EVM Tutorial

FOR IEEE 802.3cw TASK FORCE

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KEYSIGHT TECHNOLOGIES

Agenda

- Calibrated Coherent Reference Receiver for TX Testing
  - Building Blocks of a Coherent Receiver
  - Digital Signal Processing
- EVM as Transmitter Quality Metric
  - EVM Definition & Basics
  - Relationship between Metrics (EVM, OSNR, BER)
- Standardization Activities (ITU-T, OIF, IEEE)
  - Methodology for ITU-T G.698.2

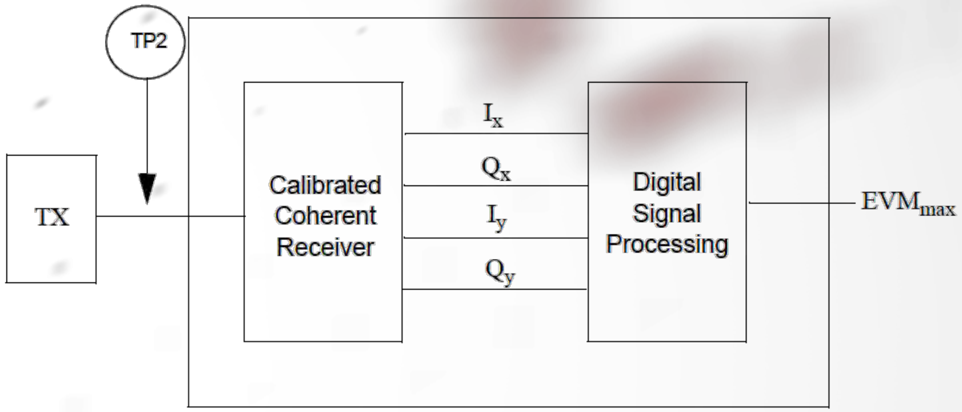
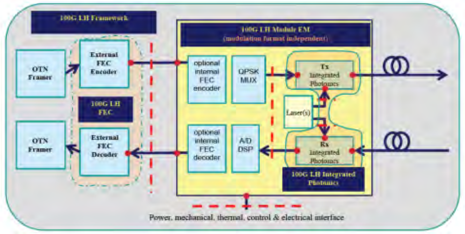


Figure 156–6—EVM reference receiver

Receivers for Complex Modulated Signals

Network Receivers

- Real time measurement and data processing
- For a known modulation speed and format
- Size and power consumption is important
- Typically proprietary algorithms optimized for performance and computational cost
- Needs to compensate CD and PMD
- Phase tracking enabled
- Impairments are removed *independent* of source
- Bit Error Rate is main optimization criterion

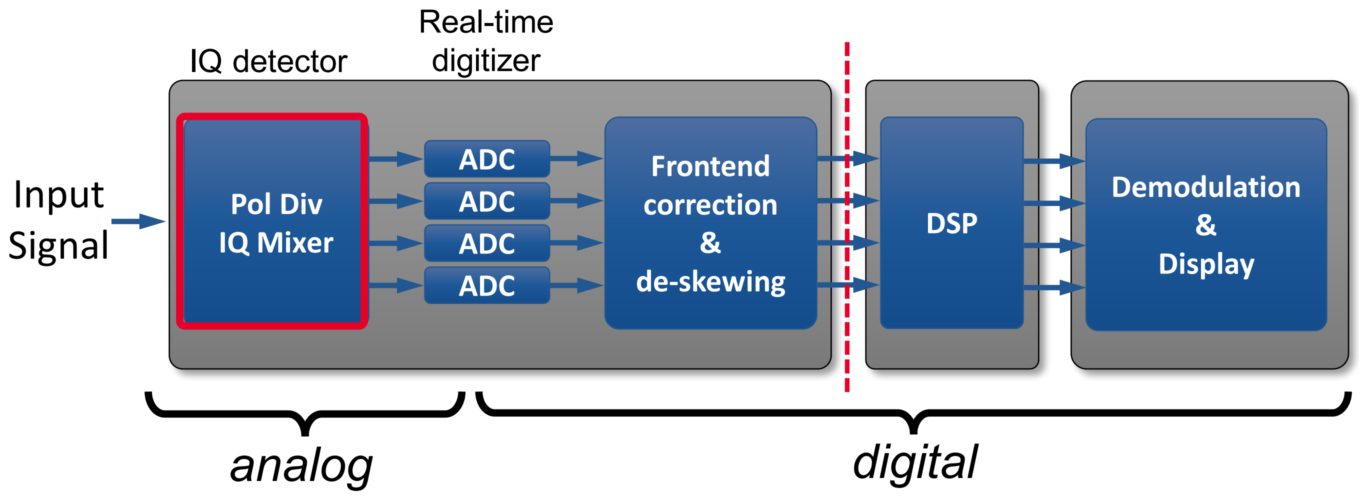


Receivers for Test & Measurement ("OMAs")

- Offline processing
- Flexible (programmable) symbol rate and format
- Size and power consumption is of lower importance
- Built-in general-purpose algorithms but capable of using customer algorithms
- CD/PMD compensation only for transmission experiments, not for b2b
- Phase tracking should be optional
- Impairments are removed *dependent* of source.
- Best signal fidelity is the optimization criterion
- Optimized to show real nature of signal

Common Building Blocks of a Coherent Receiver

POLARIZATION DIVERSITY IQ MIXER



Calibrated signal interface for subsequent DSP

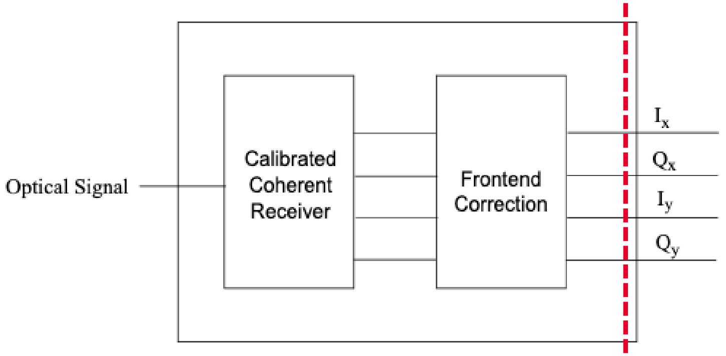
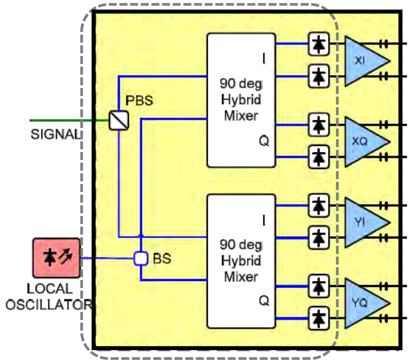


Figure 156–7—Calibrated coherent receiver

from IEEE802.3cw D1.2



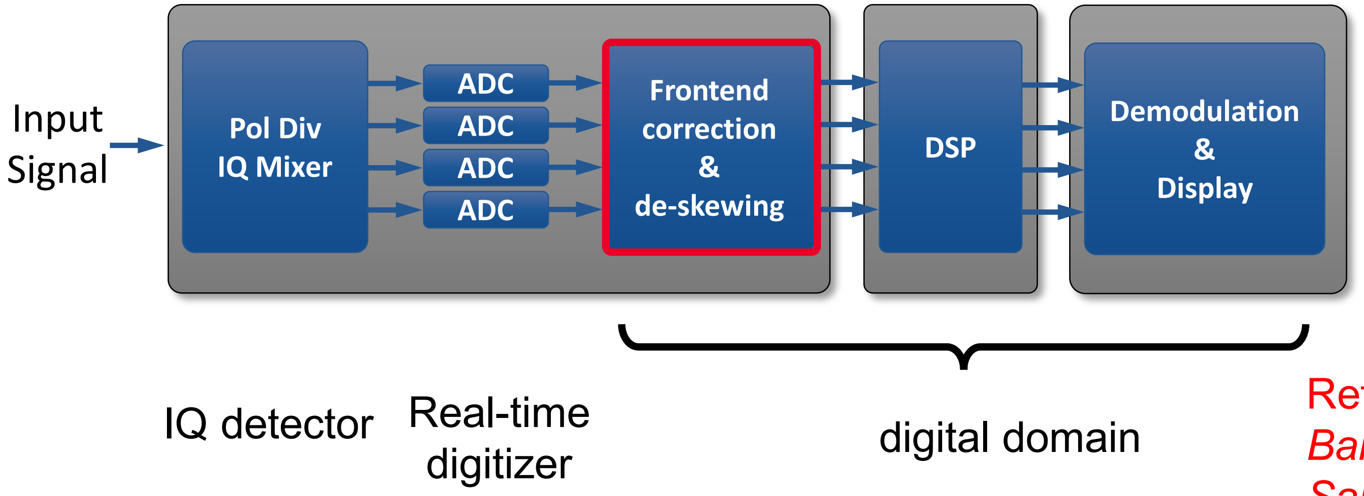
Source: OIF, Document IA # OIF-DPC-RX-01.0

Polarization Diversity IQ Mixer

- Split signal into two polarizations
- Mixing input signal with Local Oscillator
- Extracting Quadrature- and In-Phase part of the baseband signal
- Convert into four electrical signals for XI, XQ, YI, and YQ

Signal Processing Steps I

FRONT END CORRECTION & DE-SKEWING



Reference Receiver Specs tbd:
Bandwidth, Frequency Response, Sampling Rate, Receive Filtering etc.

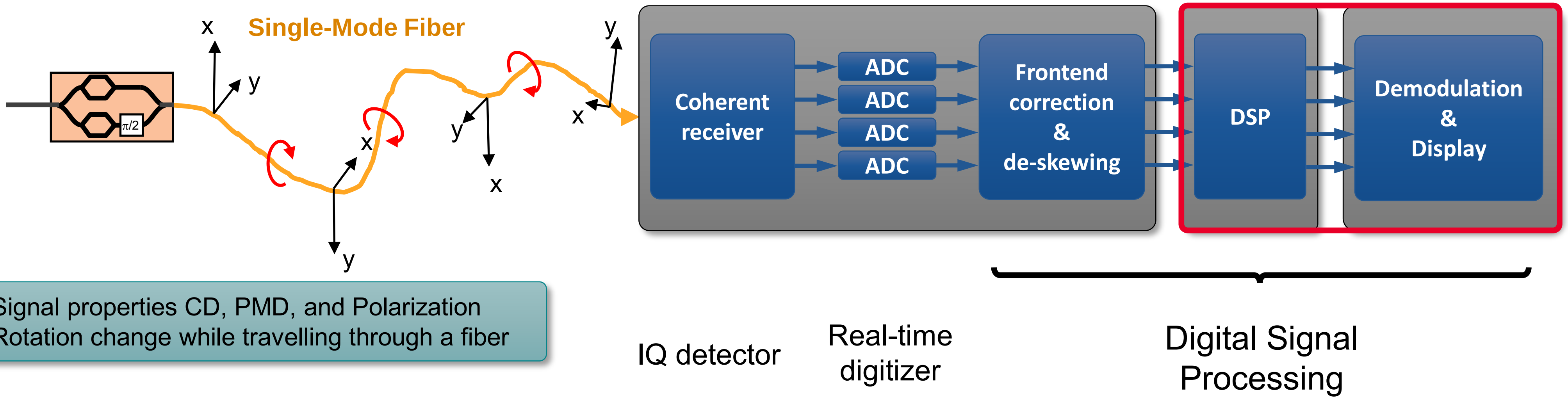
The first step after the ADC **removes imperfections** of the coherent optical receiver like:

- **Channel Imbalances** between the four electrical channels
- **IQ phase angle errors** of the IQ mixer
- **Timing skew** between the four ADC channels
- **Differential Imbalance** of the nominally balanced receiver

In order to remove these imperfections the component is typically characterized over wavelength during the instrument calibration! This is provided in commercial T&M-grade optical modulation analyzers.

Signal Processing Steps II

DIGITAL SIGNAL PROCESSING



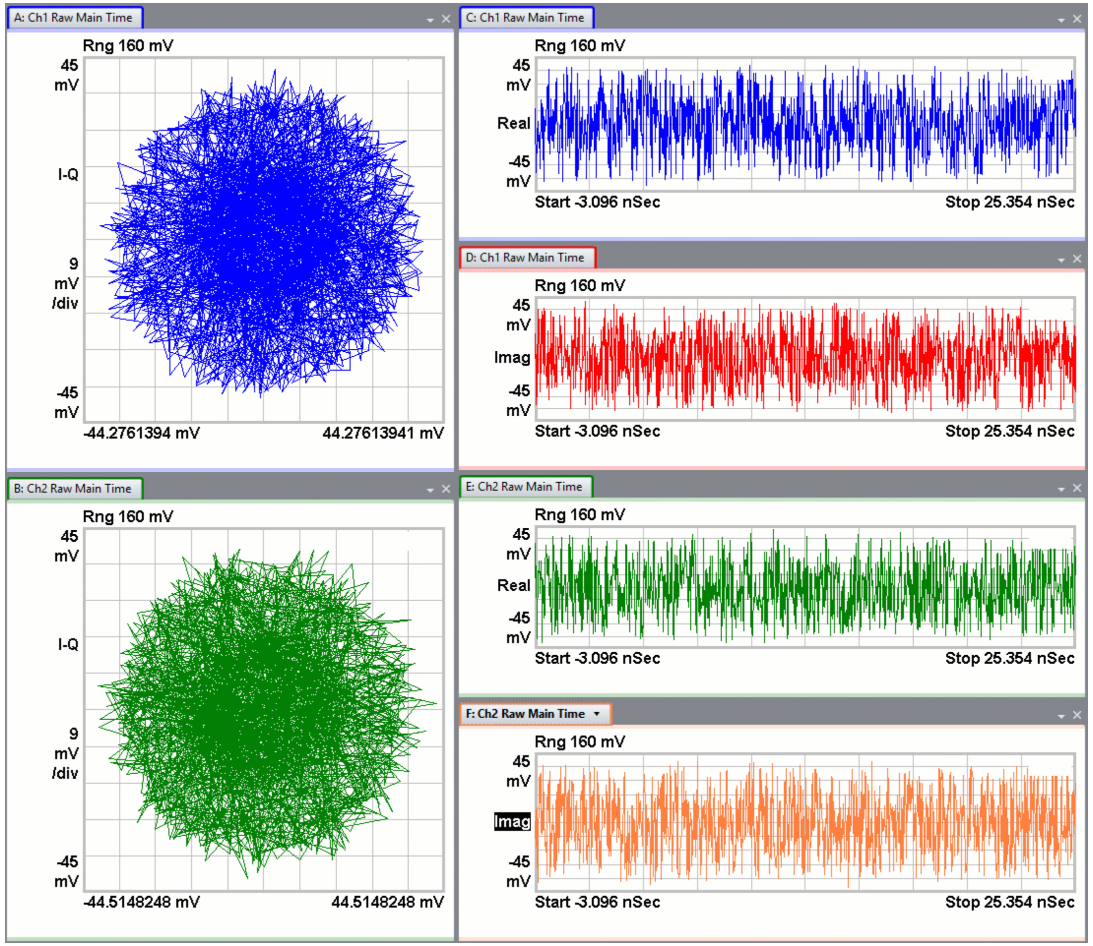
- Compensation of **Chromatic Dispersion** (typically not required for back-to-back, either using a fixed value or estimating the value from the signal)
- Compensation of **Polarization Mode Dispersion** (typically not required for back-to-back, estimation of PMD from the signal)
- **Polarization Demultiplexing** in order to provide two independent IQ baseband signals to the digital demodulator
- **Carrier Phase Tracking** to reduce phase noise (optional if performance under phase tracking condition is of interest

Not needed for b2b or Tx measurement

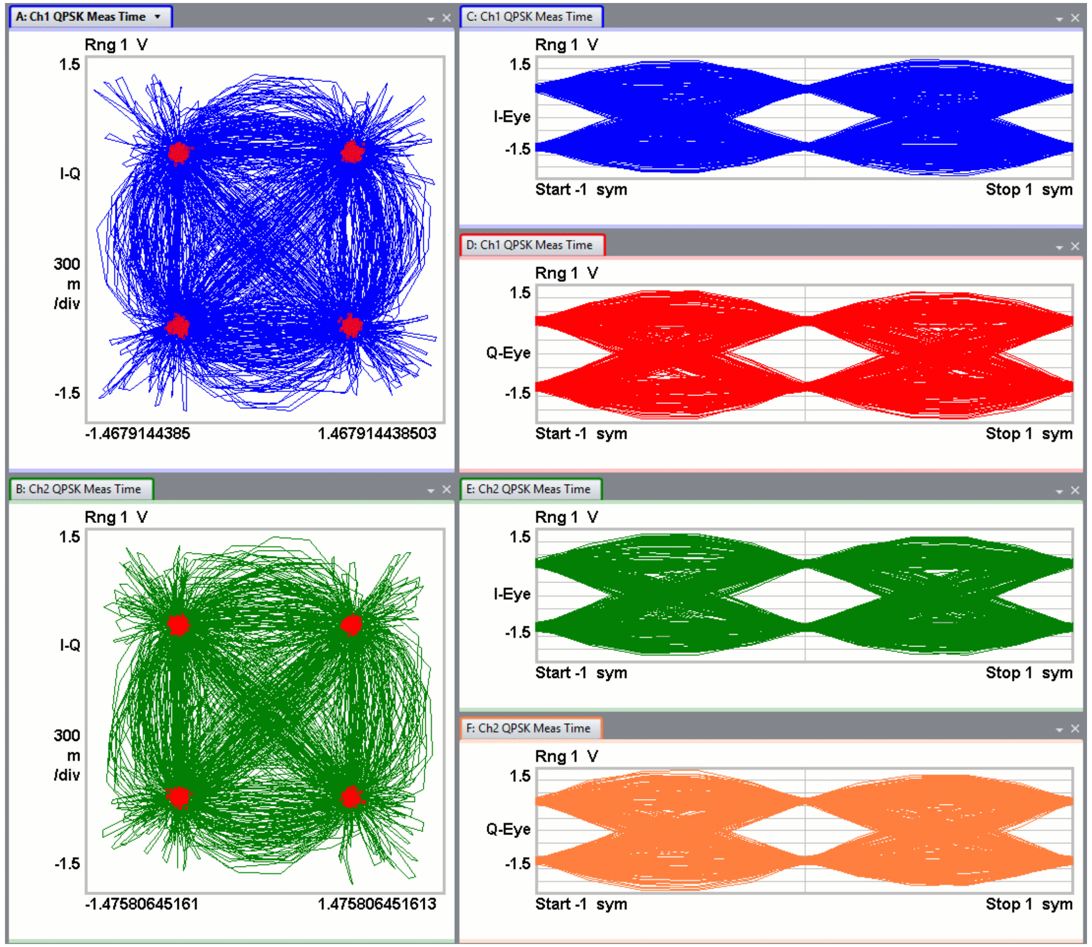
Signal Processing Steps

FROM DIGITIZED TO CONSTELLATION

What the oscilloscope receives



What we expect to see



Digital Signal Processing

MULTIPLE DSP STEPS REQUIRED

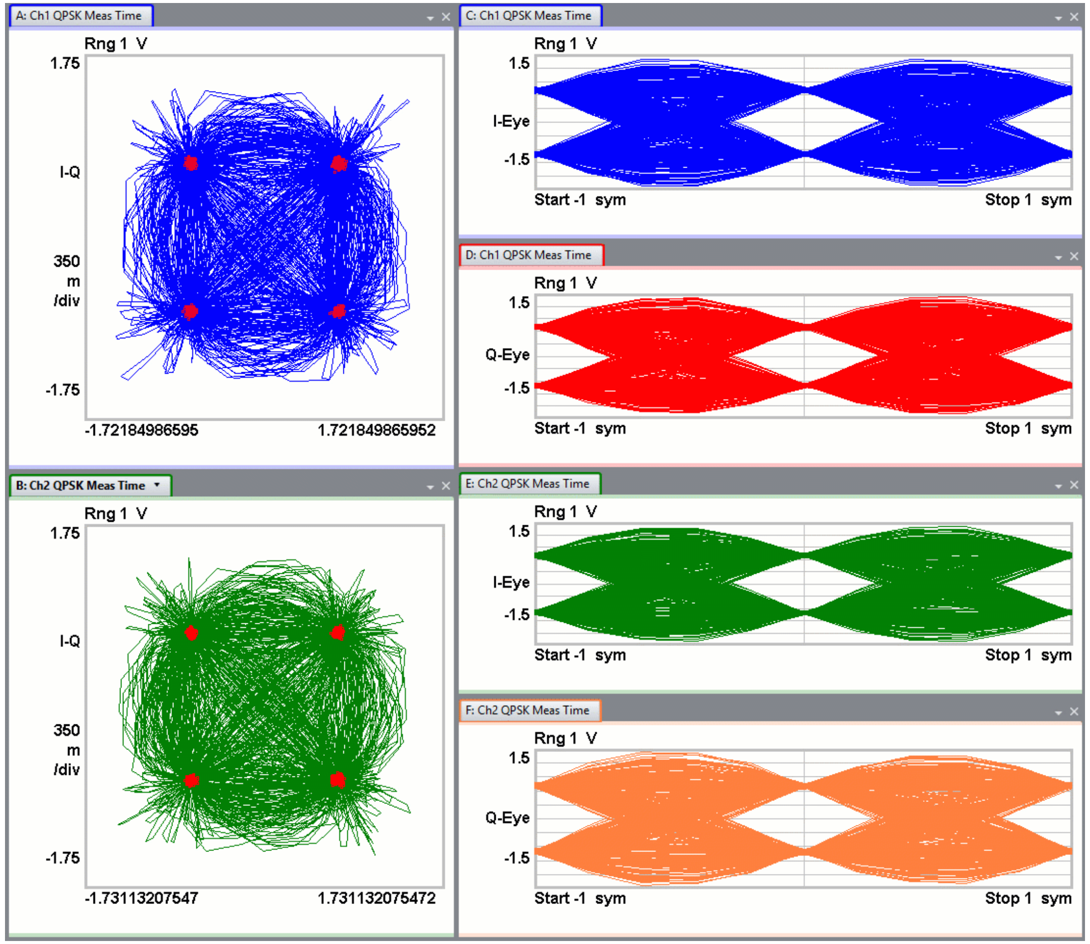


Figure 156–8— Offline digital signal processing

- Polarization De-multiplexing
- Frequency offset estimation
- Carrier phase estimation
- Receive Filtering
- I-Q Offset Compensation
- Equalizer

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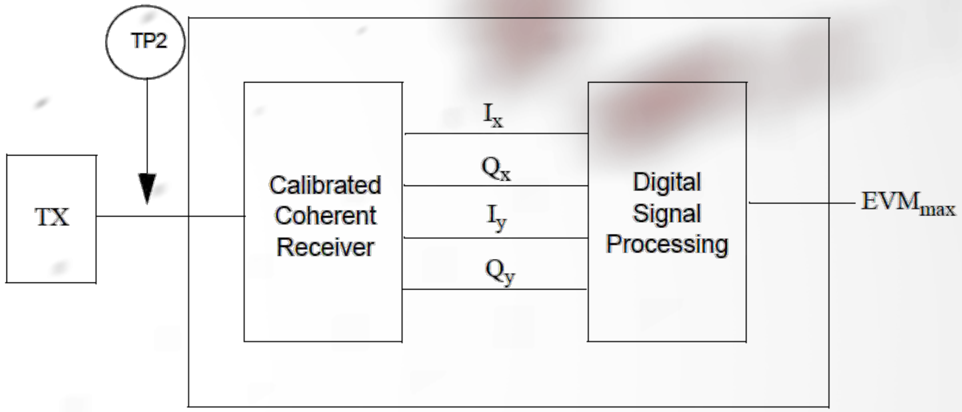


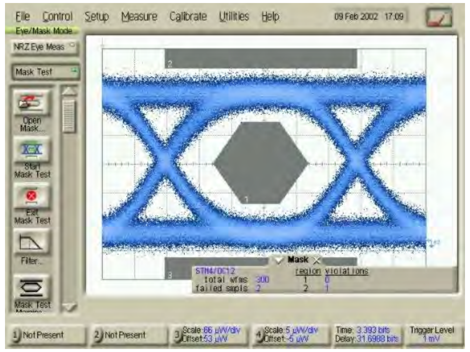
Figure 156–6—EVM reference receiver

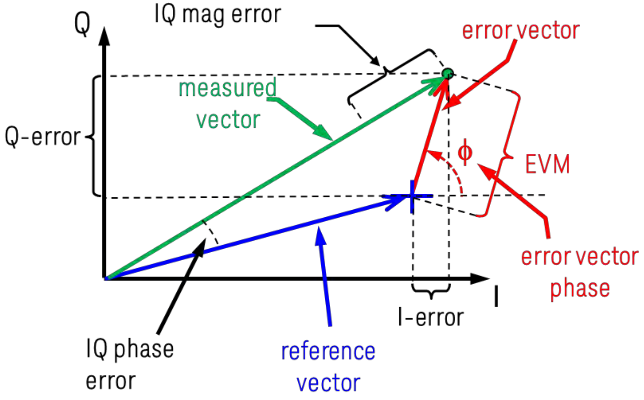
Quality Metrics for Complex Modulated Signals

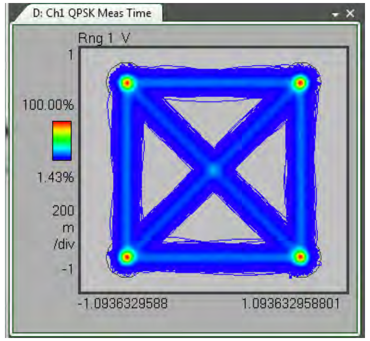
COMPLEX SIGNALS REQUIRE COMPLEX METRICS

NRZ / PAM-4
- Mask Margin
- Q-factor (amplitude axis)
- Timing jitter (time axis)
- BER (system performance)
- OSNR (system performance)
- TDEC(Q)

Complex Modulation
- EVM/SNR (MER)
- IQ Imbalance, IQ Offset
- Quadrature Error
- Magnitude Error, Phase Error
- Frequency Offset
- BER

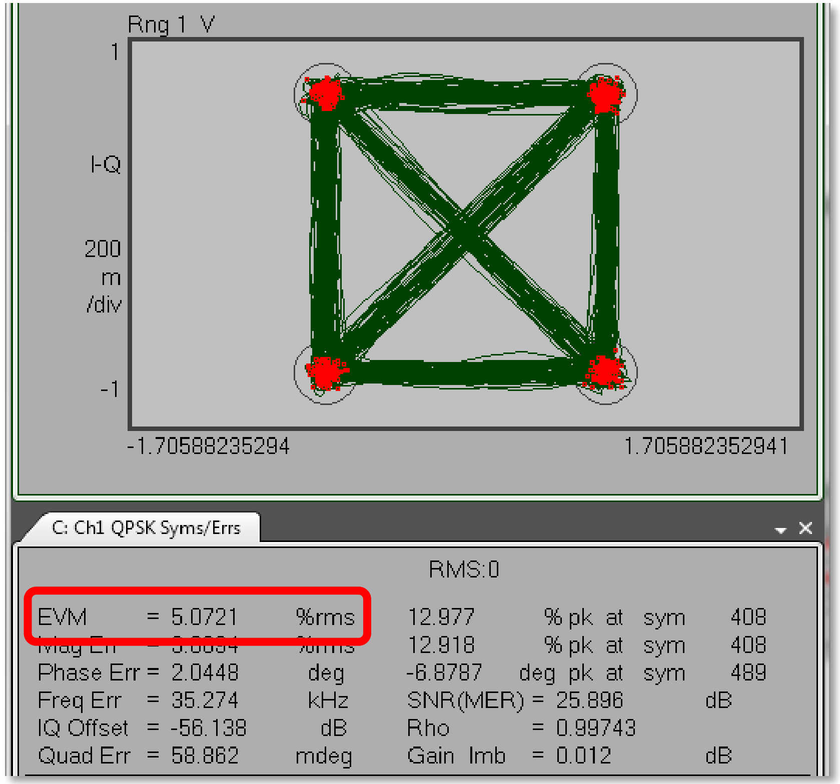


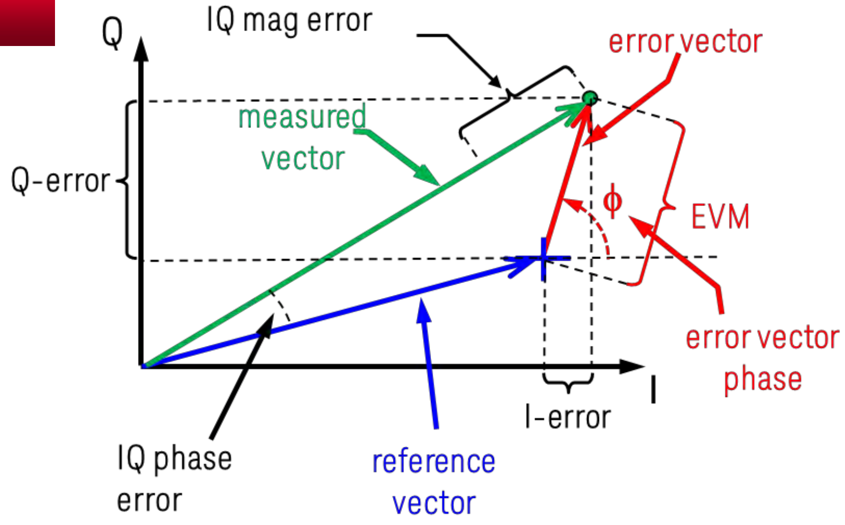




Error Vector and Error Vector Magnitude

A GLOBAL MEASURE





Error Vector connects the measured Vector and the expected vector, **EVM** is magnitude of this vector
Error Vector = 0 means we have measured an **ideal signal**!

$$EVM[k] = \sqrt{I_{error}[k]^2 + Q_{error}[k]^2}$$

$$EVM\% = \frac{\sqrt{\frac{1}{N} \cdot \sum_{k=0}^{N-1} \left(I_{error}[k]^2 + Q_{error}[k]^2 \right)}}{\left| \text{EVM normalization reference} \right|} \cdot 100\%$$

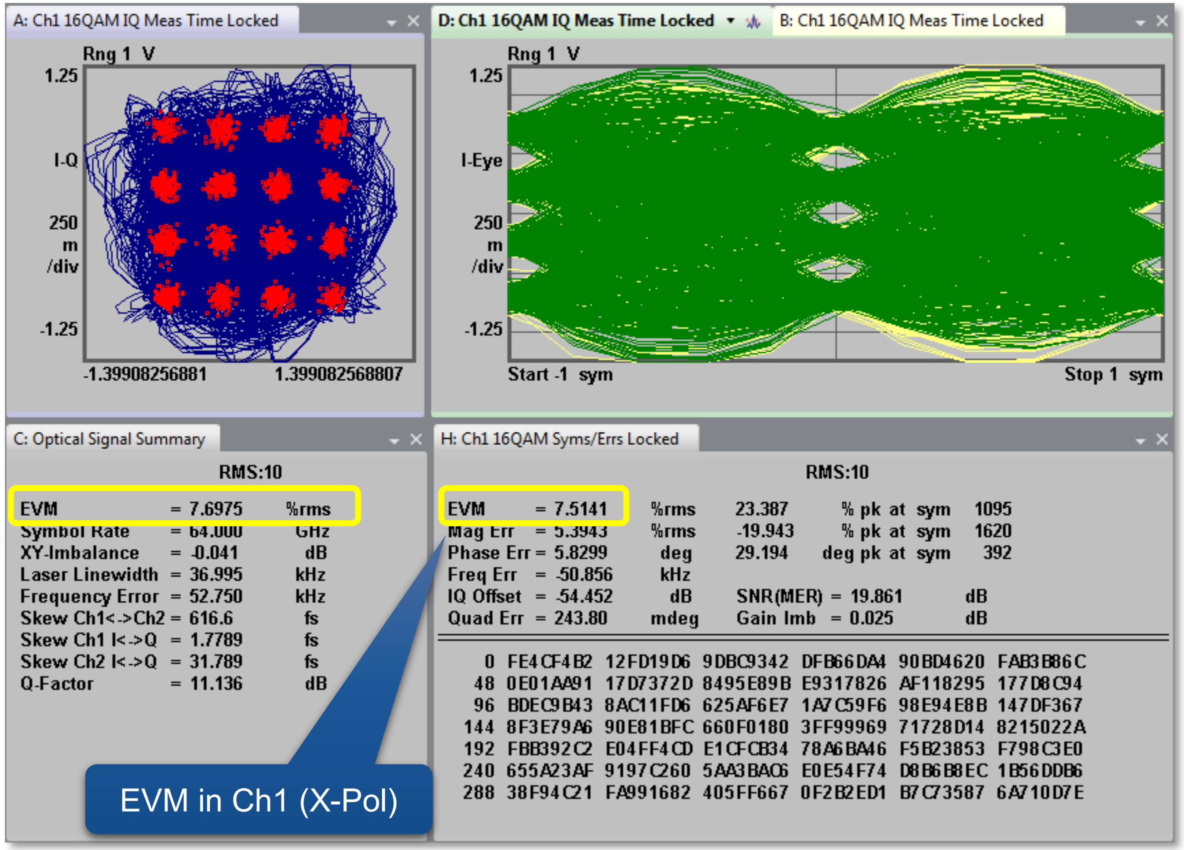
Where k = symbol index
N is the number of EVM points
$I_{error} = I_{Meas} - I_{Ref}$
$Q_{error} = Q_{Meas} - Q_{Ref}$

EVM in the measurement

EVM AND 16-QAM

Error Vector

connects the measured vector and the reference vector. **Error Vector Magnitude or EVM** is the rms average of the error vectors of all received symbols, normalized to either the maximum constellation magnitude, or the rms level of the IQ reference symbol points.



Simulation of 64 GBd PDM-16QAM, RC α=0.2, and additive white noise

Error Vector Magnitude

SUMMARY

- Error Vector Magnitude is a **global metric that works for any modulation format** that can be described with a constellation
- There are at least **three normalization methods** (peak vector, average vector, average power), be careful when comparing numbers!
- Assuming gaussian noise limited system, EVM can be **converted into other metrics** like SNR or Q-factor (for orthogonal QAM format)
- EVM results depend on **data-aided vs non-data-aided** (blind) reception (see next slides)

Mathematical Relationship between EVM and OSNR

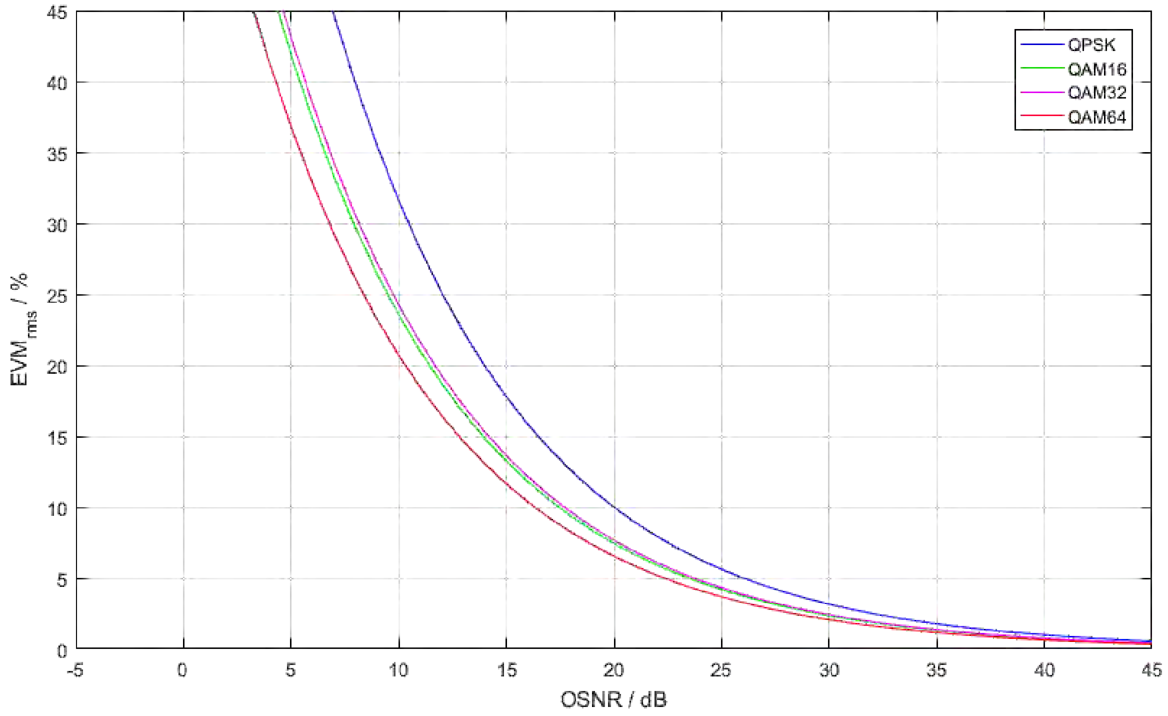
SIMPLE MODEL

Optical signal-to-noise power ratio (OSNR) and EVM can be interrelated:

$$\mathrm{EVM_{rms}} = \frac{\sigma_{\mathrm{err}}}{|E_{\mathrm{t}}|} = \sqrt{\frac{P_{\mathrm{err}}}{P_{\mathrm{S}}}},\ \mathrm{OSNR} = \frac{P_{\mathrm{S}}}{P_{\mathrm{N}}},\ \mathrm{OSNR} = \frac{2B_{\mathrm{ref}}}{B_0} * \mathrm{OSNR_{ref}}$$

If error due only to additive white Gaussian noise (AWGN):

$$P_{\mathrm{err}} = P_{\mathrm{N}}$$

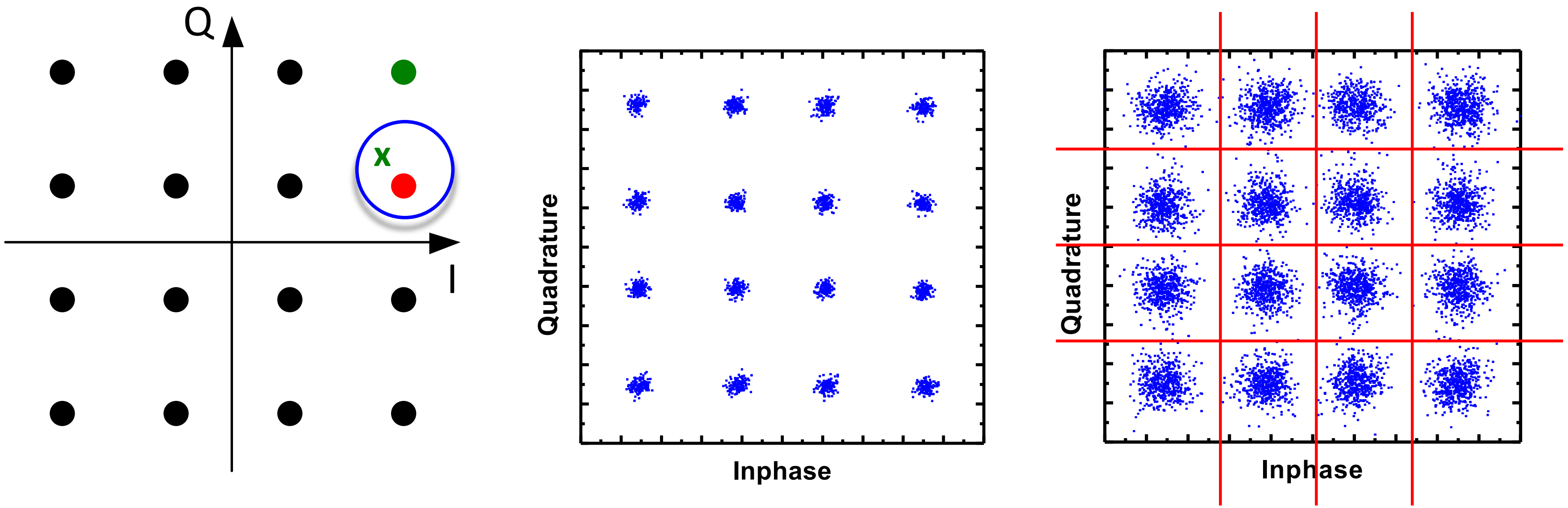


$$\mathrm{EVM_{rms}} = \frac{1}{k\sqrt{\mathrm{OSNR}}}$$

$$k^2 = \begin{cases} 1 & ,\mathrm{B/Q/8PSK} \\ 9/5 & ,\mathrm{16QAM} \\ 17/10 & ,\mathrm{32QAM} \\ 7/3 & ,\mathrm{64QAM} \end{cases}$$

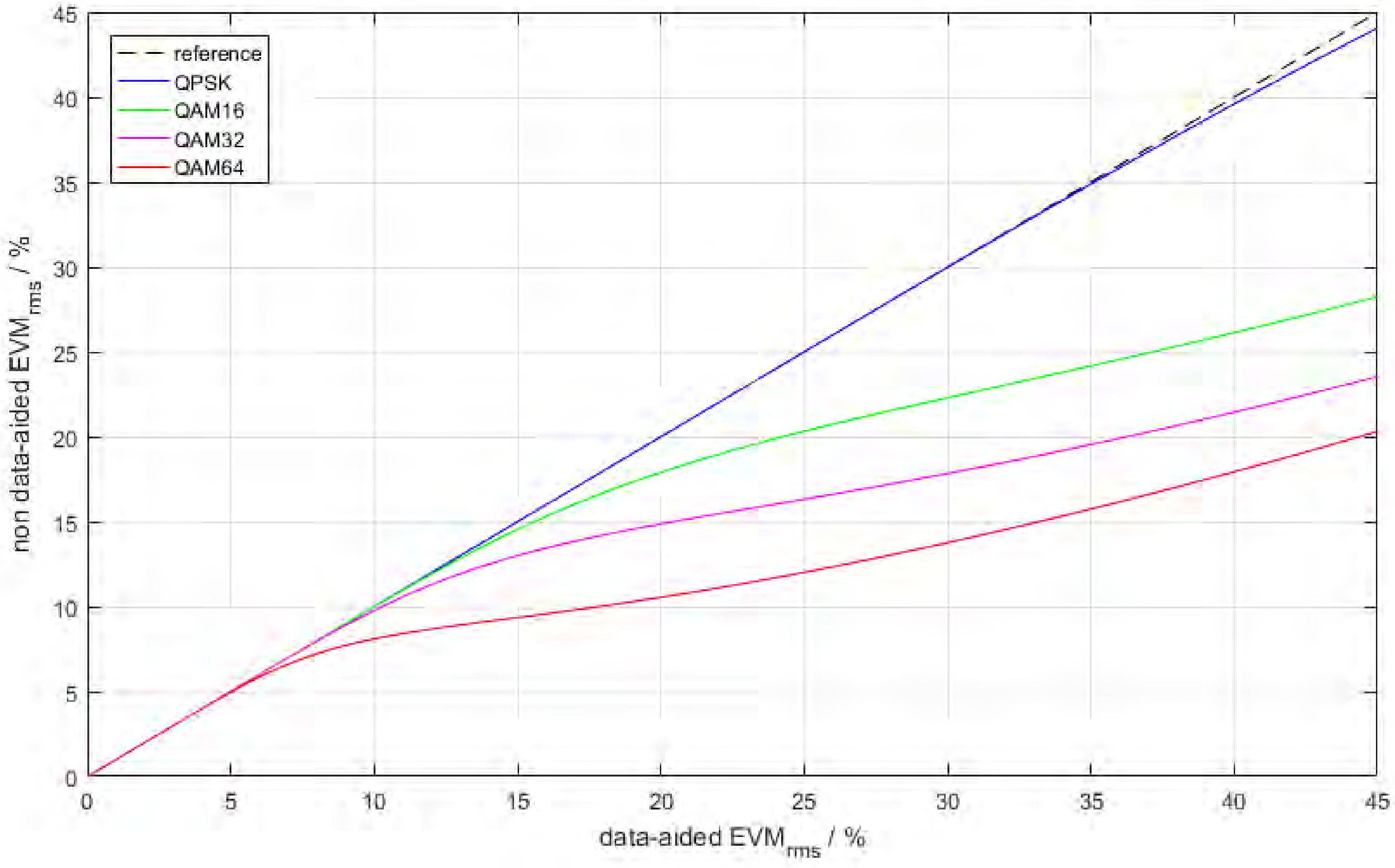
Data-aided versus Non-data-aided (blind) Reception

Data-aided:	Rx knows symbol sequence (✕ to ●, e.g., BER measurement)
Non-data-aided:	Symbol sequence unknown to Rx (e.g., *Q*-factor measurement)
Problem:	Assignment of signal point ✕ to incorrect constellation point ●
	→ error vector estimate too small if large noise



Data-Aided vs. Non Data-Aided EVM

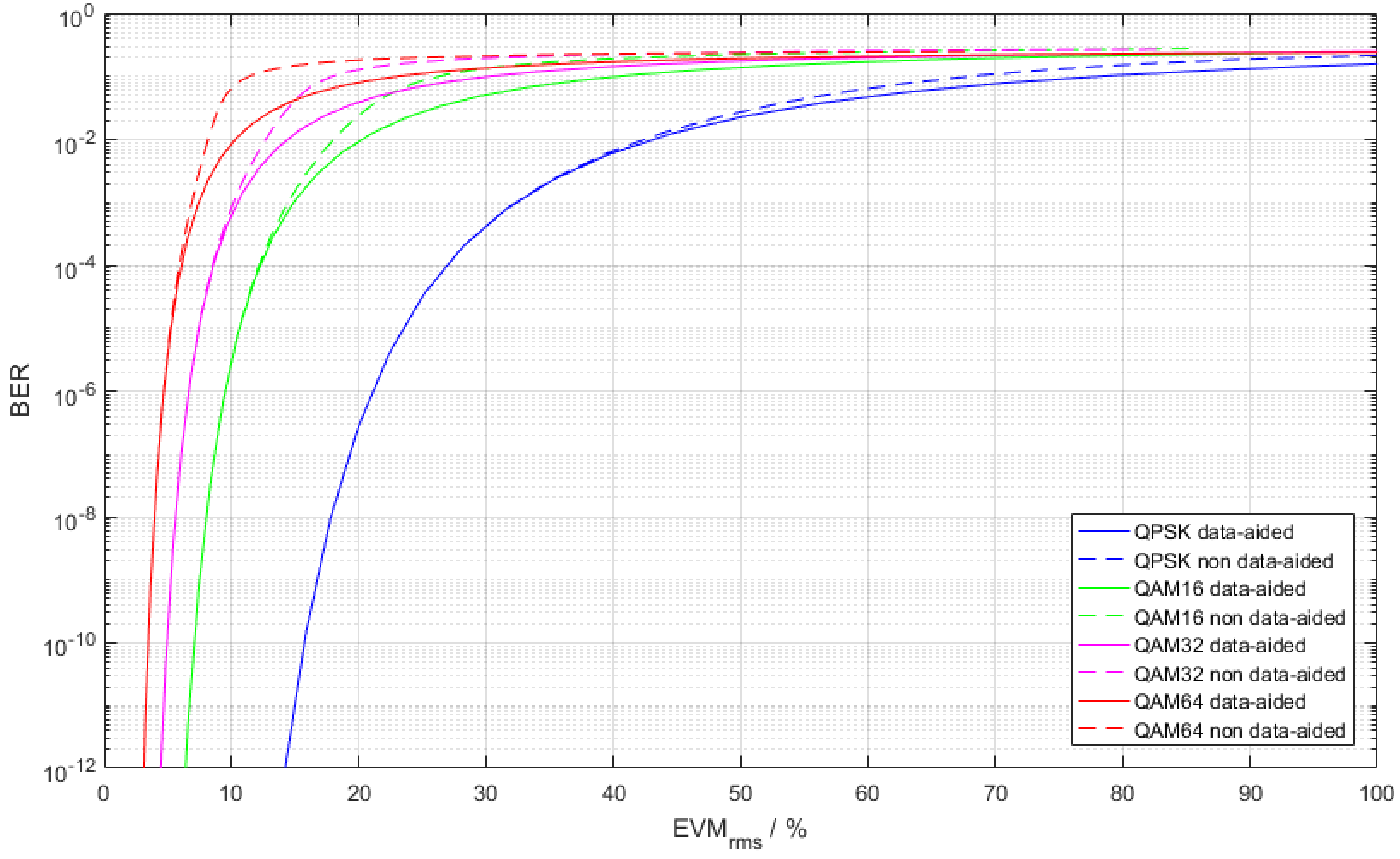
THE EFFECT OF WRONG DECISIONS



Note:
The non data-aided EVM is always lower than the data-aided EVM because wrong decisions lead to an underestimation of EVM.

This is not a problem because we are consistent between test limit determination and testing method.

Relationship between EVM and BER



$$\mathrm{BER} = \frac{1 - M^{-1/2}}{\frac{1}{2}\log_2 M}\,\mathrm{erfc}\left[\sqrt{\frac{3/2}{(M-1)(\,k\mathrm{EVM_{rms}})^2}}\right]$$

Note:
M is the number of states in the constellation.

To compensate the effect of non data-aided EVM being to low leads to a BER(EVM$_{\text{non data-aided}}$) that is above the BER(EVM$_{\text{data-aided}}$)

BER from Measured EVM

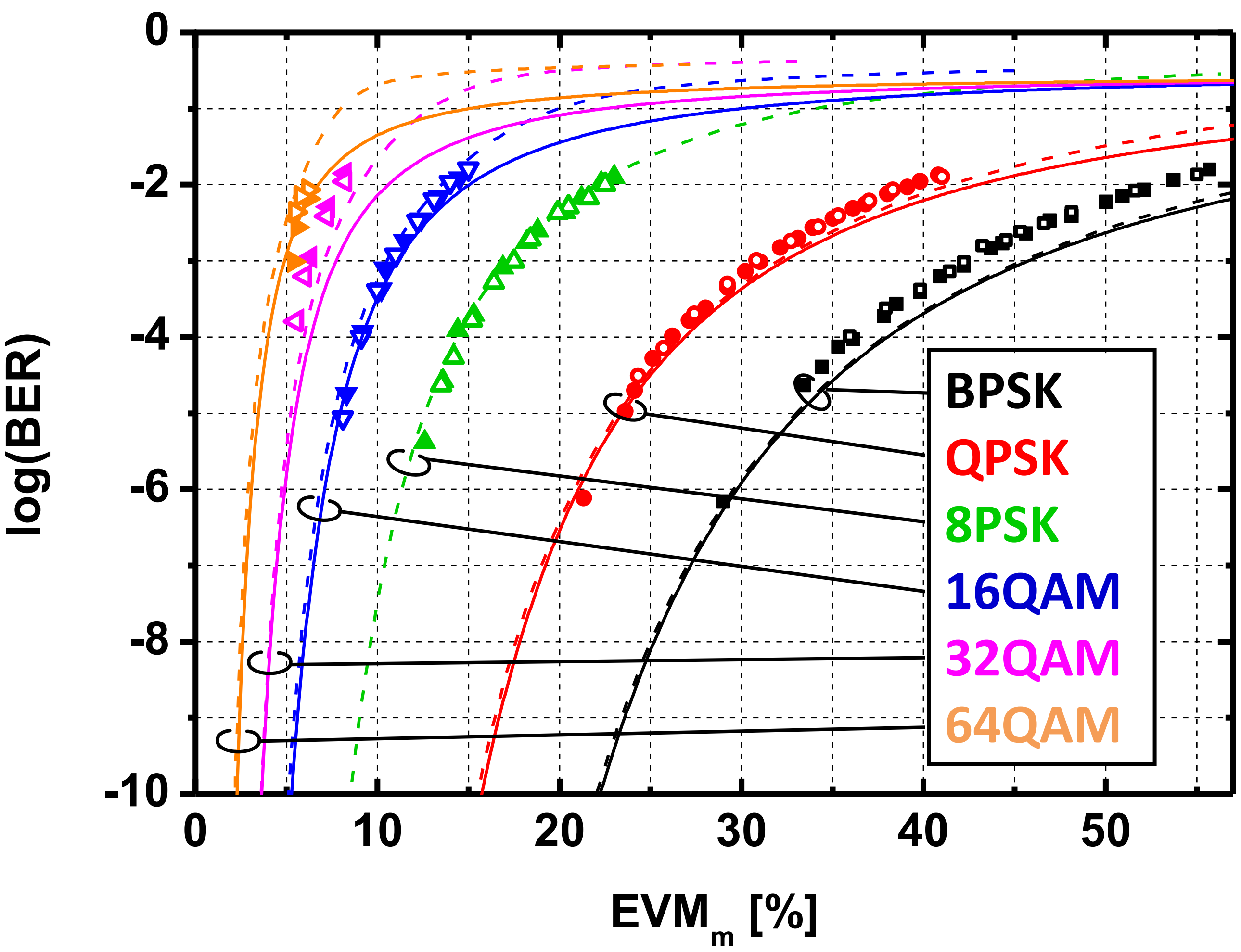
Dashed lines: Simulated
(EVM not data-aided)

Solid lines: Calculated BER(EVM)
(EVM data aided)

Open Symbols: Measured
(25 GBd, EVM not data-aided)

Full Symbols: Measured
(20 GBd, EVM not data-aided)

(PRBS length: $2^{15} - 1$)



R. Schmogrow et al., "Error Vector Magnitude as a Performance Measure for Advanced Modulation Formats," *Photonics Technology Letters, IEEE,* doi: 10.1109/LPT.2011.2172405

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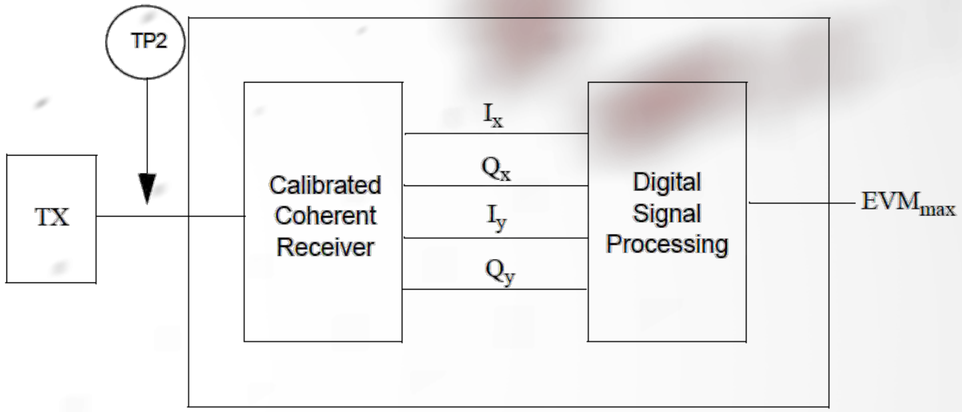


Figure 156–6—EVM reference receiver

Transmitter Impairments

IMPACT ON EVM

Measure →

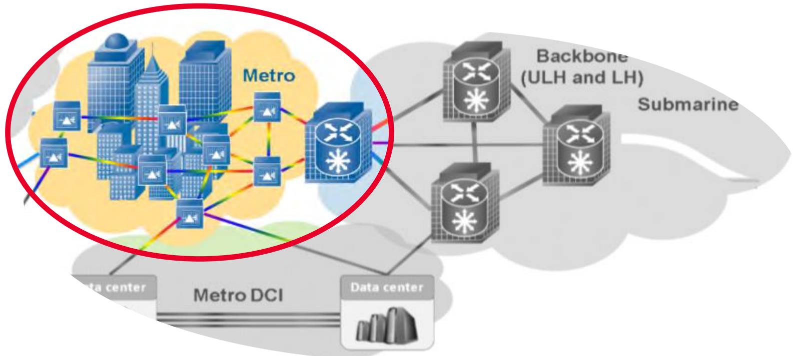
Impairment ↓

Impairment	EVM	Gain Imbalance	IQ Offset	Quad Error	Phase Error	Mag Error	Freq Error	IQ Skew	XY Skew	XY Imbalance
RF Imbalance	X	X						X		X
Bias Point	X	X	X							
IQ Phase Shifter	X			X						
IQ Skew	X							X		
Diff Imbalance			X							
Diff Skew										
Phase Noise	X				X					
Amplitude Noise	X					X				
Freq Error							X			
Symbol Rate Error	X									
XY Skew									X	
XY Imbalance										X
Nonlinearities	X									

Question: Can EVM predict OSNR Penalty for each impairment ?

In-Force Recommendation ITU-T G.698.2

SCOPE AND GOAL



INTERNATIONAL TELECOMMUNICATION

ITU-T

TELECOMMUNICATION
STANDARDIZATION SECTOR
OF ITU

SERIES G: TRANSMISSION SYSTEMS AND MEDIA, DIGITAL SYSTEMS AND NETWORKS

Transmission media and optical systems characteristics – Characteristics of optical systems

Amplified multichannel dense wavelength division multiplexing applications with single channel optical interfaces

Summary

Recommendation ITU-T G.698.2 provides optical parameter values for physical layer interfaces of dense wavelength division multiplexing (DWDM) systems primarily intended for metro applications which include optical amplifiers. Applications are defined using optical interface parameters at the single-channel connection points between optical transmitters and the optical multiplexer, as well as between optical receivers and the optical demultiplexer in the DWDM system. This Recommendation uses a methodology which does not specify the details of the optical link, e.g., the maximum fibre length, explicitly. This version of this Recommendation includes unidirectional DWDM applications at 100 Gbit/s with 100 GHz and 50 GHz channel frequency spacing.

Goal → Interoperability between multiple vendors!

In-Force Recommendation ITU-T G.698.2

METHODOLOGY

- Identify test parameters
- Develop test methods
- Conduct experiments with transmitters and receivers from various vendors
- Agree on test limits for test parameter

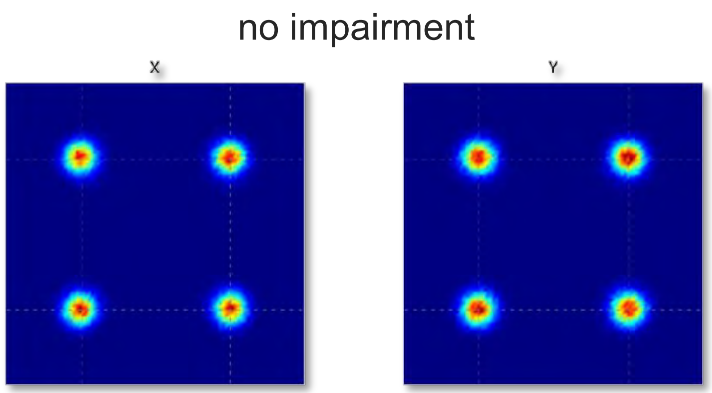
→ OSNR penalty was chosen as metric to compare various signal impairments

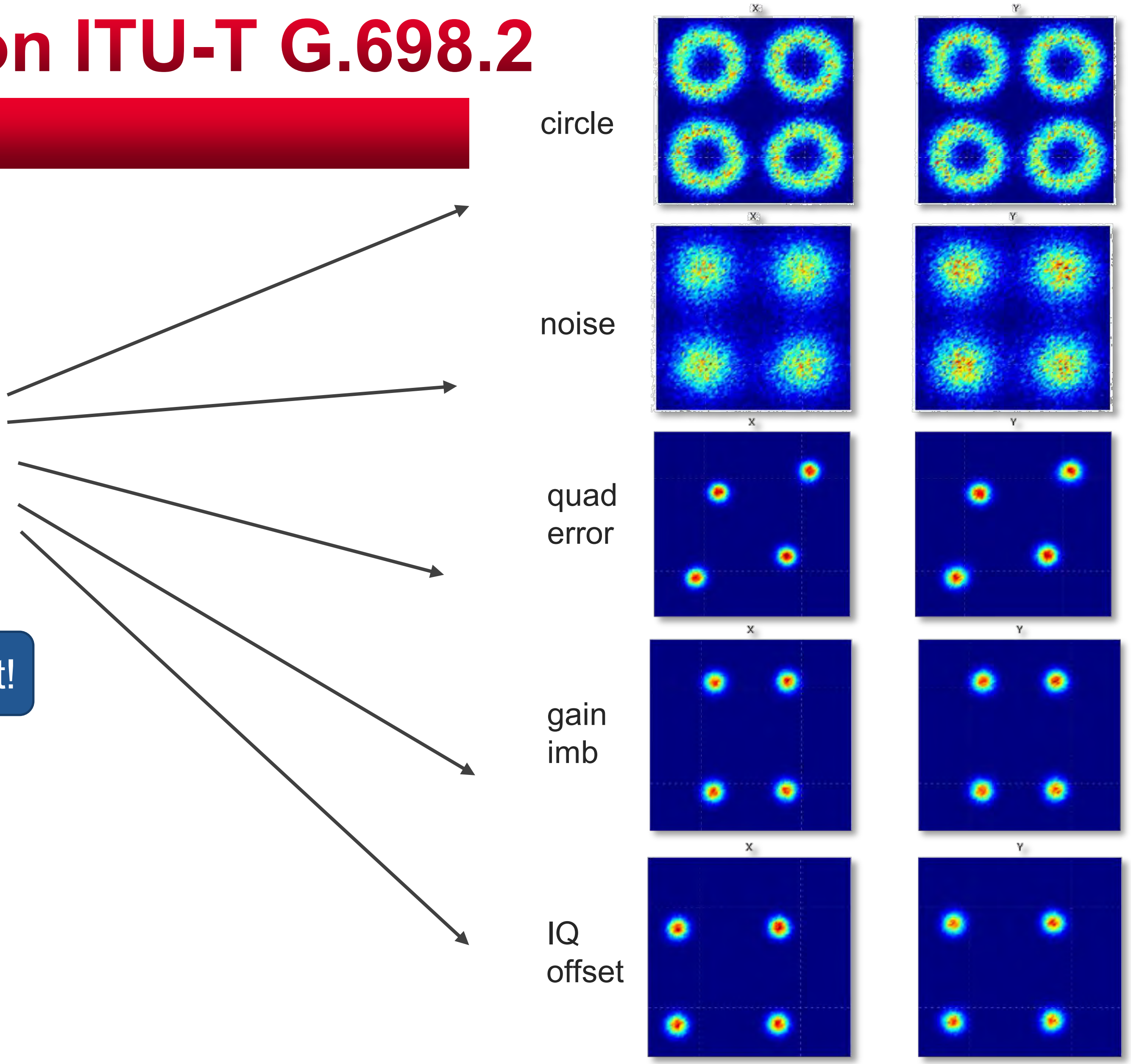
→ EVM_{rms} was found to have the best correlation to OSNR penalty

→ see next slides for details!

In-Force Recommendation ITU-T G.698.2

CIRCLE AND NOISE IMPAIRMENT





Measure OSNR penalty for each impairment!

Source: http://www.ieee802.org/3/cn/public/adhoc/18_1025/anslow_3cn_01_181025.pdf

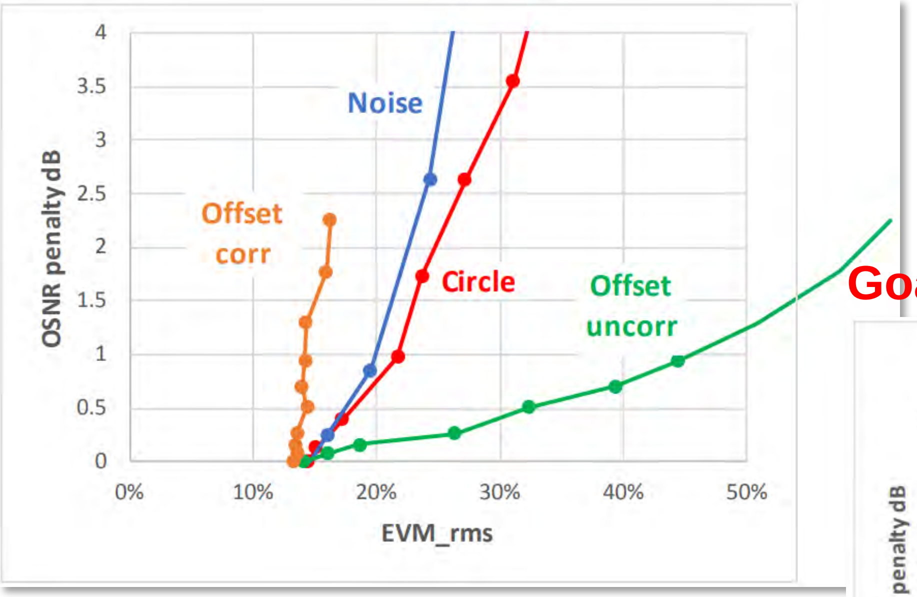
In-Force Recommendation ITU-T G.698.2

OSNR PENALTY AND EVM_{RMS}

DP-QPSK I-Q result

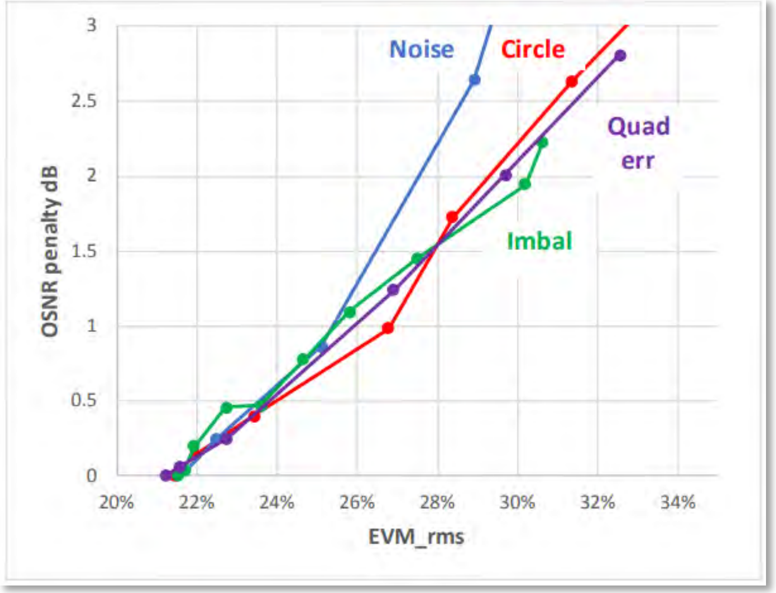
While most of the impairments show a similar curve when OSNR penalty is plotted vs EVM_{RMS} the curve for I-Q offset was found to be significantly different.
Consequently, any I-Q offset is removed from the measured data prior to the calculation of EVM_{RMS} and a separate limit for I-Q offset is applied.

All of the other impairments are plotted in the graph on the right hand side.



DP-QPSK OSNR Penalty vs. EVM_{RMS} including I-Q Offset

Goal: Recreate this plot for 16-QAM !



DP-QPSK OSNR Penalty vs. EVM_{RMS}

I-Q offset is specified separately.

Source: http://www.ieee802.org/3/cn/public/adhoc/18_1025/anslow_3cn_01_181025.pdf

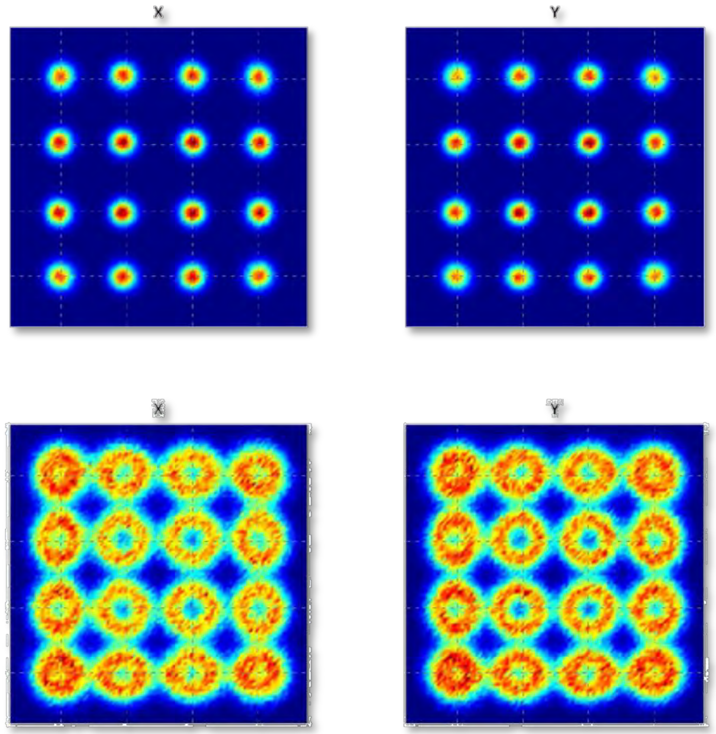
Outlook on Next Version of ITU-T G.698.2

DP-16QAM

DP-16QAM Circle impairment

No added impairment

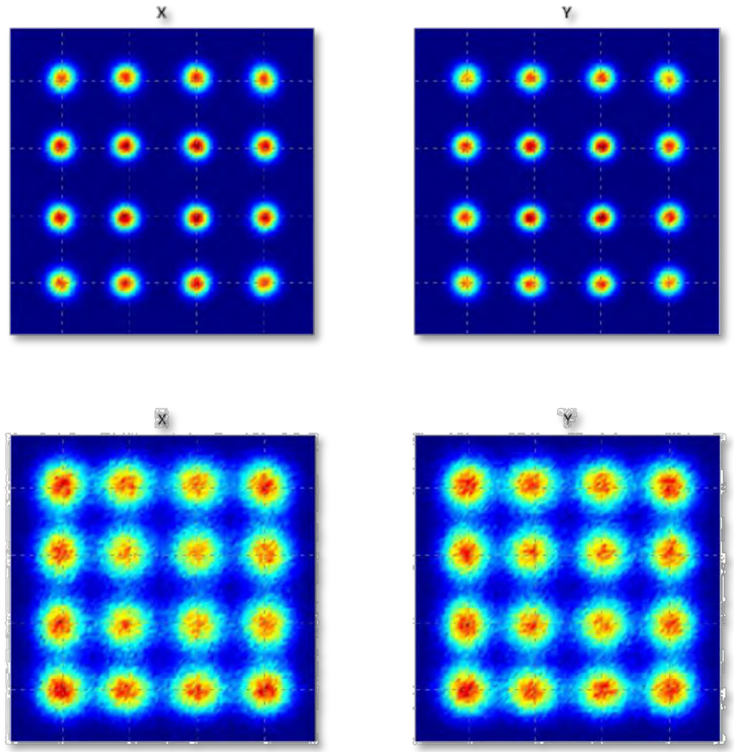
Circle impairment



DP-16QAM Noise impairment

No added impairment

Circle impairment



Source: http://www.ieee802.org/3/cn/public/adhoc/18_1025/anslow_3cn_01_181025.pdf !!!

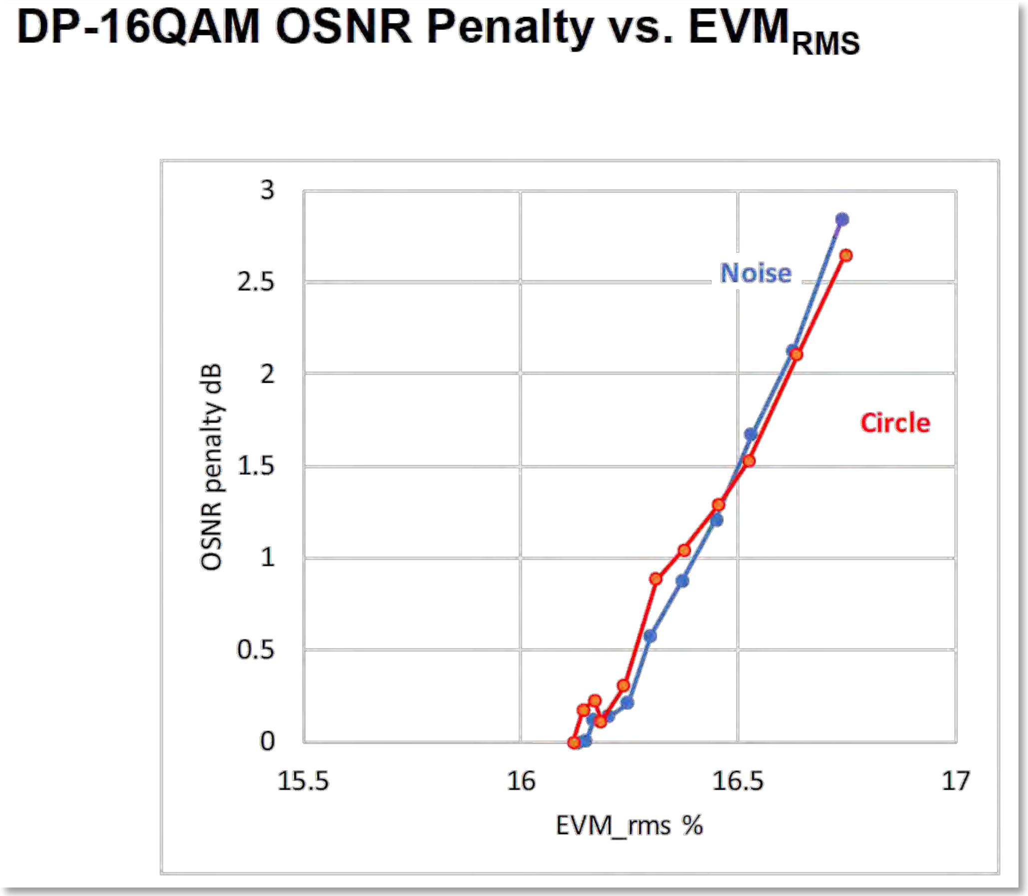
Outlook on Next Version of ITU-T G.698.2

OSNR PENALTY AND EVM_{RMS}

DP-16QAM I-Q result

First experiments seem to support that EVM_{RMS} is a good candidate for this modulation format as well.

More experiments are needed and currently conducted.



* EVM_rms dominated by noise loading here

Source: http://www.ieee802.org/3/cn/public/adhoc/18_1025/anslow_3cn_01_181025.pdf

Questions?