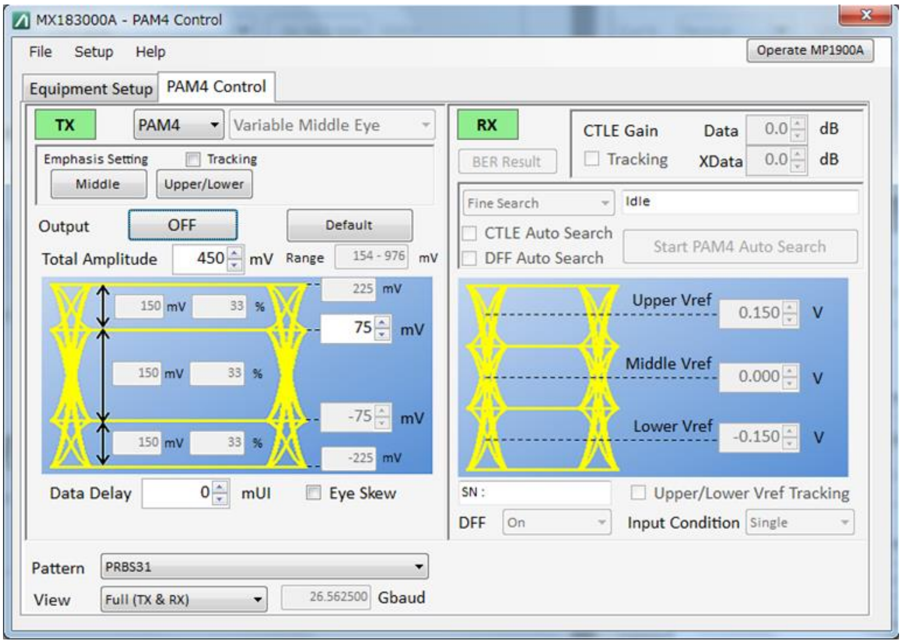


Fig. 4.5.1 PAM Application Software Screen

5. Summary

This Application Note describes how to generate 32 and 64 Gbaud PAM signals for evaluation as well as BER measurement methods and measuring instrument requirements.
Anritsu continues to develop leading-edge measurement solutions meeting customers' measurement needs.

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Specifications are subject to change without notice.

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