Keysight Technologies

Coherent Optical Communications Test Challenges

On the Way to Higher Data Rates

Application Note

KEYSIGHT TECHNOLOGIES

Introduction

Analysts predict anything between 20 and 50 billion internet devices by the year 2020, ranging from machine-to-machine (M2M) devices that transmit a few bytes per day to applications that stream multiple high-definition video channels. Studies into future user demands give network operators the goal of creating an infrastructure that provides the impression of limitless capacity in any situation, even in sports stadia and concert arenas where there are dense user populations demanding high-rate mobile access.

Regardless of the local connection to the device, traffic quickly flows into a fixed physical network: home ADSL router or cellular base station, for example. From that point, the network's backbone is a high capacity system based to a large part on interconnected optical fiber that is short of capacity for today's needs and that must grow to support an estimated data volume of more than 40 zettabytes per year by the year 2020.

Focus of this Application Note

This application note focuses on the test and troubleshooting needs of the next-generation fiber-based communication systems tasked with supporting this data explosion.

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New Test Scenarios for Higher Data Rates

In the optical communications world, capacity gains come essentially from three variables: more carriers through techniques such as polarization and multi-carrier OFDM modulation, better spectrum efficiency through higher modulation density and higher symbol rate (Figure 1).

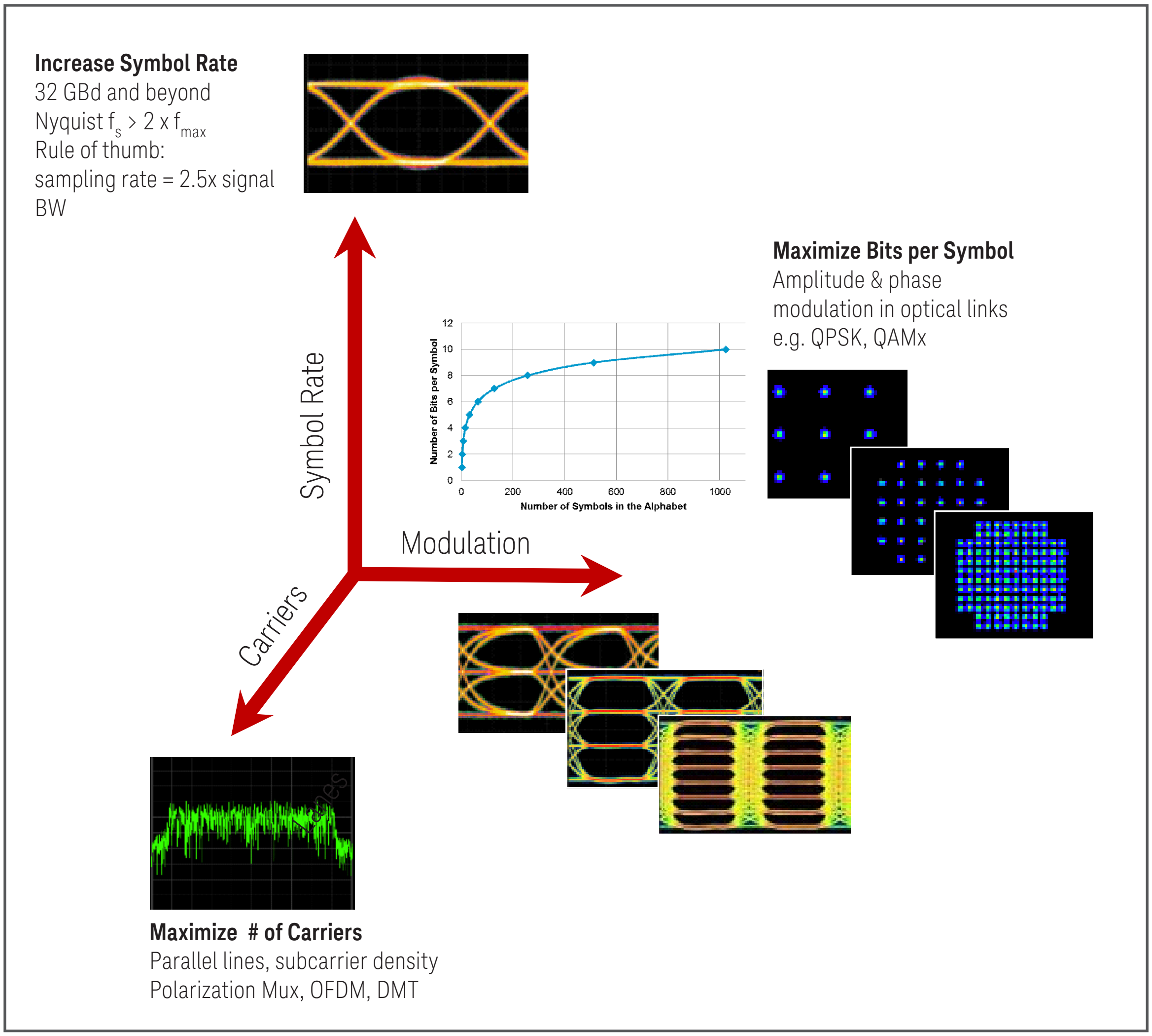


Figure 1. Factors contributing to optical system capacity.

Testing these higher order systems with data rates close to 1 Tbps requires test equipment capable of clean signal generation and analysis and a measurement bandwidth of at least 20 GHz, to be sure the measurements represent system performance, not the limitations of the test equipment. The instruments must offer the flexibility to address many different modulation schemes on 4 synchronized channels for a dual-polarization I/Q signal. Traditionally, receiver tests such as phase noise, observed signal-to-noise ratio and polarization tests have been performed using a "gold" transmitter, giving a view of the device but lacking completely deterministic knowledge (Figure 2).

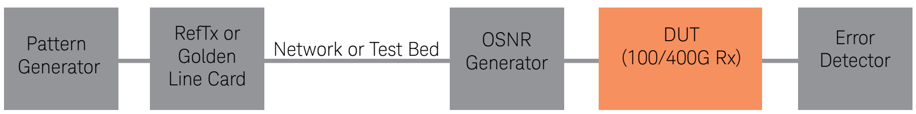


Figure 2. Traditional optical receiver test setup.

Using an arbitrary waveform generator (AWG) such as the Keysight M8196A allows the creation of test signals in the electrical domain, including both clean signals and signals with specific, known, impairments. For transmitter test, these can be fed directly to a transmitter and the resultant error rate can be measured directly. For receiver test, they can be used directly to test DSP stages and be translated to the optical domain to create both clean and stressed deterministic optical signals for full receiver test (Figure 3).

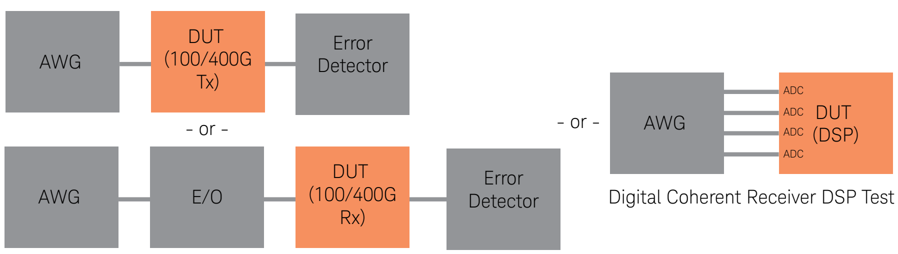


Figure 3. Optical transmitter and receiver test scenarios using an arbitrary waveform generator.

The key challenges in making measurements on coherent optical systems lie in providing known, repeatable clean and distorted test signals at data rates in excess of 32 GBaud and with the flexibility to support diverse modulation formats. Test system calibration should be possible, not only at the front panel of the test signal generator and measurement equipment, but at any point in the signal chain through embedding and de-embedding techniques using the transmission system's S-parameters.
Figure 4 shows an example of measurements across an entire communications channel, showing the ability to measure cumulative effects using the Keysight N4391A or N4392A optical modulation analyzers.

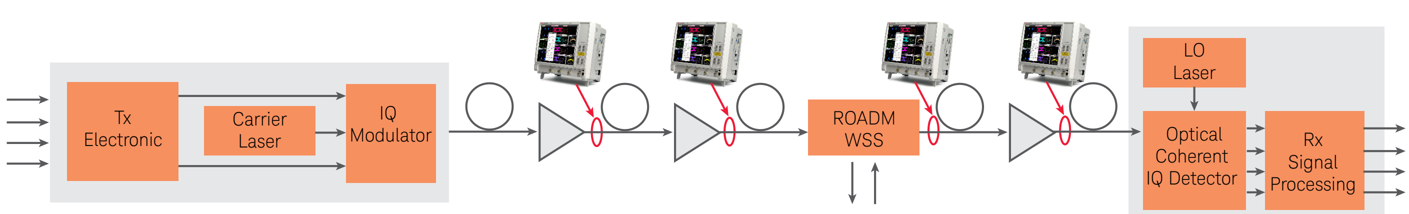


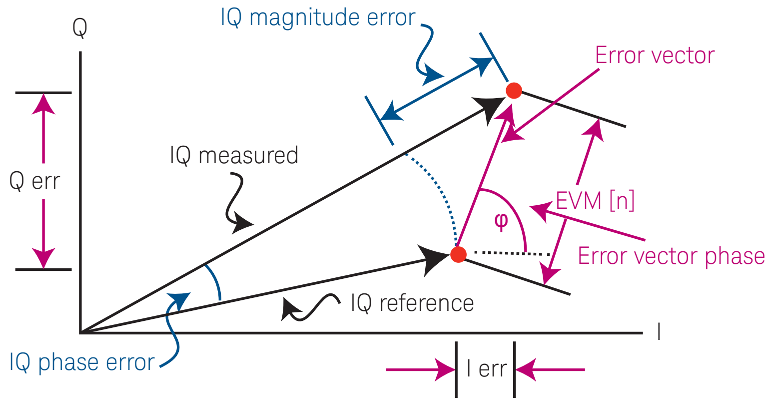
Figure 4. Cumulative optical modulation analysis using a Keysight N4391A or N4392A optical modulation analyzer.

Measuring Transmission Quality

The goal of every data transmission is to achieve highest possible transmission rates at a tolerable bit-error ratio (BER). Since BER measurements can be time-consuming there are other, faster signal quality metrics which closely correlate with the BER of a channel.

A general quality metric which is well-defined for higher-level modulation formats is the error vector magnitude (EVM) which describes in short how close the actual symbol points are to their reference points on the complex plane.

EVM is the magnitude of the vector connecting the measured and the expected vectors at any modulation point (Figure 5).



$$EVM(n) = \sqrt{Ierr(n)^2 + Qerr(n)^2}$$

$$\%EVM = \frac{\frac{1}{N}\sum_{K=0}^{N-1}\sqrt{Ierr(n)^2 - Qerr(n)^2}}{|\text{peak reference vector}|}$$ N is the number of EVM points

Figure 5. Error vector magnitude definition.

EVM provides an overall figure of merit, and it is self-evident that higher-order modulation requires better fidelity since constellation points are closer together and therefore decoding errors are more likely.

The Q-factor describes the signal-to-noise ratio (SNR) ratio at decision points. It can be calculated from the EVM and also provides an estimate for the BER. It is used for on-off-keying signals and modulation formats up to QPSK. The Q-factor is the BER a receiver would expect assuming that white Gaussian noise is the dominant impairment. The result is displayed in dB and is calculated as follows:

$$Q - factor \approx 1 / EVM$$

Calibrating The Test Signals

Using waveform creation software like the 81195A optical modulation generator with the AWG to create, and VSA software to analyze test signals ensures that both clean signals and ones with known impairments designed to stress-test the receiver can be generated. Figure 6 shows an example of a setup to measure the signals at the output of the AWG.

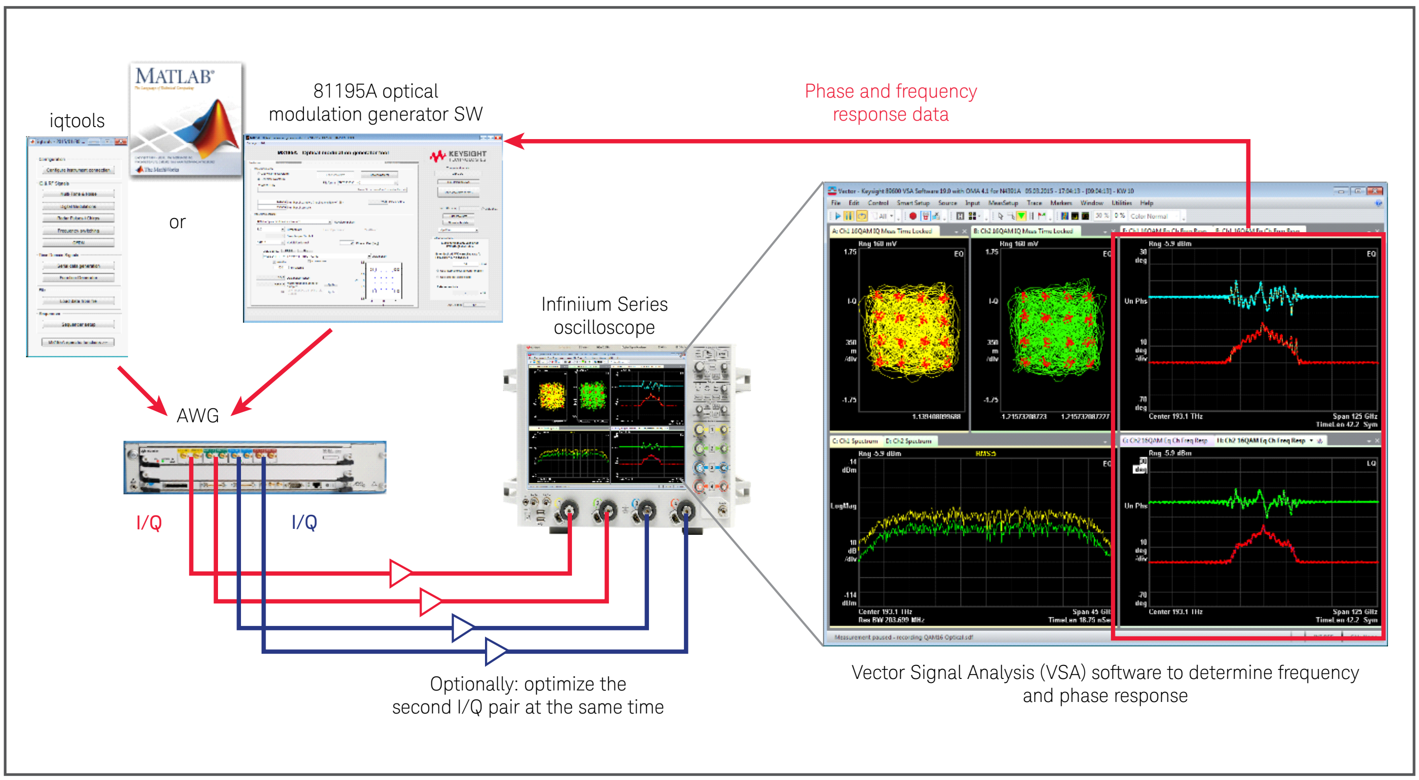


Figure 6. Calibration at the front panel.

A known signal is generated with the arbitrary waveform generator and compared with the measured version of the signal. This way the frequency and phase response of the generator, amplifiers (if needed) and cables can be derived. Figure 7 shows a system calibrated at the receiver input by measuring the transmission channel's S-parameters and embedding the results to create a clean, calibrated signal.

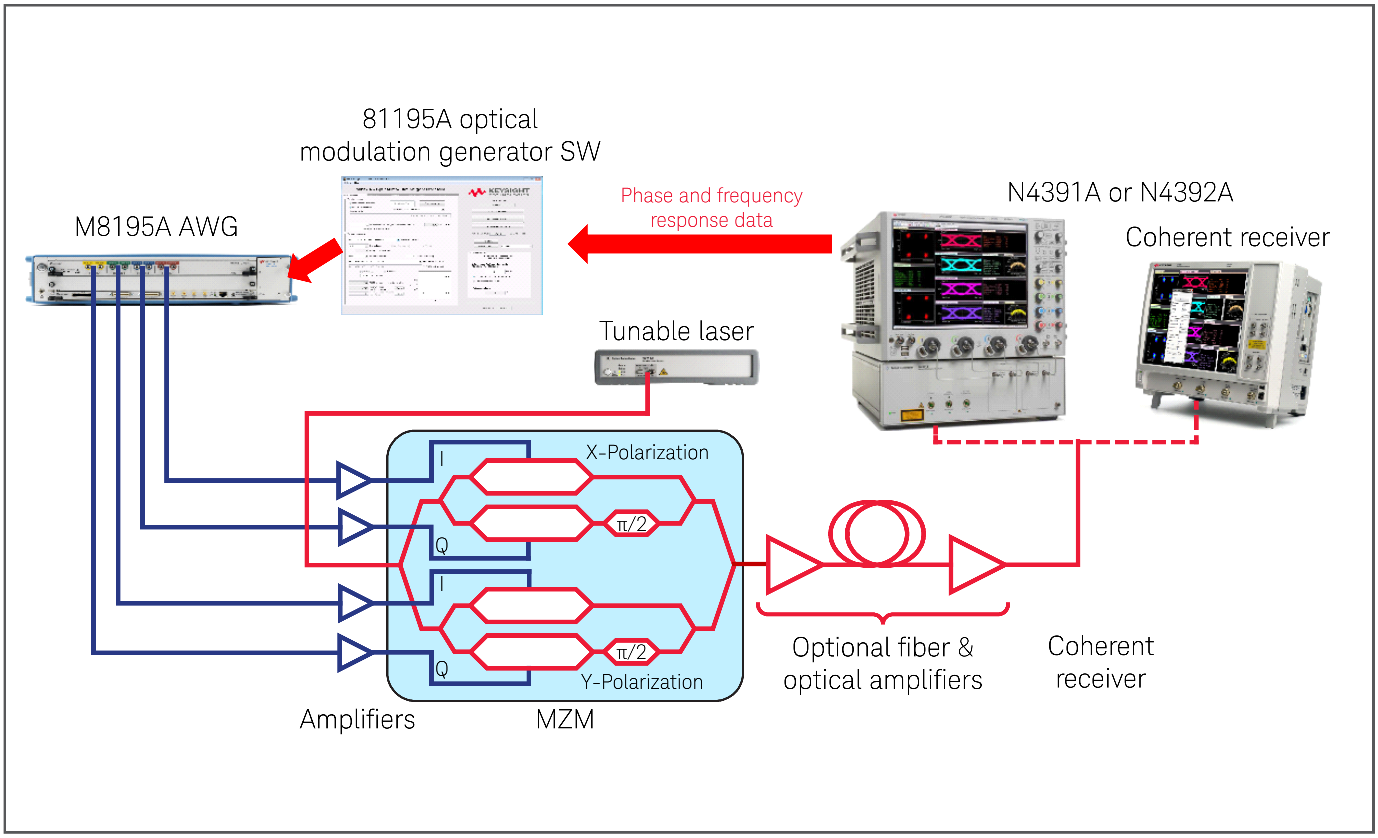
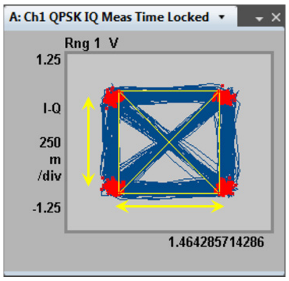


Figure 7. Calibration at the receiver input.

Identifying Typical Transmission Problems

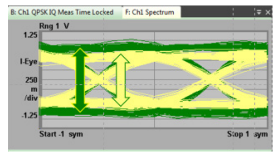
Closer analysis of the constellation and eye diagrams provide an excellent mechanism for finding and correcting poor EVM results. Examples of typical problems are shown below.

IQ gain imbalance

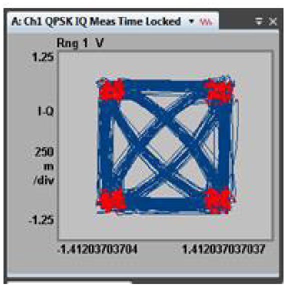


Gain Imbalance compares the amplitude of the I signal with the amplitude of the Q signal. Note the constellation width is different from its height (compare to the square yellow reference).

IQ gain imbalance is best observed in the constellation diagram, though it will also show in eye diagrams as a difference between the amplitudes in I- and Q-Eye.

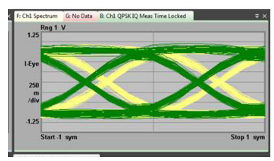


IQ skew

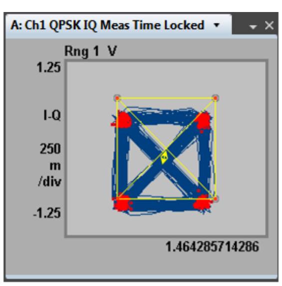


In the constellation diagram, IQ skew shows as a deviation from the expected straight line between 45 degree transition points.

The eye diagram shows a timing difference between the I- and Q-eye, which is more readily interpreted.

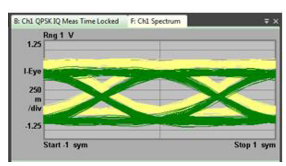


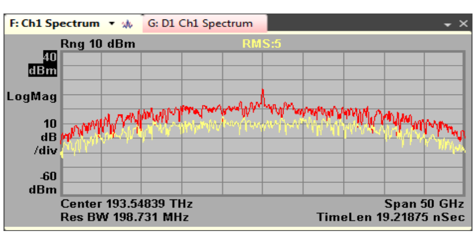
IQ offset



DC offsets at the I- or the Q-signals cause a shift between the origin of the measured constellation with respect to the origin of the reference constellation shown in yellow.

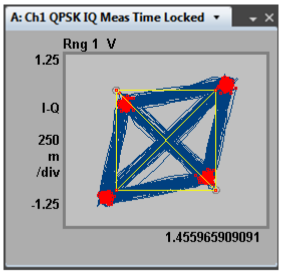
In the eye diagram, it shows as vertically shifted eye-diagram traces.





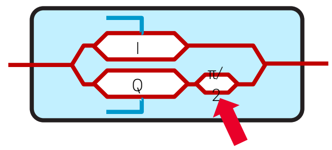
This also shows as carrier feedthrough in a spectrum display.

Quadrature error

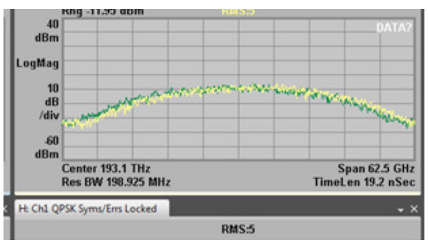


Ideally, I and Q should be orthogonal (90 degrees apart). Quadrature error is the difference between the ideal and actual I and Q quadrature phase. In the screenshot a quadrature error of 22 degrees means I and Q are 67 degrees apart instead of 90 degrees.

This normally results from an incorrect setting for the 90° phase shifter in the Mach-Zehnder modulator. It is a distortion that is not readily observed in the eye diagram.



Frequency error



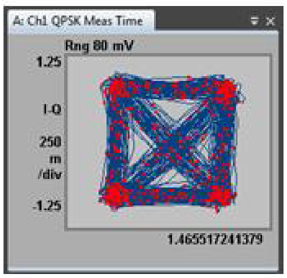
Frequency error shows the carrier's frequency relative to the expected center frequency displayed in Hertz. It is the amount of frequency shift that the receiver must perform to achieve carrier lock. The maximum allowable frequency error depends on the modulation format used, as shown in Table 1.

Table 1. Allowable frequency error by modulation type.

Modulation format	Maximum frequency offset
QPSK	9.6% symbol rate
16-QAM	4.8% symbol rate
32-QAM	3.15% symbol rate
64-QAM	4.65% symbol rate
128-QAM	0.3% symbol rate
256-QAM	0.3% symbol rate
512-QAM	0.15% symbol rate
1024-QAM	0.15% symbol rate
2048-QAM	0.1% symbol rate*
4096-QAM	0.1% symbol rate*

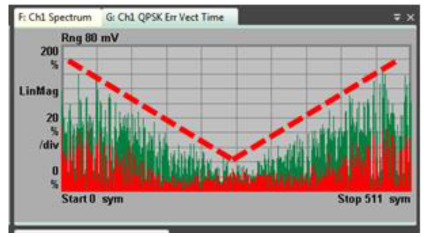
* For the highest order modulation types it is recommended to use the low-SNR (signal-to-noise ratio) enhancement in VSA to make frequency locking robust for these QAM formats.

Symbol rate error

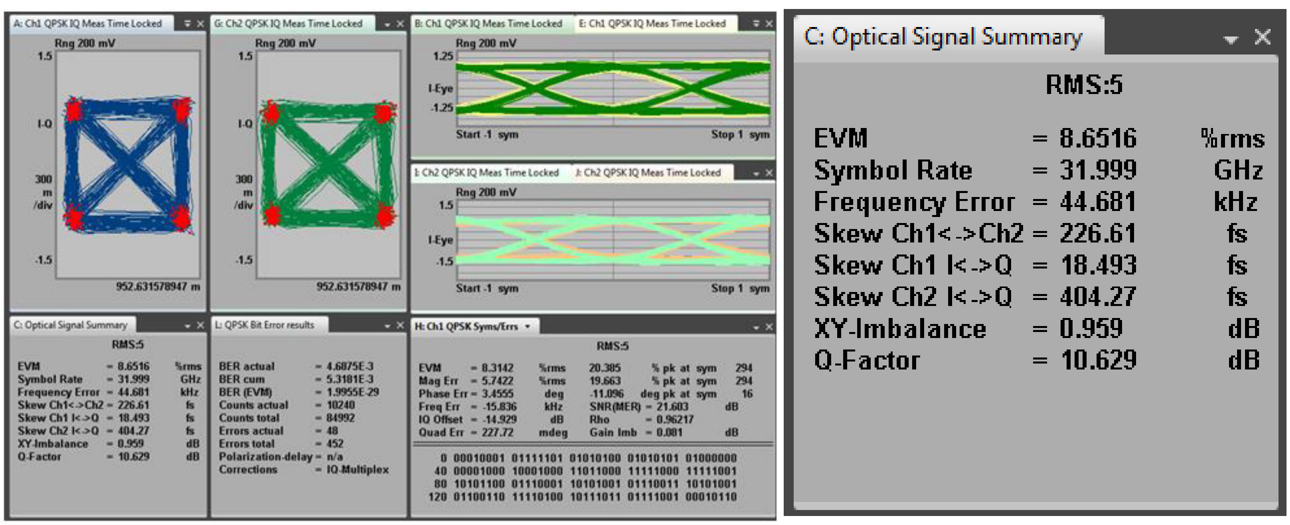


If the digital demodulator is only able to recover the clock phase but not the clock rate, symbols start to spread all over the constellation, as shown in the figure.

A wrong symbol rate shows up as typical V shape when looking at the EVM-versus-time plot.



It is relatively easy to interpret impairments shown in the constellation diagrams above for single-mode fiber transmission. When a second channel polarized at 90 degrees is added, the task becomes more difficult. The Keysight N4391A optical modulation analyzer (OMA) which incorporates all the features of the vector signal analysis software allows comprehensive analysis of both channels and the interaction between them.



This screenshot shows the timing skew between I- and Q-signals for X- and Y-polarization, the timing skew between X- and Y-polarization, the gain imbalance between X and Y polarization, the symbol rate, frequency error and bit error rate statistics.

Products

This is an overview of the products used in making the measurements described in this Note.

M8196A 92GSa/s Arbtrary Waveform Generator

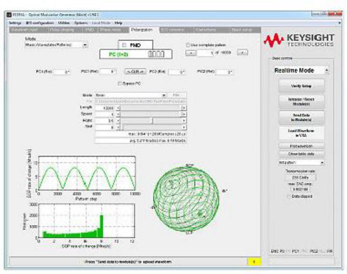
The M8196A arbitrary waveform generator has the highest combination of speed, bandwidth and channel density, with a 92 GSa/s sample rate to support signals up to 64 GBaud on 4 channels in a 1-slot AXIe module - simultaneously.

For 200 G, 400 G and 1 Terabit optical communications applications test, its 4 synchronized channels allow deterministic emulation and pre-distortion of 2 independent I/Q baseband signals.

Key performance features

– Sample rate up to 92 GSa/s, 8-bit vertical resolution
– 32 GHz analog bandwidth
– Amplitude up to 1 Vpp(se) (2 Vpp(diff.)), voltage window -1.0 to +2.5 V
– Supporting signals up to 64 GBaud and beyond
– 512 kSa of waveform memory per channel
– Ultra-low intrinsic jitter
– Transition times < 9 ps (20% to 80%), with frequency response compensation

81195A Optical Modulation Generator Software



The Optical Modulation Generator software 81195A introduces a new approach to optical test. Combined with the M8195A AWG it speeds up test by a factor of up to 100 with its unique real-time mode.

The 81195A generates dual-I/Q signals for polarization-multiplexed coherent signal transmission test with defined signal parameters and optical signal properties.

In conjunction with the M8195A 4-channel AWG it generates transmission signals with up to 32 GBaud and up to 8 GSym per channel using a single M8195A option RSP module in real-time encoding mode.

Option OSP allows the deterministic emulatioin of optical signal properties and receiver stress conditions (including phase noise, polarization rotation and polarization mode dispersion) on the M8195A or the M8196A AWG.

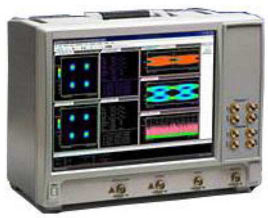
– Generate dual I/Q signals (from BPSK to 256-QAM) with flexible signal parameters (e.g. pulse shape, delay) from up to 8 GSym per I/Q pair
– Option RSP (real-time signal processing): In conjunction with the M8196A, change the signal parameters (e.g. pulse shape, delay) on the fly at runtime, without the need to download a new waveform
– Option OSP: In conjunction with the M8195A or the M8196A, synthesize optical signal properties, including phase noise (laser line width), polarization rotation, and static polarization mode dispersion (PMD)

N4391A Optical Modulation Analyzer

The N4391A is a high-end turn-key optical modulation analyzer for advanced research in single- and multi-carrier 400 Gbit/s and 1Tbit/s complex modulated transmission systems. It is based on the latest Z-Series Keysight oscilloscopes, a 40 GHz dual polarization coherent receiver and optical modulation vector signal analysis software offering most flexible analysis tools and smart setup for easiest instrument setup.

– Fully integrated Vector Signal Analysis software with smart setup
– User-configurable APSK and OFDM demodulator
– Modulation-format transparent polarization alignment
– Optical characterization results for each polarization plane separately
– Optical summary results for complete signal
– BER and Q factor separated for each polarization plane and overall signal
– Internally select internal or external local oscillator laser for best long-term test results
– Easy integration of user DSP algorithms

Products *(continued)*

N4392A Integrated Optical Modulation Analyzer		Key performance features
	The new Keysight N4392A is an ultra-compact, portable, fully-integrated optical modulation analyzer with a 15'' laptop-size screen. It is optimized for daily R&D work and designed for the most affordable performance verification in manufacturing and component test for 40/100G components, modules and systems. It is the first optical modulation analyzer that provides built-in performance verification and recalibration, extending the factory recalibration cycles significantly.	– Symbol rate 32 Gbaud – Sampling rate 63 GSa/s – Receiver bandwidth 23 GHz – Wavelength range 1527.6 to 1565.5 nm – Integrated coherent receiver (ICR) test option

Related Literature

Publication title	Publication no.
N4391A Optical Modulation Analyzer Data Sheet	5990-3509EN
N4392A Integrated Optical Modulation Analyzer Data Sheet	5990-9863EN
Infiniium Z-Series Oscilloscopes Data Sheet	5991-3868EN
M8196A 92 GSa/s Arbitrary Waveform Generator Data Sheet	5992-0971EN
Generating Clean Modulated Signals Using the M8195A 65 GSa/s AWG Application Note	5992-0134EN
Characterizing High-Speed Coherent Optical Transmission Systems Application Note	5992-0022EN
Essentials of Coherent Optical Data Transmission Application Note	5991-1809EN
Quality Measures for Complex Modulated Signals Reaching for Standardization Appliation Note	5991-1619EN
Metrology of Advanced Optical Modulation Formats White Paper	5990-3748EN

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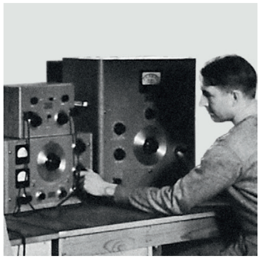

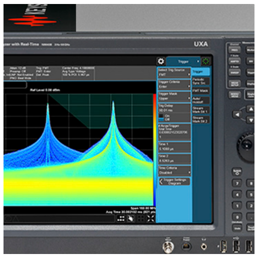

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Published in USA, August 31, 2017
5992-2481EN
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