SELECTING THE RIGHT OPTICAL MODULATION ANALYZER FOR MANUFACTURING TEST

APPLICATION NOTE

A deep dive into the relationship between signal bandwidth and Optical Modulation Analyzer bandwidth.

OMA 2 Stack with **QP IQRX**

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Introduction

As coherent optical communication technology matures and its use expands to applications such as short haul transmission, optical engineers have to make critical investment decisions when selecting a suitable Optical Modulation Analyzer (OMA) test system. Faced with a limited choice of commercially available OMA systems, users must carefully plan and consider their options to ensure this vital piece of equipment meets their specific test requirements now, and into the future.

One of the key questions OMA users should ask is "how much bandwidth do I need for my OMA system?"

The required bandwidth for the Optical Modulation Analyzer (OMA) system depends on two main considerations:

1. The goals of the experiment.
2. The SUT spectral content.

Testing Goals

In the research or product development phase, the user's testing goals can be quite varied. They may be testing new signal processing algorithms, new bias control algorithms, or they could be measuring the rise/fall times of the optical transitions. These testing goals dictate different bandwidth requirements to ensure that measurements are not adversely impacted by instrument limitations.

In a manufacturing setting, the testing goals can fall within a more limited range. For example the user may be generating a constellation mask and identifying manufacturing defects that may impact bias performances. Manufacturing SUTs are likely to be dominated by Nyquist filtered signals with well-defined signal spectrums that were shaped at the signal source. In this case the purpose of the modulation analyzer is to mimic a commercial transceiver while providing greater insight to the SUT.

This application note will aim to clarify how much bandwidth is required to test coherent-based modulation formats in a manufacturing setting.

Optical Modulation Analyzer

A modulation analyzer has three primary components:

1. Coherent receiver
2. Four-channel high-speed digitizer
3. Signal processing software with user interface

Together these three components form the OMA system. Let's explore each of these in more detail.

Figure 1:

Complete OMA system.

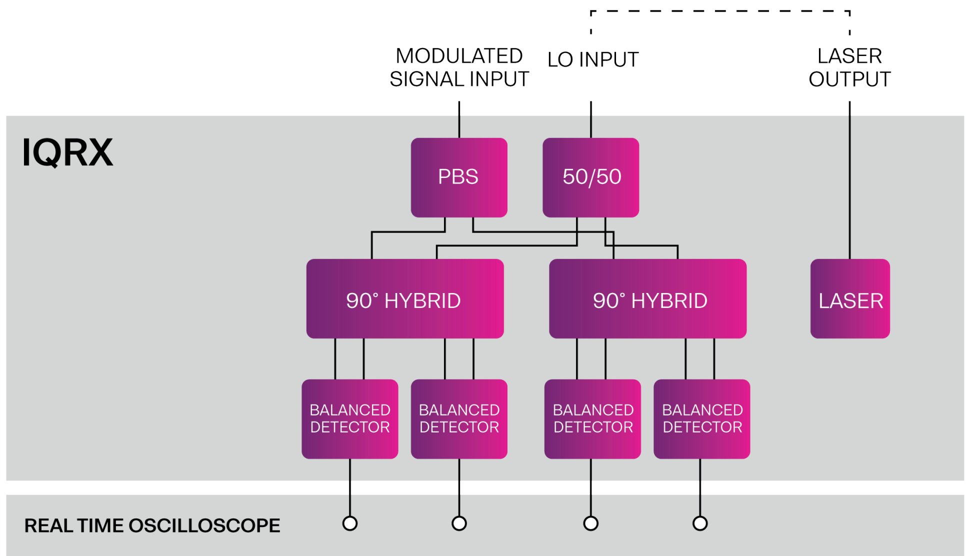
Optical Coherent Receiver

The Optical Coherent Receiver converts the amplitude, phase and polarization of the modulated optical signal into four analog electrical signals. These four signals are often referred to as the tributaries of the signal. Together they represent all the information about the optical carrier signal over a given frequency range.

Figure 2 shows the functional diagram of the simplified coherent receiver. The optically modulated signal is first split into two orthogonal states of polarization by the polarization beam splitter. A local laser (also known as the Local Oscillator, or LO) is tuned to the carrier frequency of the SUT and mixed with the modulated signal in an optical hybrid.

Figure 2:

Functional diagram of the coherent receiver.



Intradyne detection - mixing the LO with the incoming signals in the optical hybrid mixer - results in four differential optical signals known as Xi, Xq, Yi and Yq. Four separate high-speed balanced photodetectors convert the mixed optical signals into four separate single-ended electrical signals. The balanced detectors each accept a differential optical signal, and output a single-ended electrical signal. Now that the optical signal is represented by four analog electrical waveforms, they can be passed to a digitizer (a real-time digital sampling oscilloscope) for acquisition.

Four Channel High-Speed Digitizer

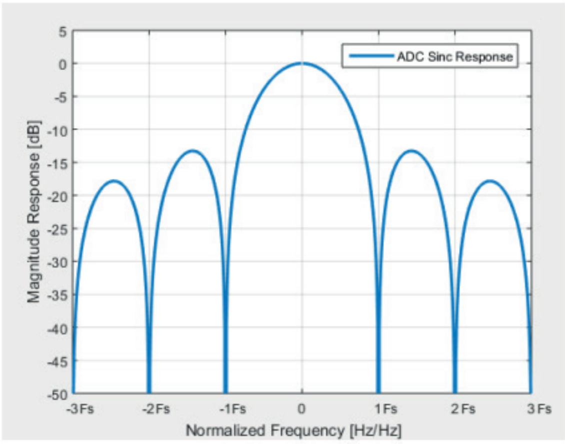
The purpose of the digitizer is to sample the four analog electrical waveforms from the balanced photodetectors and convert these into a digital representation of the waveform. Once the waveform is converted into the digital domain, we can use the digital signal processing algorithms built into the OMA library to manipulate the waveforms and recover the original modulated information from the modulated signal input.

The digitizer (generally referred to as a fast digital sampling oscilloscope) is essentially an Analog-to-Digital Converter (ADC). An uncalibrated ADC will have frequency responses that fluctuate considerably based on the sampling rate, the slew rate and the parasitics in the design.

The ideal frequency response of an ADC follows the sinc function in Figure 3. Any signal content beyond Fs/2 (common referred to as the Nyquist frequency) will be attenuated by the sinc function as well as folded back as a lower frequency alias (commonly referred to as aliasing).

Figure 3:

Ideal ADC frequency response.



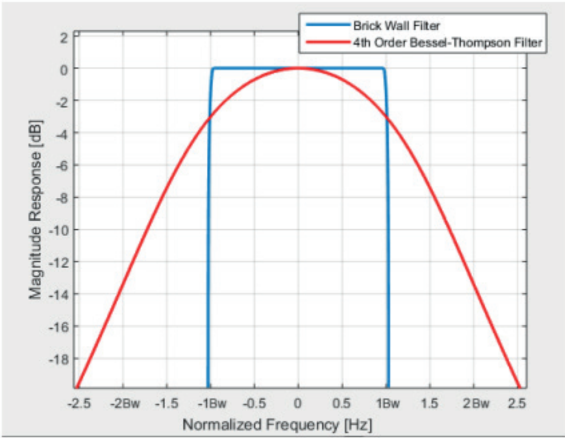
Fast, digitally-sampling oscilloscopes (DSO) are commonly used as the digitizers for OMA systems. The frequency response of the commercial oscilloscope used for the OMA is calibrated to achieve a known frequency response that conforms to either a fourth order Bessel-Thompson filter response or a Brick Wall response as demonstrated in Figure 4.

The Brick-Wall response has a flat frequency response in the passband and a very sharp roll off past the specified bandwidth. The Brick-Wall filter is particularly useful for a commercial oscilloscope. Over the desired bandwidth the frequency response maintains the spectral content of the SUT as closely as possible up to the specified bandwidth, therefore presenting the most accurate representation of the SUT.

Oscilloscopes achieve this conformity by sampling the analog signal at rate that is significantly greater than twice the desired bandwidth (a sampling rate of 100 GS/s for a 30 GHz bandwidth would be an oversampling rate of 100G/60 G = 1.666 for example), along with factory tuning of the analog frequency response and digital signal processing after sampling.

Figure 4:

Frequency response profiles.



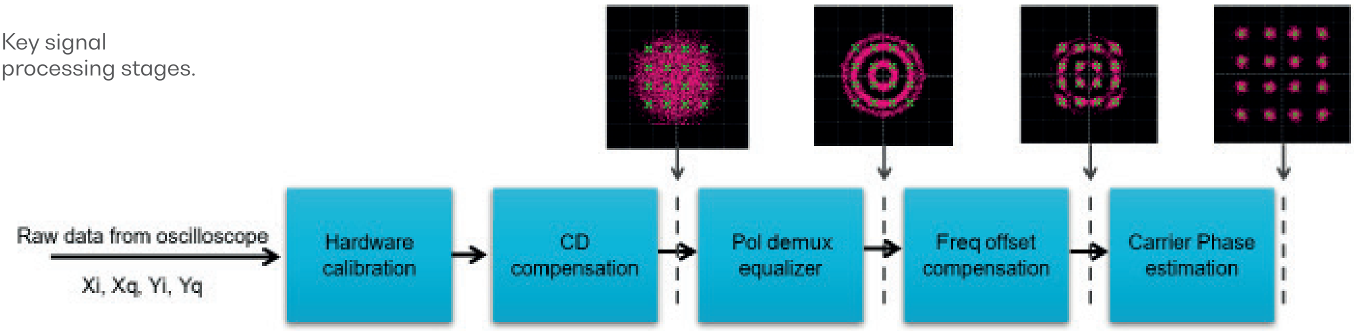
Beyond the bandwidth and sampling rate, there are other important specifications that impact the performance of the digitizer, and therefore the entire OMA system. Other important specifications include the effective number of bits, non-linearities, spurious content as well as the inherent sources of stochastic noise.

Digital Signal Processing & User Interface

The basic signal processing stages that are required to demodulate the incoming signals are highlighted in Figure 5.

Figure 5:

Key signal processing stages.



Starting from the left-hand side, four digitized tributaries (Xi, Xq, Yi, Yq) are fed into the hardware calibration DSP stage. This stage corrects any non-ideal responses of the coherent receiver and the digitizer. This stage also applies any filters that may be required by the SUT such as root-raised-cosine matched filters.

The next stage, CD Compensation, stands for Chromatic Dispersion Compensation. This stage removes any chromatic dispersion that may have occurred as a result of the optical signal propagating through the length of fiber from the original transmit point to the coherent receiver.

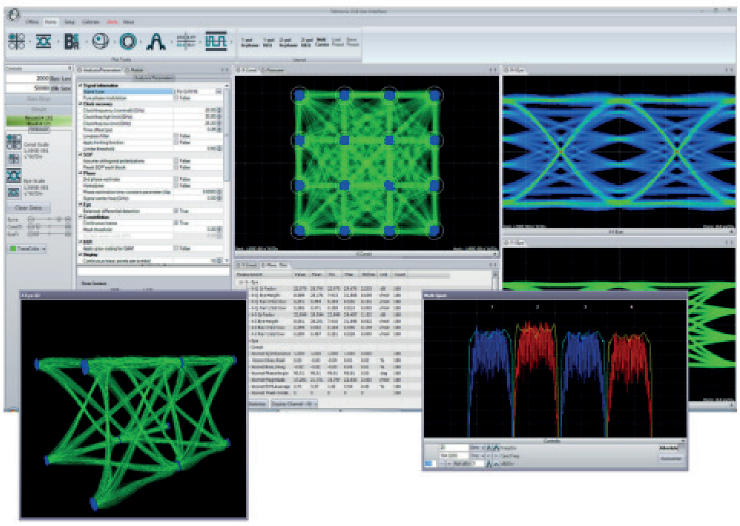
The next stage of signal processing is the Polarization Demultiplexing stage. This stage uses the known properties of the modulated signals to realign the four tributaries so that all of the Xpolarization ($LP_{01}{}^{X}$ Linear Polarized mode) information is realigned to Xi and Xq tributary signals and the Ypolarization ($LP_{01}{}^{Y}$ Linear Polarized mode) information is realigned to Yi and Yq tributary signals.

Once the X & Y polarizations have been demultiplexed, they can be treated independently. There remains both a frequency offset and phase noise on the modulated signal. The frequency offset is a result of the frequency difference between the carrier frequency of the SUT and the Local Oscillator (LO) in the coherent receiver. This frequency offset is a common property of intradyne detection and is relatively easy to detect and remove in signal processing if the frequency offset is within 10% of the baudrate.

The final stage of signal processing is the carrier phase estimation. This removes the residual phase noise that results from the laser linewidth of both the carrier and the LO.

Figure 6:

Signal processing and user interface.



SUT: Commerical Coherent Transceivers

Commercially available coherent optical transceivers use high-speed Arbitrary Waveform Generators (AWG) to generate the Xi, Xq, Yi, and Yq transmitter signals. AWGs have the advantage of being able to generate different modulation formats on the fly to cater to the demands placed on the transceiver. This enables the system to optimize the modulation formats based on variables such a reach, client traffic demands, channel noise and nonlinearities. Using an AWG also has the additional advantage of being able to pre-distort the transmit signal for the channel dispersions as well as to accurately control the signal spectrum that the resulting modulated signal creates in the frequency domain.

It is desirable to control the transmit signal's frequency spectrum content for two reasons. The first is to ensure that the channel will fit into its allocated spectrum in a Wavelength Division Multiplexed (WDM) system, therefore ensuring that the channel will not be overly impacted by optical filters and wavelength selective switches as well as adjacent channels that may be present in the system.

The second reason is to shape the signal spectrum by matching the filter on the transmitter with the filter on the receiver. By doing this, the Signal-to-Noise Ratio (SNR) of the detected signal is maximized, providing the user the best possible performance (reach, bit-error ratio, spectral efficiency) out of the OMA system.

Optical transceivers control their signal spectrum by using Nyquist filtering. Nyquist filters are a class of filters for which the impulse response is ZERO at integer multiples of the sampling location. This type of filter minimizes the interference between adjacent symbols in time, while simultaneously increasing the spectral efficiency by reducing the spectral content of the signal.

A raised-cosine filter is a common example of a Nyquist filter. Such a filter is computationally efficient to generate in DSP with Finite Impulse Response (FIR) coefficients. Figure 7 shows the spectrum of a raised-cosine filter and Figure 8 shows the corresponding impulse response. The roll-off parameter controls the width of filter; notice that all values of roll-off guarantee that the -3 dB frequency is maintained. The impulse response shows a lot of ringing that can persist for many symbols and it has the desired property of zero intersymbol interference at the center of the adjacent symbols, as is required for Nyquist type filters.

Figure 7:

Raised-cosine filter for different roll-off parameters.

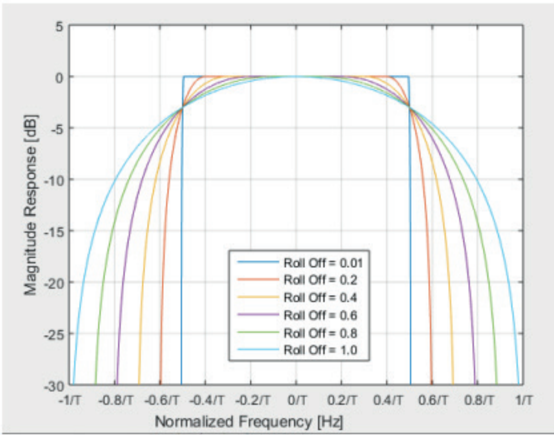
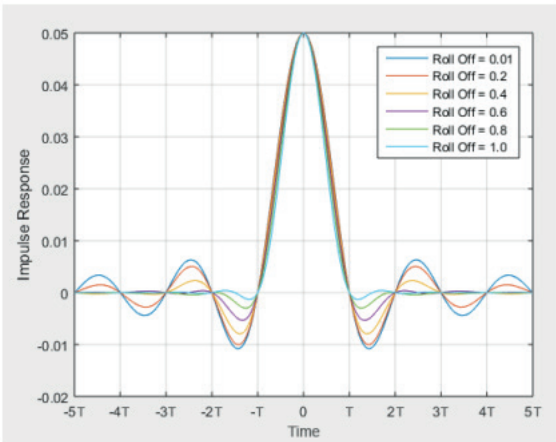


Figure 8:

Impulse response for raise-cosine filter of varying roll-off factors.



As previously mentioned, in a linear system, it is advantageous to split the raisedcosine filter between the transmitter and the receiver. The root-raised-cosine filter on the transmitter will limit the signal spectrum in the transmit channel, while the rootraised-cosine filter on the receiver will filter the out-of-band noise introduced in the channel and complete the total filter for the channel to achieve the raised cosine filter.

Real Life Examples

Up to this point we have been describing theoretically ideal models. In the next section we will explore how well these ideal models compare to real life examples.

Selecting the Signal Under Test (SUT)

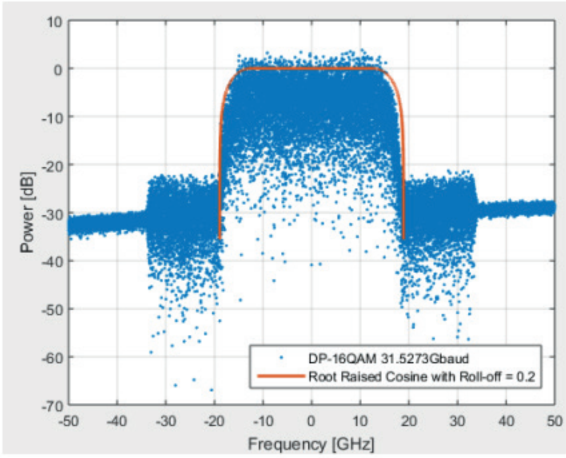
For the comparison of ideal models versus real world signals, we use a commercial coherent transceiver capable of up to 400 Gb/s. We can control the baudrate as well as the modulation format of such a transceiver. The signal has a root-raised-cosine filter on the transmitter side with a roll-off factor of 0.2.

For this example we drive the transceiver's transmitter with a baud rate of 31.5273 GBaud and the modulation formats known as Dual-Polarization QPSK, 16QAM and 64QAM for our initial exploration (QAM refers to Quadrature Amplitude Modulation).

The optical power spectrum of the SUT can been seen in Figure 9. It is a reasonable approximation of a root-raised-cosine spectrum with a roll-off factor of 0.20.

Figure 9:

Power spectrum of SUT.



OMA Configuration

Continuing this comparison of ideal model versus real-world signals we will use a four-channel real-time oscilloscope from Tektronix (model DPO77002SX) with 100 GSamples/s on each channel of the oscilloscope and a configurable brick wall filter with bandwidth up to 33 GHz.

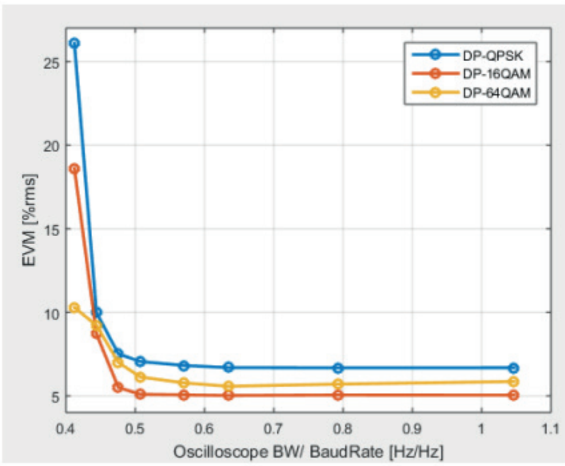
The OMA system includes a calibrated coherent receiver from Quantifi Photonics (model IQRX-1002) and the modulation analyzer software that demodulates the optical signals. The OMA was configured with the same filter as the transmitter (root-raisedcosine with roll-off of 0.2) to achieve the total channel Nyquist filter of raised-cosine.

Results

Figure 10 demonstrates that as the bandwidth of the oscilloscope was changed, the error vector magnitude of the signal was unaffected until the oscilloscope bandwidth starts to approach half the baudrate.

Figure 10:

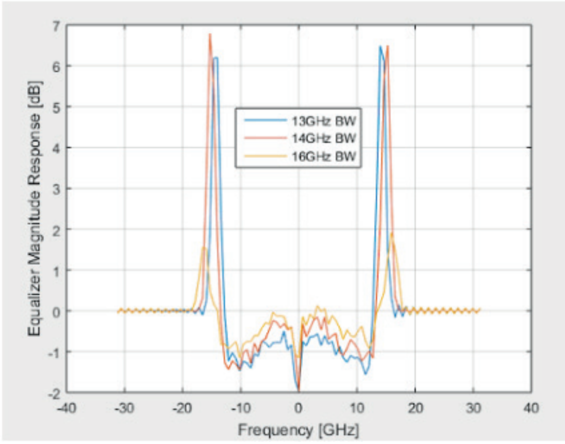
EVM versus SUT BW.



As seen in Figure 11, any further reduction in oscilloscope bandwidth forces the adaptive equalizer in the DSP to try to compensate by adding gain to the missing frequency content. Since the energy content of the original signal is quite weak in this frequency range, this introduces a significant amount of high frequency noise into the system.

Figure 11:

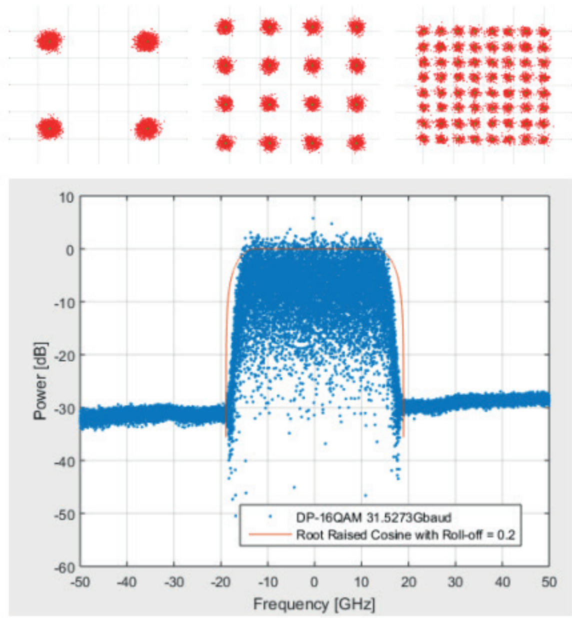
Adaptive equalizer in OMA DSP.



Scope BW Greater than 3 dB Spectrum (16 GHz)

Figure 12:

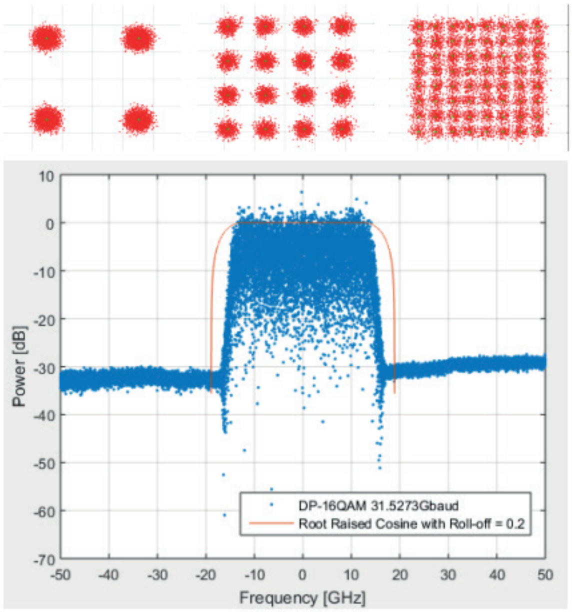
Constellation diagrams of QPSK, 16QAM, 64QAM with scope BW of 16GHz.



Scope BW at near 3 dB Spectrum (14 GHz)

Figure 13:

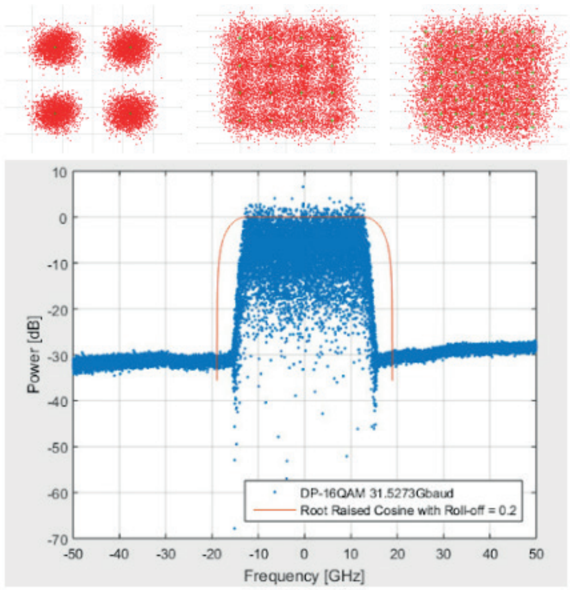
Constellation diagrams of QPSK, 16QAM, 64QAM with scope BW of 14 GHz.



Scope BW at near 3 dB Spectrum (14 GHz)

Figure 14:

Constellation diagrams of QPSK, 16QAM, 64QAM with scope BW of 14 GHz.

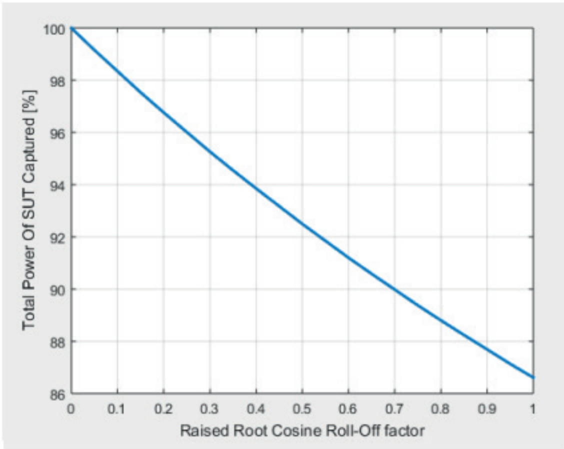


Useful Guidelines for Using OMA

It is often convenient to distil these concepts and analytics into more general principal that can guide us. For a Nyquist signal, your oscilloscope should have enough bandwidth to at least capture all of the signal spectrum up to the -3 dB point. For a root-raised-cosine signal this will ensure the user captures between 86% and 100% of the total signal power depending on the roll-off factor as shown in Figure 15.

Figure 15:

Percentage of SUT power captured.



In practice, roll-off factors of 0.3 or less are used commercially. Table 1 shows the digitizer bandwidth requirements to capture the signal spectrum down to the -3 dB point for different roll-off factors of root-raised-cosine shaped SUTs.

Table 1:

Digitizer bandwidth requirements.

Roll-off Factor	Bandwidth/Baudrate	Baudrate for 33 GHz digitizer
0.30	0.55	60 Gbaud
0.25	0.54	61.11 Gbaud
0.20	0.53	62.26 Gbaud
0.15	0.525	62.86 Gbaud
0.10	0.52	63.46 Gbaud
0.05	0.51	64.71 Gbaud

400G-ZR

Coherent transmission techniques were initially used for long-haul, high-capacity fiber transmission links (such as submarine links under the Atlantic or Pacific Oceans). As coherent transmission technology begins to mature and its cost-per-bit declines, the technology is emerging as a viable way to connect datacenters.

The use of coherent techniques to increase datacenter fiber links to 100 km is first being deployed following the standards set forth by the Optical Internetworking Forum (OIF) and the IEEE; the first standard to utilize these coherent techniques for datacenter 100 km links is known as 400GBASE-ZR, commonly referred to as "400G-ZR".

The OIF stipulates that the baudrate of the Dual-Polarization 16QAM signal is to be 59.84375 GBaud ± 20 ppm. While the 400-ZR implementation agreement from the OIF does not specify a transmitter spectrum, it does specify a minimum excess bandwidth in order "to guarantee multi-vendor clock recovery interoperability".

The optical signal spectrum must match or exceed the spectrum of a root-raisedcosine with a roll-off of 0.125 as seen in Figure 16. For a roll-off of 0.125, the electrical -3 dB spectrum will be 31.18 GHz and the -6 dB roll-off frequency of 32.45 GHz.

A digitizer with 33GHz of bandwidth (such as the Tektronix DPO77002SX), has sufficient bandwidth to capture 99.85% the signal spectrum for the 400G-ZR signal if it has the minimum excess bandwidth specified by the OIF.

Figure 16:

Excess bandwidth from OIF implementation agreement 400ZR OIF-400ZR-01.0.

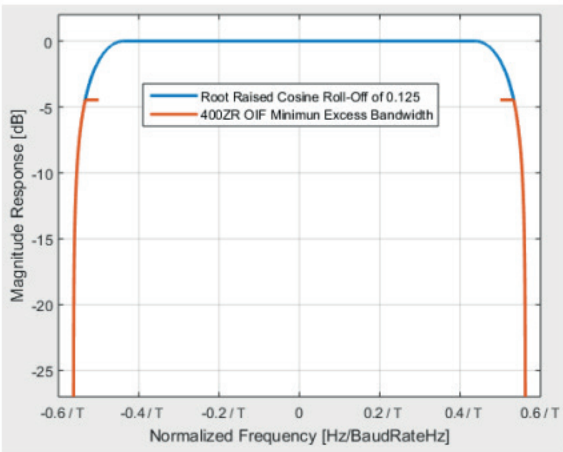


Table 1 implies that for the Tektronix DPO77002SX based OMA with 33 GHz of bandwidth, we should be able to capture and faithfully demodulate Nyquist filtered coherent signals with baud rates up to 62.26 Gbaud if the roll-off factor is 0.2.

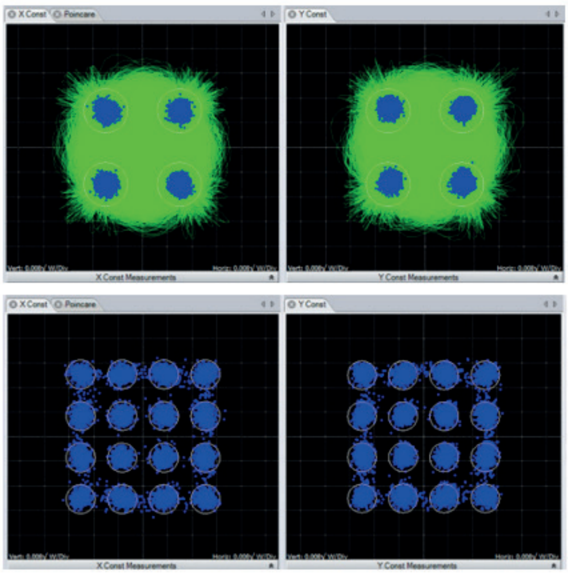
Real World Results

In this section we will see how the recommendations apply to a commercial transceiver with a baudrate of 63.05 GBaud. This rate is slightly higher than our example in table 1 our example has a sufficient margin and that it also exceeds the 400G-ZR 59.84375 Gbaud rate.

Figure 17 shows the constellations for both DP-QPSK and DP-16QAM at 63.05 Gbaud using 33 GHz of bandwidth from the Tektronix DPO77002SX oscilloscope.

Figure 17:

Excess bandwidth from OIF implementation agreement 400ZR OIF-400ZR-01.0.



Conclusion

For typical signals encountered in the manufacture and test of coherent transceivers, we have successfully demonstrated that an OMA system can have a fraction of the bandwidth with respect to the baudrate. For example, with a 33 GHz OMA system we could comfortably measure 63 Gbaud signal. This represents a total bitrate of up to 756 Gbps for Dual-Polarization 64QAM modulation formats.

One final important point to note, is that users engaged in leading edge R&D with coherent signals may have a different set of requirements; such users are very likely to need more bandwidth in order to perform cutting edge research and development of next generation devices and systems.

For more details on the OMA offering: https://www.quantifiphotonics.com/products

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Quantifi Photonics is transforming the world of photonics test and measurement. Our portfolio of optical and electrical test instruments is rapidly expanding to meet the needs of engineers and scientists around the globe. From enabling ground-breaking experiments to driving highly efficient production testing, you'll find us working with customers to solve complex problems with experience and innovation.

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