Test Metrics and Test Methods for Coherent Optical Communication Transmitters

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Keysight Technologies

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Increasing communication efficiency

Original Binary data stream	0 0	1 0	1 1	1 0	0 1	0 1	0 0	1 0	1 1	1 1	0 0	1 0
Possible symbol alphabet for coding at 2 bits per symbol	A	B	D	B	C	C	A	B	D	D	A	B

This data stream can be coded into a 4 symbol alphabet

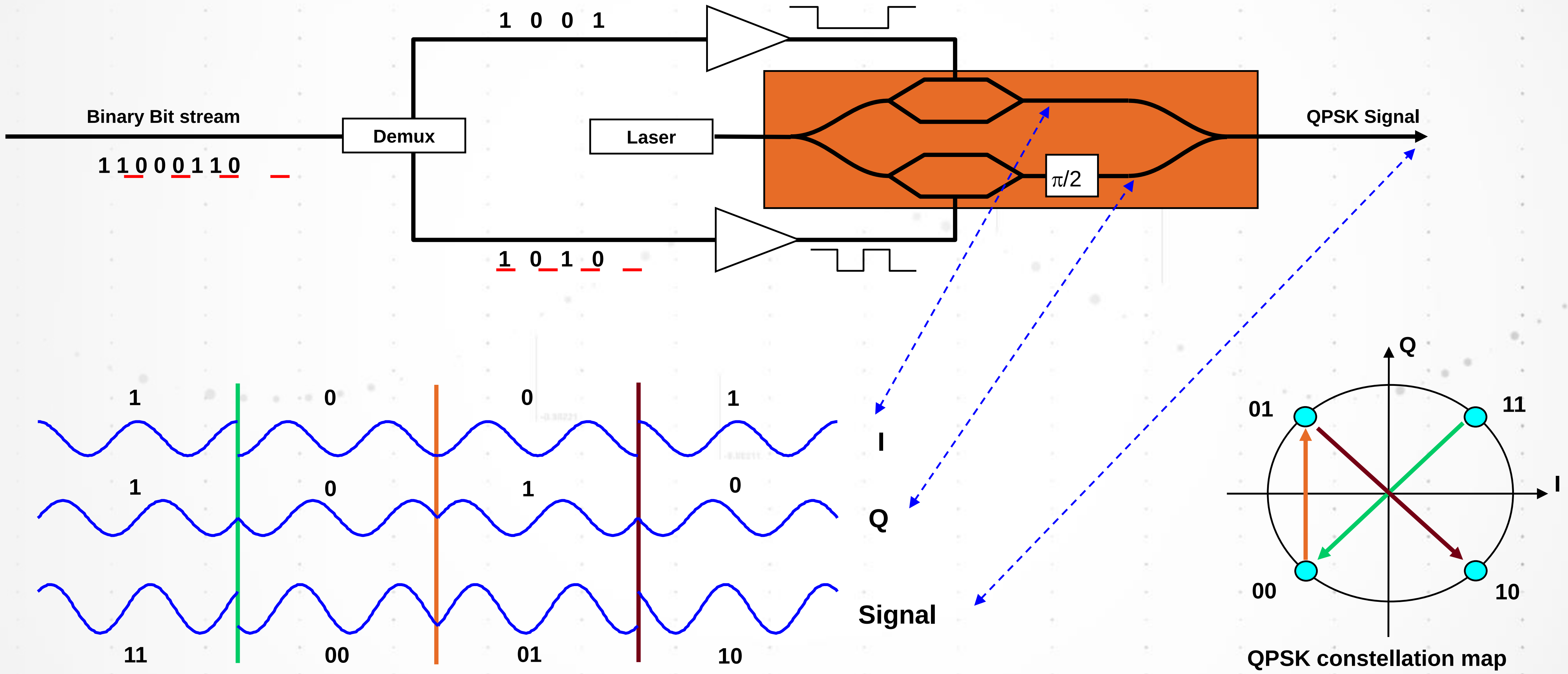
Each symbol contains two bits of information (similar to PAM4)

But rather than use four discrete amplitudes, coherent system encode information in the phase of the carrier

00 → $a \sin(\omega t + \pi/4)$
01 → $a \sin(\omega t + 3\pi/4)$
10 → $a \sin(\omega t + 5\pi/4)$
11 → $a \sin(\omega t + 7\pi/4)$

Coding increases the transmission capacity without increasing the symbol rate

The optical IQ modulator creates unique phase states for the optical carrier



Binary Bit stream

1 1 0 0 0 1 1 0

Demux

Laser

1 0 0 1

1 0 1 0

$\pi/2$

QPSK Signal

1 0 0 1

I

1 0 1 0

Q

11 00 01 10

Signal

Q

I

01

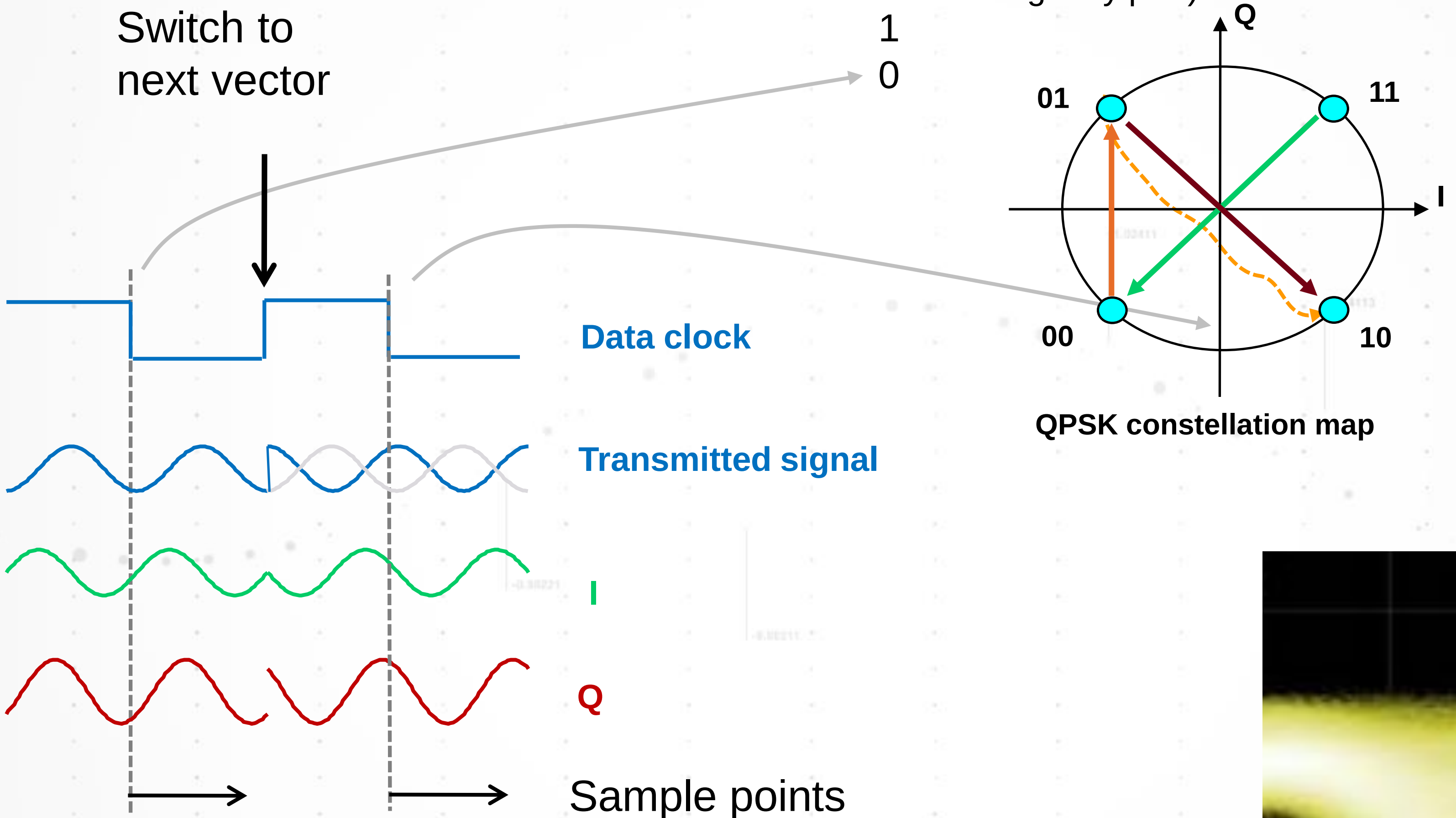
11

00

10

QPSK constellation map

Transmitting vectors that code symbols (not bits)



Switch to
next vector

1
0

Q (quadrature,
imaginary part)

Q

I

01

11

00

10

I (in-phase or real part)

Data clock

Transmitted signal

I

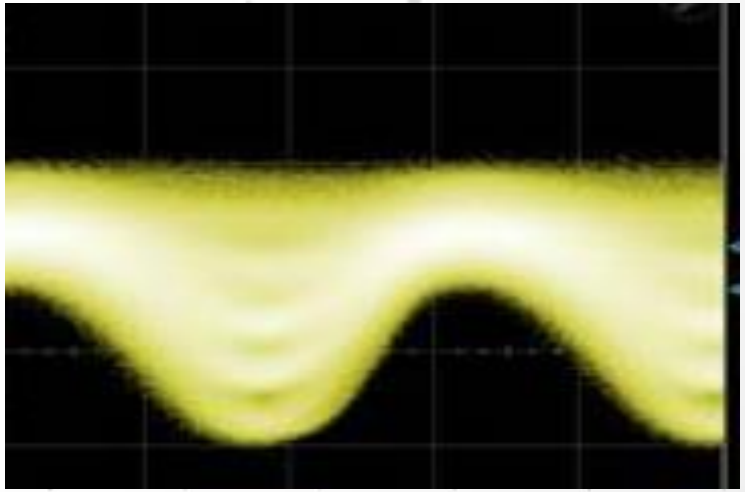
Q

Sample points

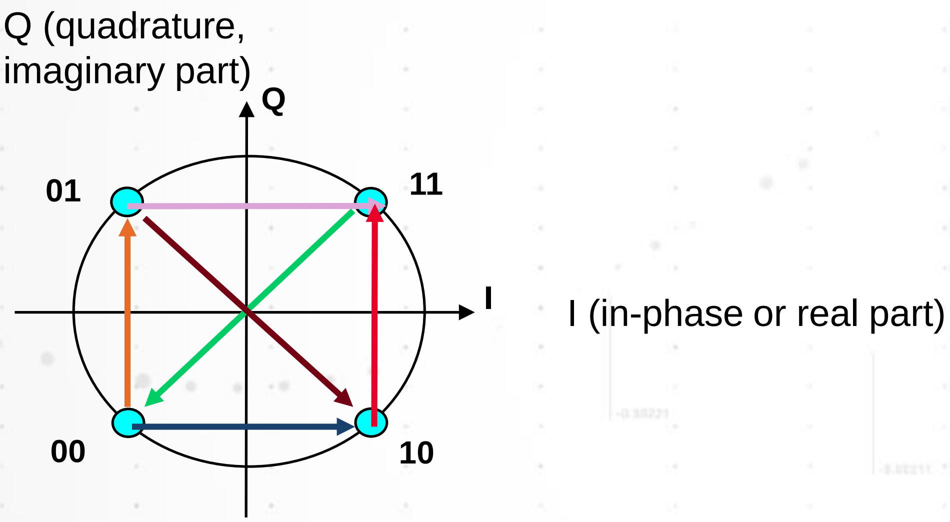
QPSK constellation map

- - - - - - -
Transition between
sampling points

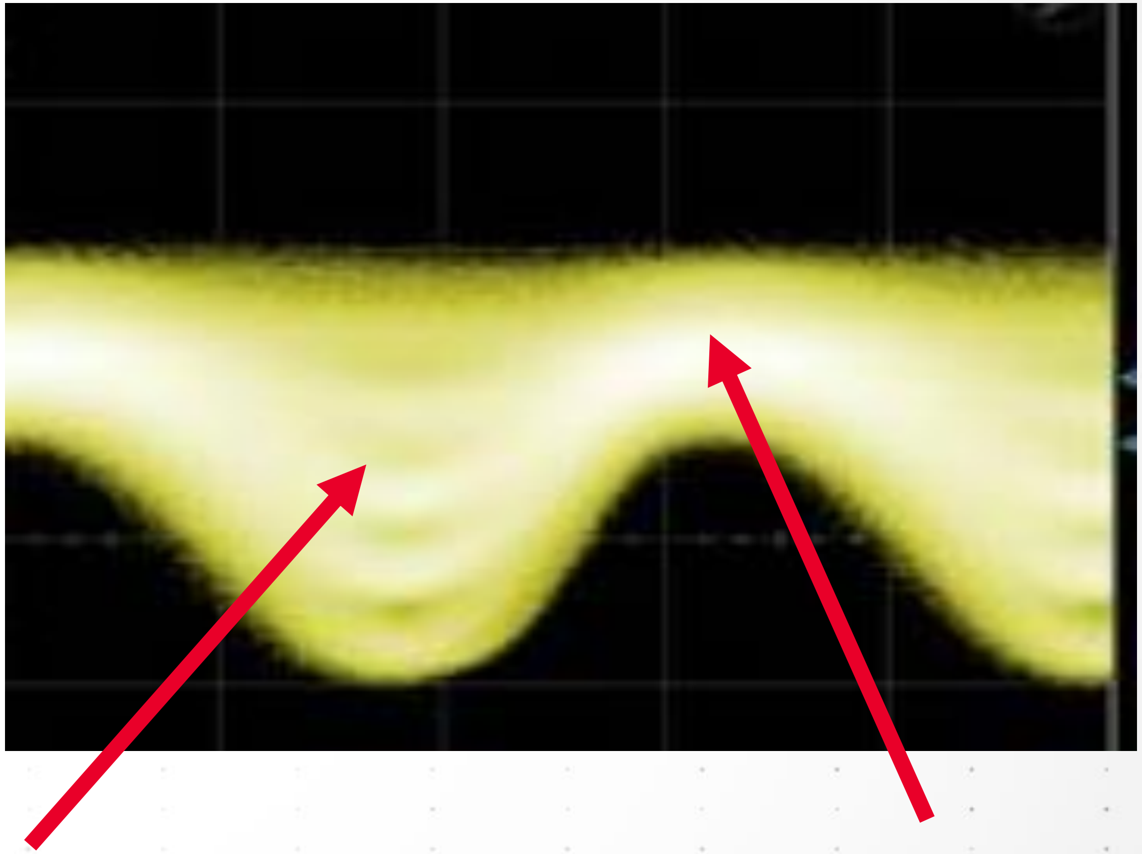
Vectors defined by amplitude and phase are transmitted with a clock that is at the symbol rate. Both phase and amplitude change when transitioning from one vector state to another



Analyzing the phase modulated signal with conventional direct detection oscilloscopes



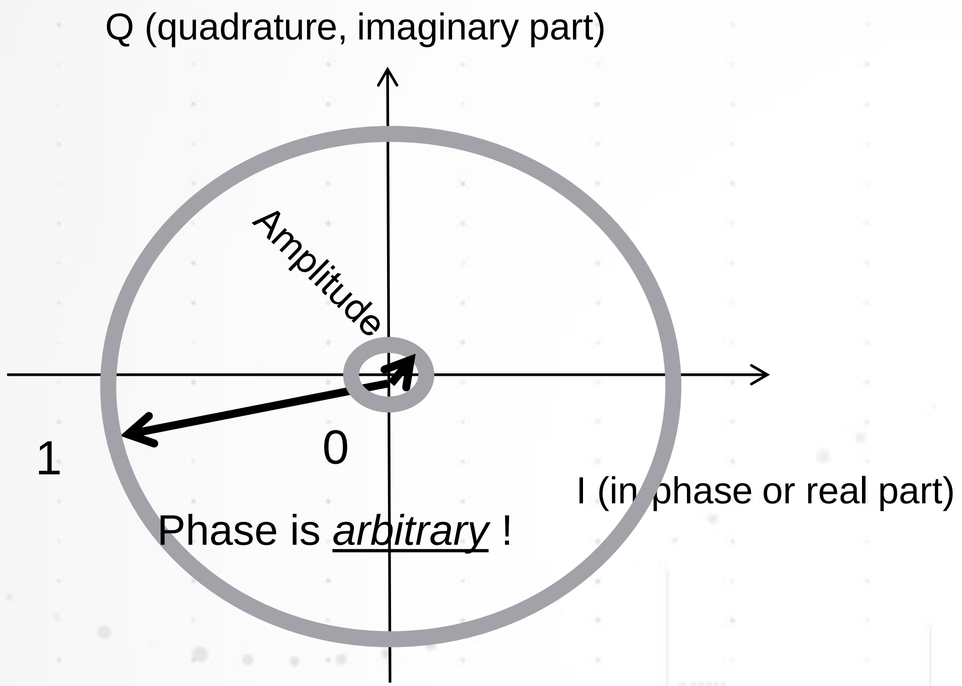
QPSK constellation map



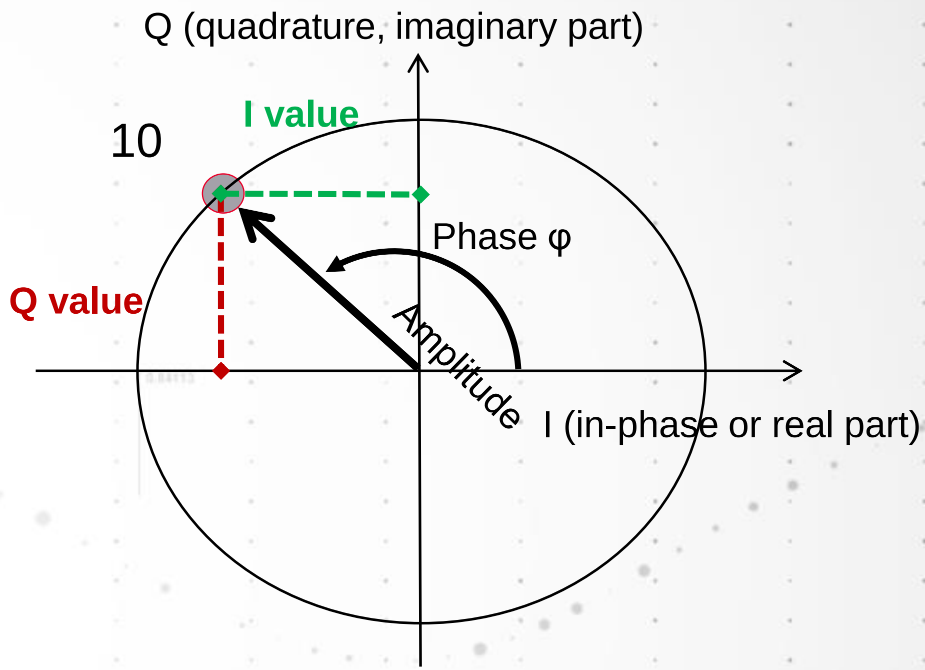
This is the region of transition between symbols

This is the region where the symbol/vector state should be stable and where communications quality is assessed

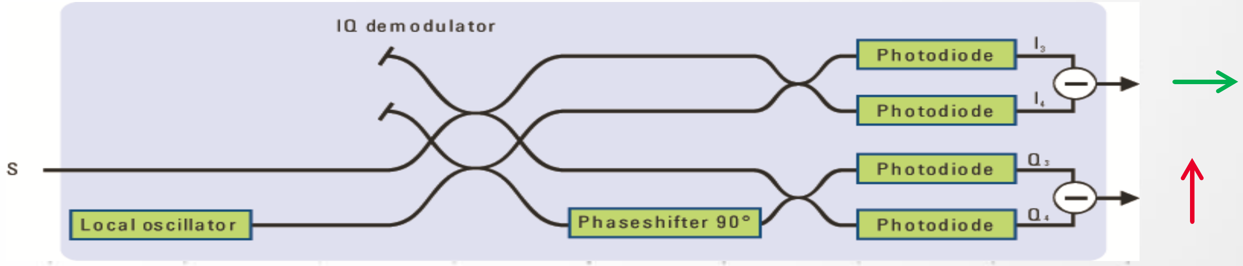
Digital ON-OFF modulation vs. vector modulation



1) Amplitude is relevant

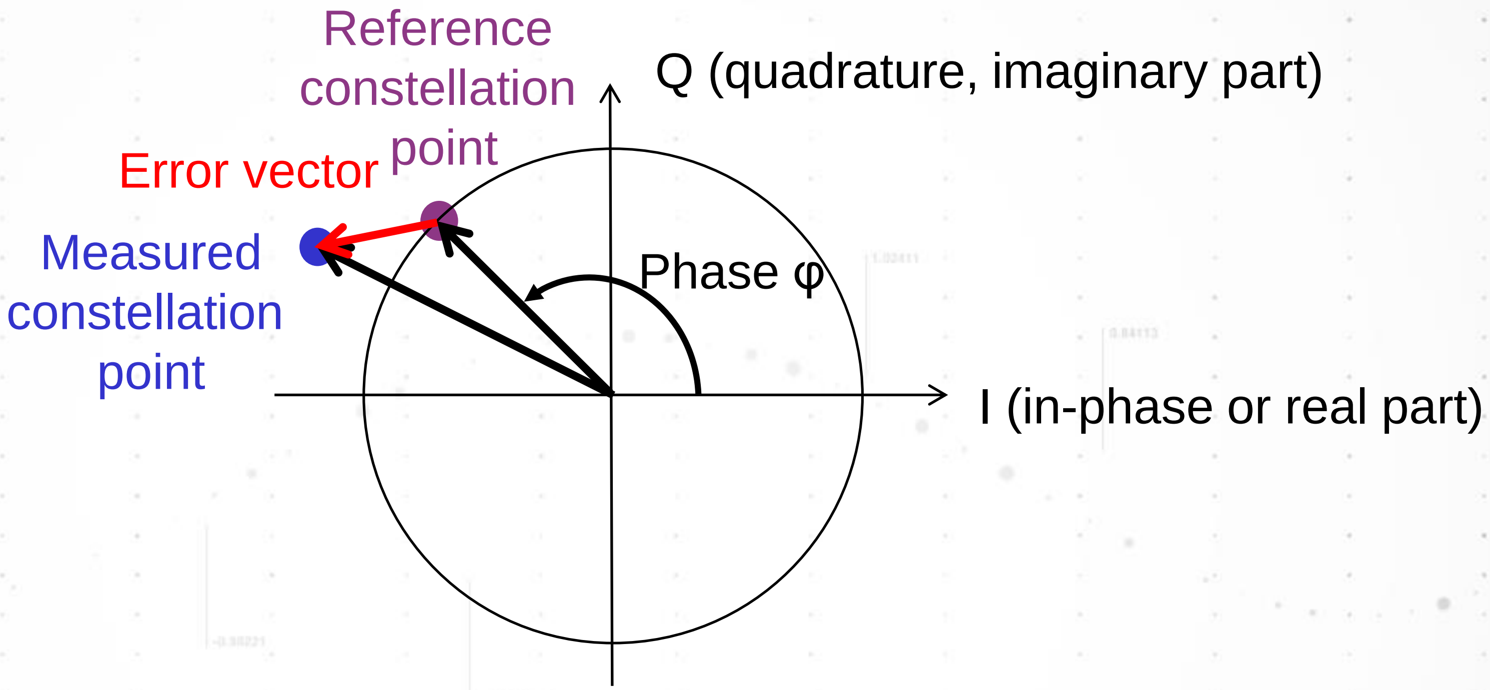


1) Amplitude is relevant
2) Phase is relevant and might be relative to the preceding symbol



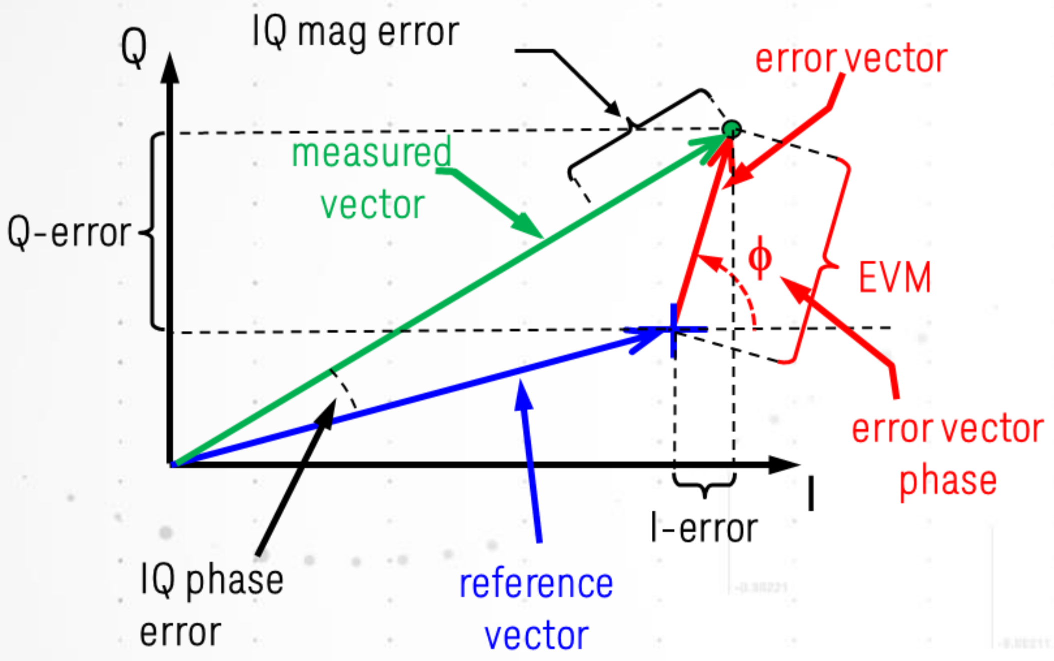
S =Signal
R=Reference for phase detection

Quality metrics for phase modulated data signals



The **Error Vector** connects the measured vector and the reference vector! An **Error Vector = 0** means we have an **ideal signal**!

Quality measure for complexly modulated data signals



$$EVM(n) = \sqrt{I_{err}(n)^2 + Q_{err}(n)^2}$$

where $n =$ symbol index

$$I_{err} = I_{meas} - I_{ref}$$

$$Q_{err} = Q_{meas} - Q_{ref}$$

$$EVM_{rms} = \frac{\sqrt{\frac{1}{N}\sum_{n=1}^{N} EVM(n)^2}}{|peak\ ref.vector|}$$

where N is the number of EVM points

Key issue: Gauging the impact of EVM on Symbol Error Ratio to create a metric that can be used as part of a link budget

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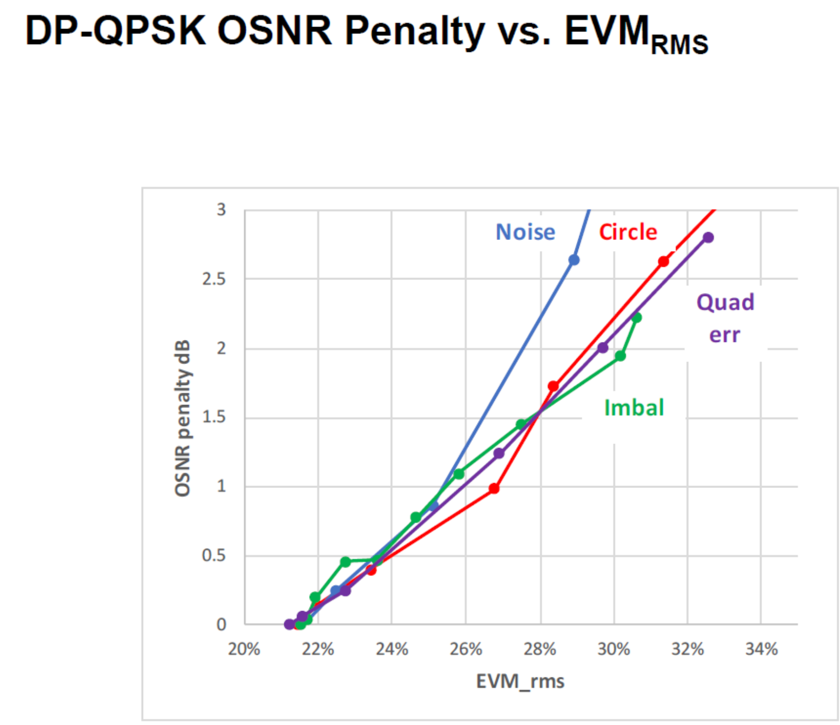
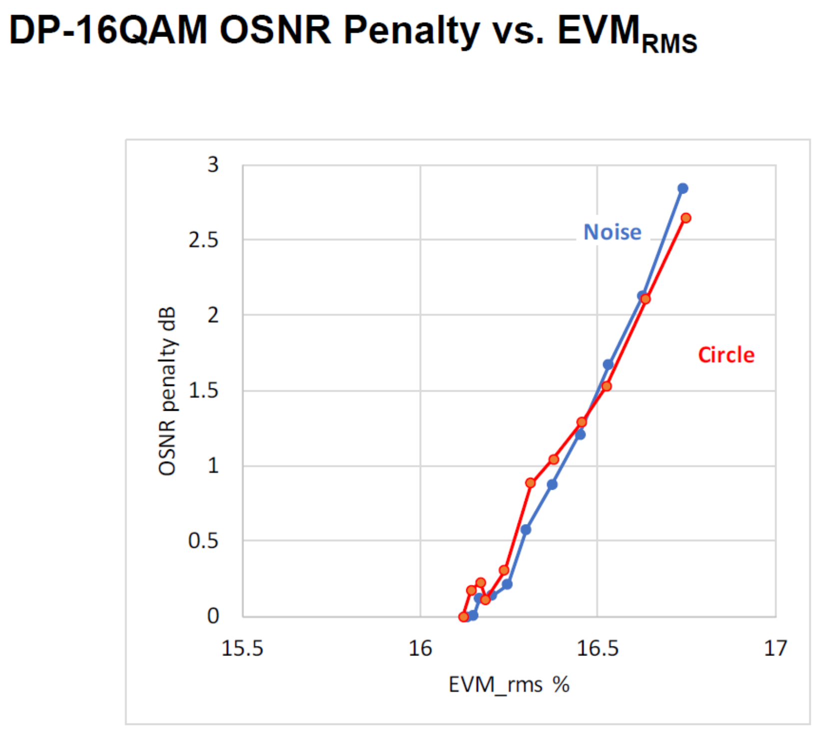
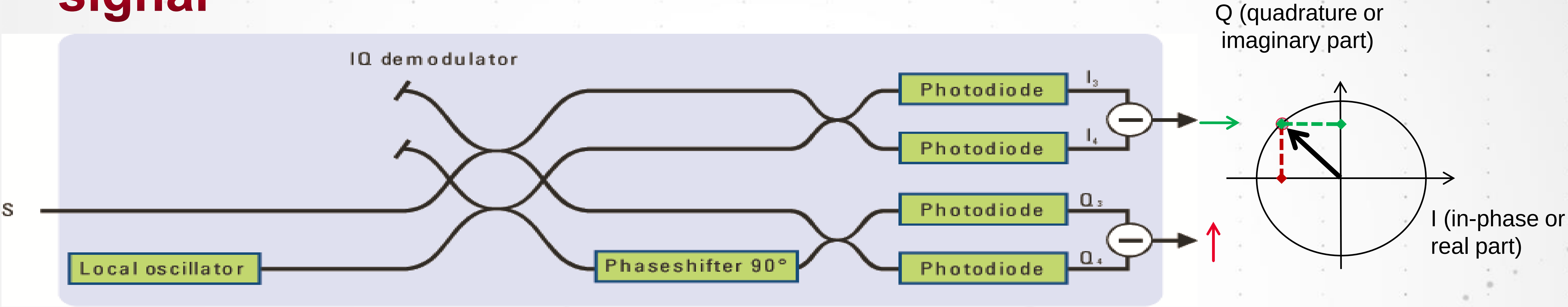
Going from EVM to the link budget

- See Pete Anslow ad hoc contribution: http://grouper.ieee.org/groups/802/3/cn/public/adhoc/18_1025/anslow_3cn_01_181025.pdf
- What is the effective power penalty of EVM?





Method to determine EVM: Generate I and Q from the test signal

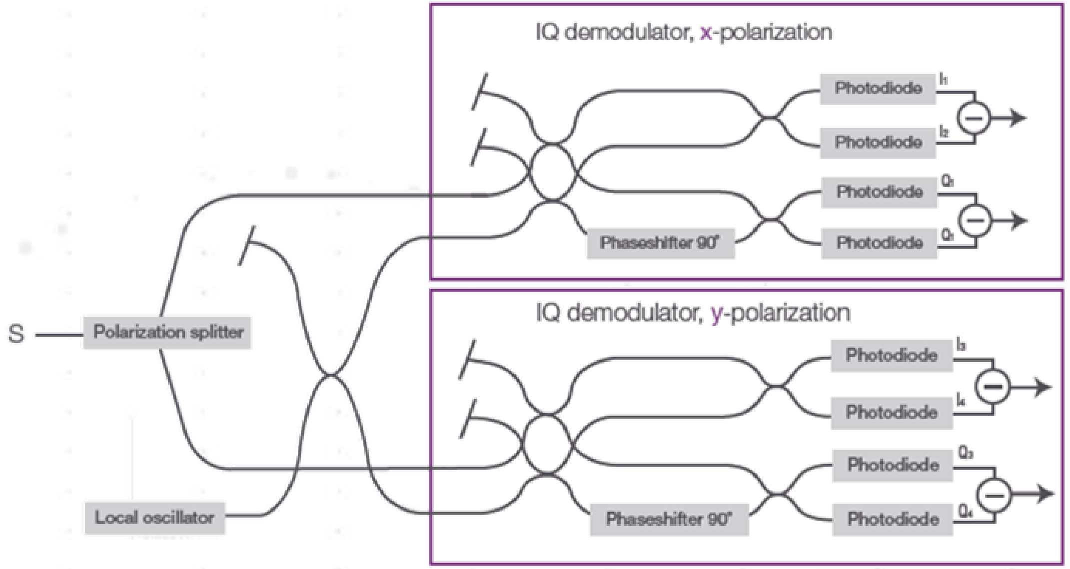


- A local oscillator (similar frequency as the carrier signal) is split with one leg shifted 90 degrees
- The test signal ‘S’ is split
- One leg of the test signal is combined with the LO, the other with the phase shifted LO
- Each signal is sent to a balanced photodetector, producing I and Q, combined to yield magnitude and phase

The coherent receiver

ADDING POLARIZATION DIVERSITY

- Orthogonal polarization states are typically independently modulated
- Polarization diversity built into the receiver
- One IQ demodulator per input polarization state



$$I_1 - I_2 \sim 4 \cdot A_S^h \cdot A_R \cdot \cos(\Delta\phi - \Delta\omega \cdot t)$$

$$Q_1 - Q_2 \sim 4 \cdot A_S^h \cdot A_R \cdot \sin(\Delta\phi - \Delta\omega \cdot t)$$

$$I_3 - I_4 \sim 4 \cdot A_S^v \cdot A_R \cdot \cos(\Delta\phi - \Delta\omega \cdot t)$$

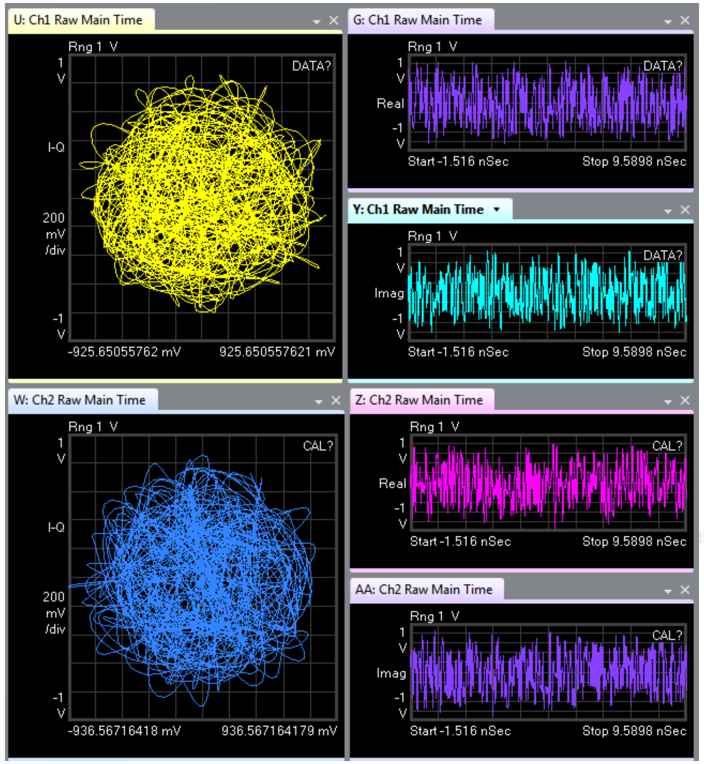
$$Q_3 - Q_4 \sim 4 \cdot A_S^v \cdot A_R \cdot \sin(\Delta\phi - \Delta\omega \cdot t)$$

‘Local Oscillator’ requirement results in measurement challenges

- Any frequency difference between the LO and the test signal results in a changing phase in the output of the IQ demodulator
- This can be ‘tracked’ by the test system, but requires a ‘real-time’ acquisition system (oscilloscope or ADC)
- The equivalent time sampling oscilloscopes (‘DCA’s’) commonly used for optical waveform analysis do not meet this requirement.
  - Exceptions:
    - Homodyne detection (Local oscillator laser phase locked to the carrier laser)
    - Using periodic signals and accepting really long acquisitions times which requires stable polarization and very low phase noise lasers

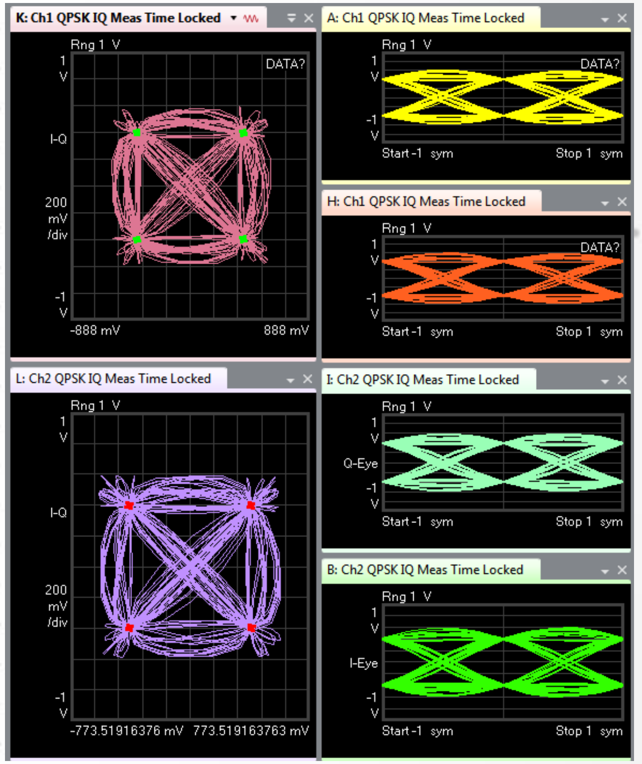
From digitized signal to EVM

What the ADC/digitizer/scope receives



Need defined reference receiver characteristics for consistent results

What is needed to evaluate EVM



Need defined processing blocks for consistent results

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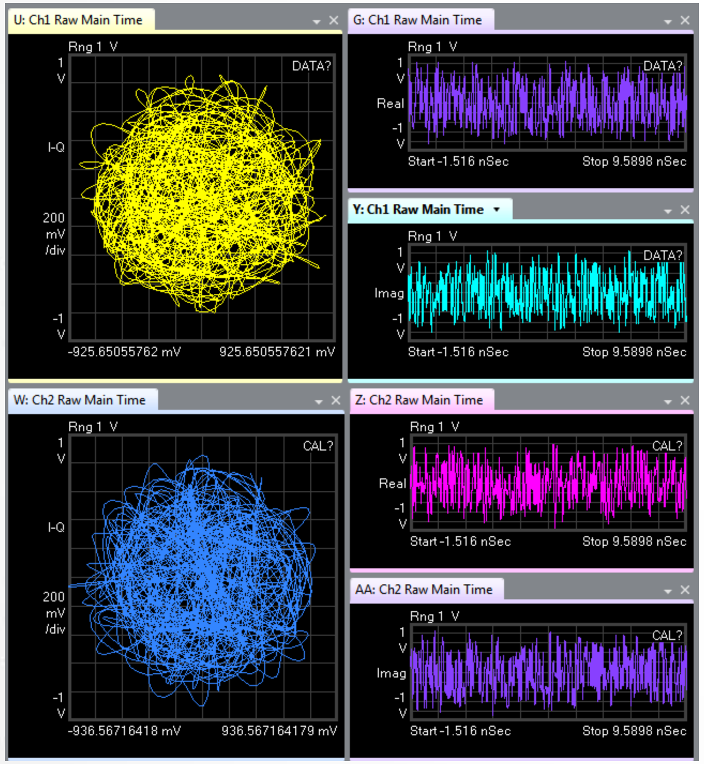
From digitized signal to EVM

What the ADC/digitizer/scope receives



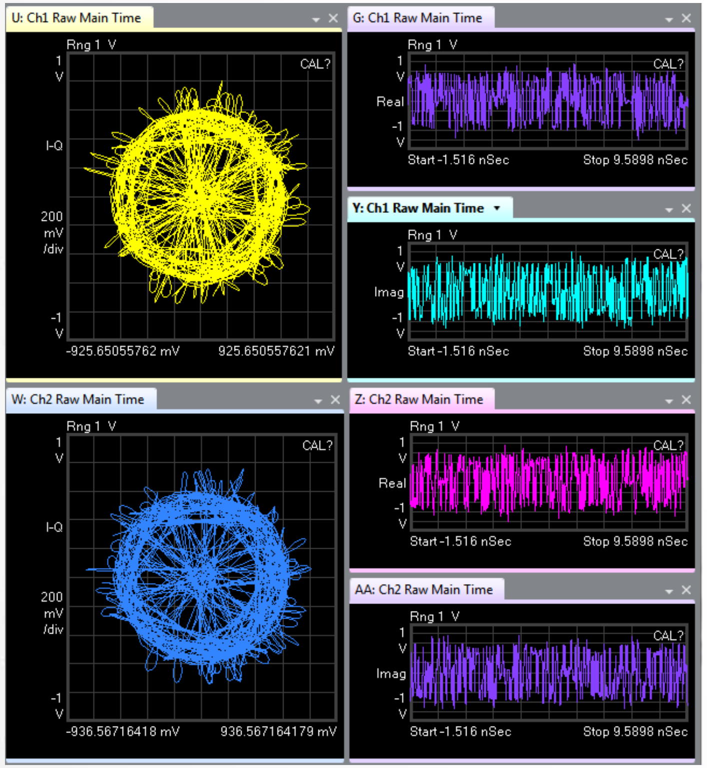
- Optical front-end
- ADC / Digitizer / Oscilloscope
- Polarization alignment
- Frequency offset estimation
- Carrier phase estimation
- Clock frequency and phase recovery
- EVM evaluation

Should be calibrated over wavelength for

- Frequency response
- Channel imbalances
- IQ phase angle errors
- Timing skew

From digitized signal to EVM

After Polarization alignment



Optical front-end

ADC / Digitizer / Oscilloscope

Polarization alignment

Frequency offset estimation

Carrier phase estimation

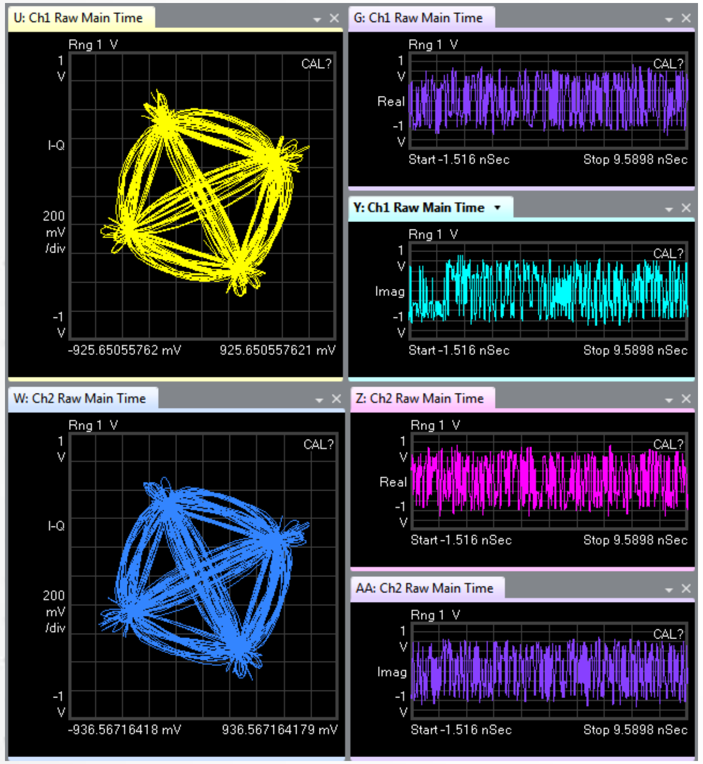
Clock frequency and phase recovery

EVM evaluation

This step should neither improve *(devices could later fail in field)* nor impair *(lowers the yield)* the signal quality.

From digitized signal to EVM

After carrier frequency offset estimation



Optical front-end

ADC / Digitizer / Oscilloscope

Polarization alignment

Frequency offset estimation

Carrier phase estimation

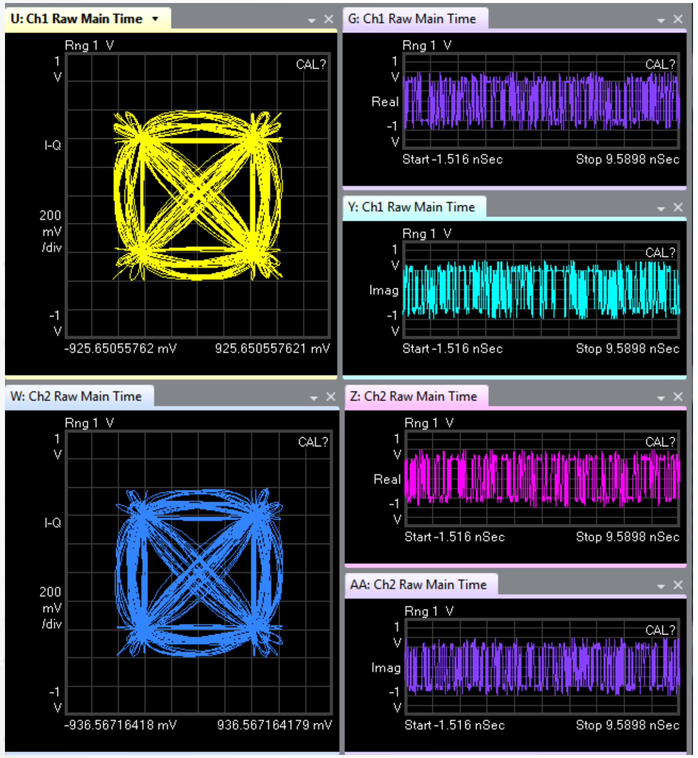
Clock frequency and phase recovery

EVM evaluation

Assume constant frequency offset (linear phase over time) for given block length.

From digitized signal to EVM

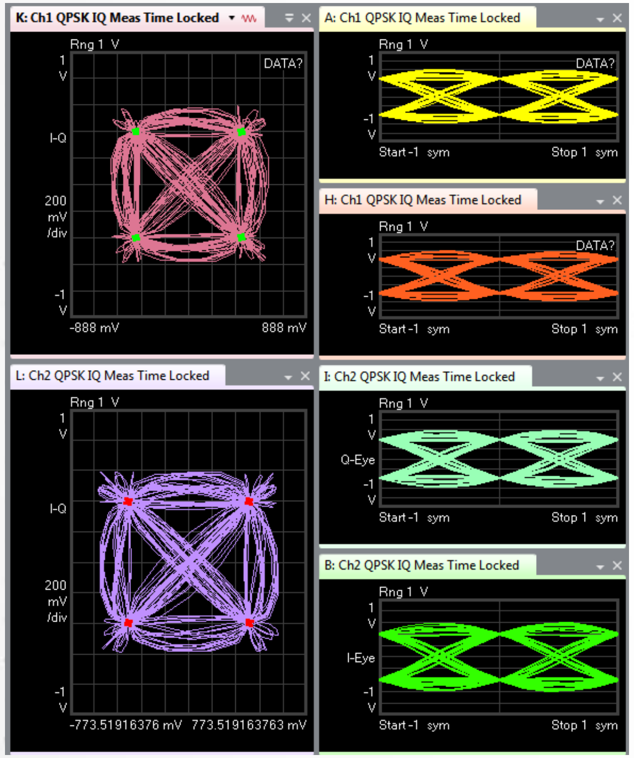
After carrier phase estimation



- Optical front-end
- ADC / Digitizer / Oscilloscope
- Polarization alignment
- Frequency offset estimation
- Carrier phase estimation
- Clock frequency and phase recovery
- EVM evaluation

From digitized signal to EVM

After resampling and retiming



- Optical front-end
- ADC / Digitizer / Oscilloscope
- Polarization alignment
- Frequency offset estimation
- Carrier phase estimation
- Clock frequency and phase recovery
- EVM evaluation

As the system architecture is defined, and specifications are formulated, consider these issues to aid in the test process

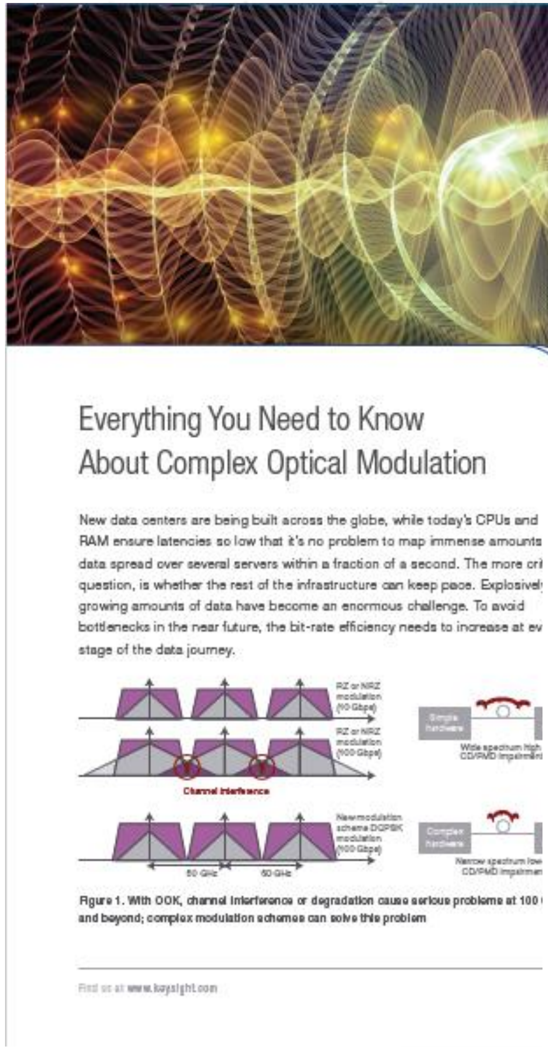
- EVM measurement uses blocks of data.
  - Too small block size results in higher standard deviation of results
  - Too big block size will overemphasize laser phase noise and increase measurement time
  - Optimum is in the range between 1k and 4k symbols
  - No restriction on data pattern lengths when real-time acquisition is used
- Processing algorithms are complicated and currently in development in the ITU and OIF. Consider reuse rather than reinvention

Existing work to possibly leverage

- OIF-400ZR 0.10-Draft Annex B includes text describing EVM and the corresponding reference receiver
- ITU G.698.2 contains an EVM spec for 100G DP-DQPSK signals and a detailed description of the processing steps
- IEC TR 61282 -10, Edition 1.0, 2013 contains basic descriptions of EVM and discusses some measurement techniques

For your information

- An excellent white paper tutorial on coherent technology:
  - “Everything You Need to Know About Complex Optical Modulation”
  - http://literature.cdn.keysight.com/litweb/pdf/5992-2888EN.pdf
- IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 24, NO. 1, JANUARY 1, 2012 61 “Error Vector Magnitude as a Performance Measure for Advanced Modulation Formats” Rene Schmogrow,
  - (EVM data can be used to reliably estimate BER)



WHITE PAPER

Everything You Need to Know About Complex Optical Modulation

New data centers are being built across the globe, while today’s CPUs and RAM ensure latencies so low that it’s no problem to map immense amounts data spread over several servers within a fraction of a second. The more cri question, is whether the rest of the infrastructure can keep pace. Explosively growing amounts of data have become an enormous challenge. To avoid bottlenecks in the near future, the bit-rate efficiency needs to increase at ev stage of the data journey.

Figure 1. With OOK, channel interference or degradation cause serious problems at 100 and beyond; complex modulation schemes can solve this problem

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Error Vector Magnitude as a Performance Measure for Advanced Modulation Formats

Rene Schmogrow, Bernd Nebendahl, Marcus Winter, Arne Josten, David Hillerkuss, Swen Koenig, Joachim Meyer, Michael Dreschmann, Michael Huebner, Christian Koos, Juergen Becker, Wolfgang Freude, and Juerg Leuthold

***Abstract*—We examine the relation between optical signal-to-noise ratio (OSNR), error vector magnitude (EVM), and bit-error ratio (BER). Theoretical results and numerical simulations are compared to measured values of OSNR, EVM, and BER. We conclude that the EVM is an appropriate metric for optical channels limited by additive white Gaussian noise. Results are supported by experiments with six modulation formats at symbol rates of 20 and 25 GBd generated by a software-defined transmitter.**

***Index Terms*—Advanced modulation formats, bit-error ratio (BER), error vector magnitude (EVM), software defined transmitter.**

I. INTRODUCTION

COHERENT optical transmission systems and advanced modulation formats such as M-ary quadrature amplitude modulation (QAM) are establishing quickly [1]. To encode these formats a variety of new optical modulator concepts have been introduced [2]. Among them are modulators dedicated to a particular modulation format [3] as well as novel software-defined optical transmitters that allow encoding of many modulation formats at the push of a button [4], [5]. In light of the capabilities to encode such advanced modulation formats there is a need to reliably judge the quality of the encoded signals. In laboratory experiments so far most receivers employ offline digital signal processing (DSP) at much reduced clock rates. This offline processing makes it very time consuming to reliably compute the bit error ratio (BER), especially if the signal quality is high. As a consequence, a faster — yet reliable — performance measure is needed, in particular when investigating wavelength division multiplexing (WDM) [6] or multicarrier systems [7].

Traditionally, the Q-factor metric is well established for on-off keying (OOK) optical systems. To estimate BER from Q, marks and spaces in the detected photocurrent are assumed to be superimposed with additive white Gaussian noise (AWGN), the probability density of which is fully described by its mean and variance. A large Q leads to a small BER.

Unfortunately, the method cannot be simply transferred to QAM signals, where the optical carrier is modulated with multilevel signals both in amplitude and phase. Instead, the error vector magnitude (EVM) is employed. It describes the effective distance of the received complex symbol from its ideal position in the constellation diagram. If the received optical field is perturbed by AWGN only, the EVM can be related to BER and to the optical signal-to-noise ratio (OSNR) [8], [9]. A small EVM leads then to a small BER. The EVM metric is standard in wireless and wireline communications. However, its connection to BER and OSNR is not well established in optical communications. Especially one has to discriminate between data-aided reception, where for measurement purposes the actually sent data are known, as opposed to nondata-aided reception, where the received data are unknown. The first case is standard for BER measurements, while the second case is more common for real-world receivers (disregarding, e.g., training sequences). For strongly noisy signals, nondata-aided reception tends to underestimate the EVM, because a received symbol could be nearer to a “wrong” constellation point than to its “right” position.

In this letter we confirm experimentally and by simulations that the BER can be estimated from EVM data by an analytic relation [8]. Strictly speaking, this BER estimate is valid for data-aided reception only, but we found that the method can be also applied for nondata-aided reception if BER $< 10^{-2}$ holds. Further, the EVM can be estimated [9] if the OSNR has been measured. Both estimates are valid for systems limited by optical AWGN. To support our findings we compare measured OSNR, EVM and BER for symbol rates of 20 GBd and 25 GBd with calculated BER and EVM estimates for the modulation formats binary phase shift keying (BPSK), quadrature PSK (QPSK), 8PSK, 16QAM, 32QAM, and 64QAM.

II. ERROR VECTOR MAGNITUDE

A. EVM Definition

Advanced modulation formats such as M-ary QAM encode a data signal in amplitude and phase of the optical electric field. The resulting complex amplitude of this field is described by points in a complex constellation plane. Fig. 1(a) depicts the

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Thank you!