VPI University Program

Photonics Curriculum Version 7.0

Lecture Series

VPIphotonics™

Performance Benefits of Advanced Modulation Formats

System4

Developed in cooperation with
Acreo AB

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Module Prerequisites

- FOC1, FOC2
- Tx1, Tx2, Rx1
- Fiber1, Fiber2

Module Objectives

- Multilevel modulation
- Coherent Detection
- Equalization & digital signal processing (DSP)

Introduction

Transmission of 100Gb/s on a single wavelength:

- Binary modulation formats (NRZ, Duobinary, NRZ/VSB)
  - \+ Simple transmitter and receiver structures
  - \- Increased requirements on electrical and electro-optical components (electrical signals with ~100GHz)
  - – Sensitivity against CD & PMD (broad spectrum)

- Multilevel modulation formats (Pol-Mux-(RZ)-DQPSK, 16QAM, 8PSK)
  - \+ Narrower Spectrum (increased robustness against PMD &CD, higher spectral efficiency)
  - \+ Generic transmitter scheme (IQ modulator)
  - \- Receiver complexity for direct detection (DD) scheme

Multilevel Modulation & Coherent Detection

System Capacity → Spectral Efficiency → Multilevel Signaling → Coherent Detection

Utilize Amplifier Bandwidth

Power Penalty

	Modulation Format	Spectral Efficiency (Bit/s/Hz)
Binary	OOK	0.4
Binary	CRZ	0.8
Binary	CSRZ-DPSK	0.8
Multilevel	NRZ-QPSK	1.05
Multilevel	CSRZ-DQPSK	1.6 (pol-Mux)
Multilevel	QPSK	2.5 (pol-Mux)
Multilevel	64 QAM	3

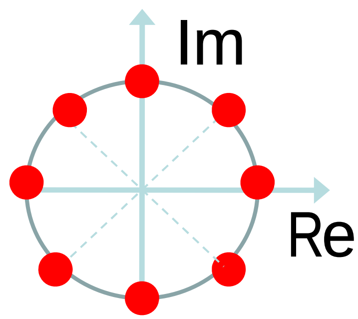
m \ Format	PSK	QAM	OOK	DPSK
2	0.0	-	3.5	0.45
4	0.0	0.0	8.9	2.2
8	3.5	2.6	13.7	6.5
16	8.2	4.0	-	11.2
32	13.2	6.0	-	-
64	-	8.5	-	-

SNR penalty per bit (dB) for multilevel signals [1]

[1] K.P. HO "Phase Modulated Optical Communication Systems", Springer, chapter "Multilevel Signaling"

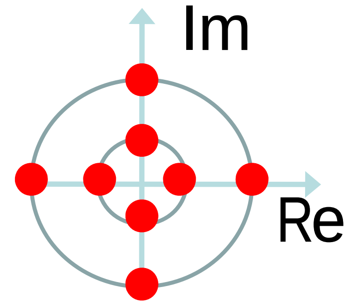
Constellations

mPSK-based constellations



Phase modulated

&

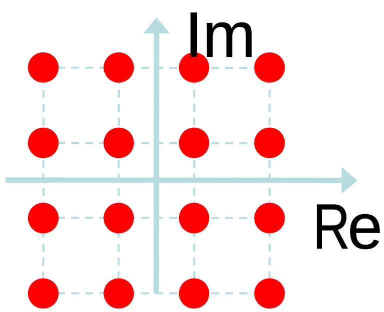


Star QAM (PSK + AM)

convenient Tx Structure:
I-Q, DD MZM, Serial PM (+AM)

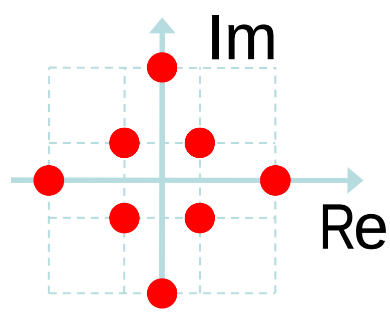
convenient Rx Structure:
90° Hybrid + 2 Balanced Detectors (4 for pol. Diversity Rx)

mQAM constellations ($m=2^N$)



QAM constellation (even N)

&

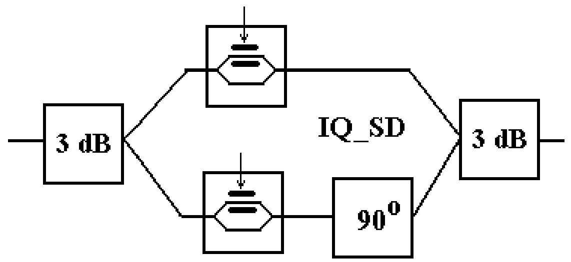


cross-constellation (odd N)

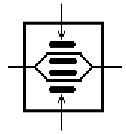
convenient Tx Structure:
I-Q, DD MZM, Serial PM+AM

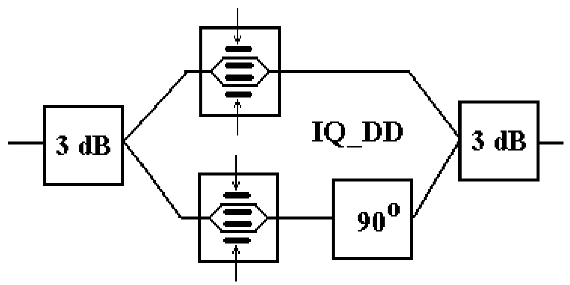
convenient Rx Structure:
90° Hybrid + 2 Balanced Detectors (4 for pol. Diversity Rx)

Tx Architectures

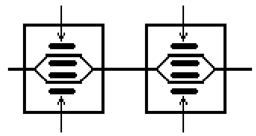


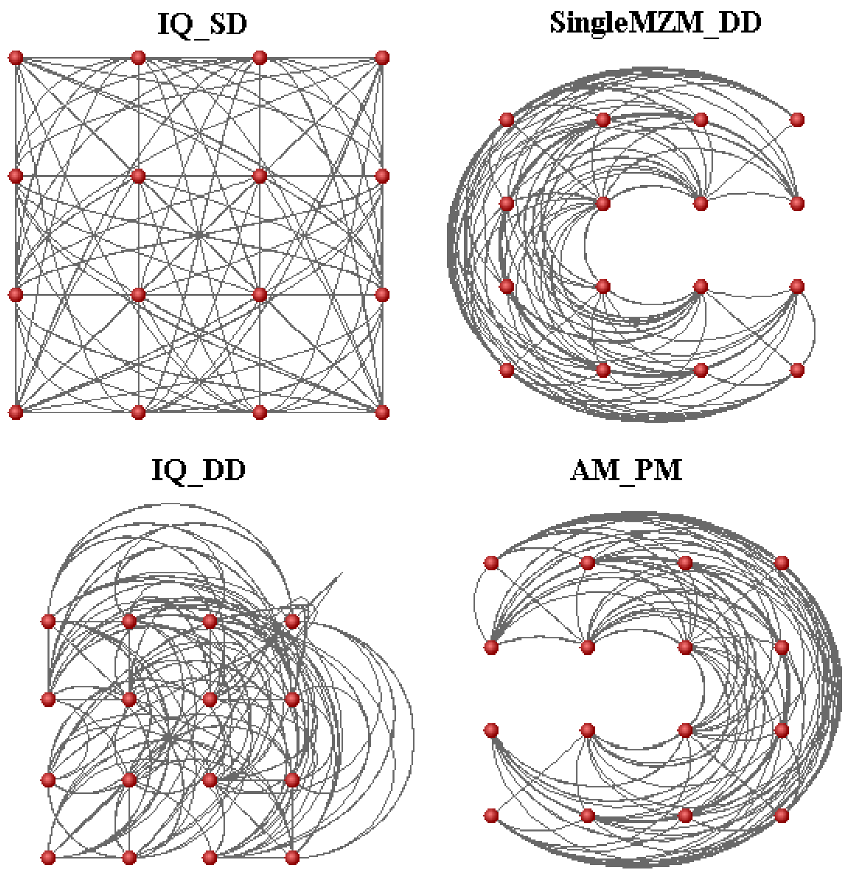
SingleMZM_DD





AM_PM





Various implementations possible

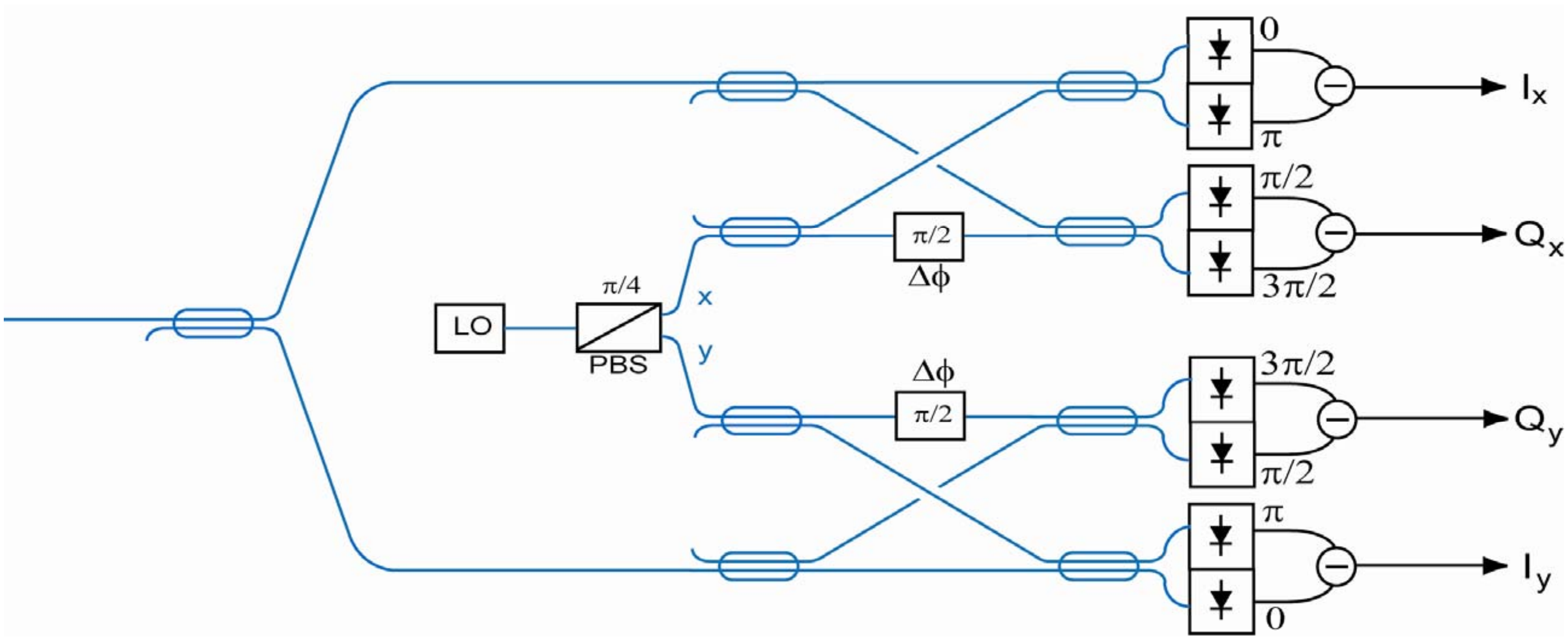
⇨ Consequences on transitions between constellation points

Coherent detection

- In DQPSK a MZI is used to compare the phase of a symbol with the preceding symbol. This allows to use direct detection we are all familiar with.
- Reasons for using coherent detection
  - Access to both **amplitude** and **phase** of the signal. Receiver is linear: in principle, **perfect equalization** of CD and PMD is possible using linear filters.
  - Improvement in receiver sensitivity
- Why has coherent detection not been used until now?
  - A local oscillator (LO) with frequency and phase locking is needed at the receiver. Optical phase lock loops (PLL) difficult to implement
  - The state of polarisation (SOP) of the LO needs to be aligned with the incoming signal, which has a random and not constant SOP. Adaptive polarisation tracking system is needed at the receiver which is difficult to implement
- Alternative solutions
  - Digital signal processing (**DSP**) to perform phase & carrier recovery

Coherent detection

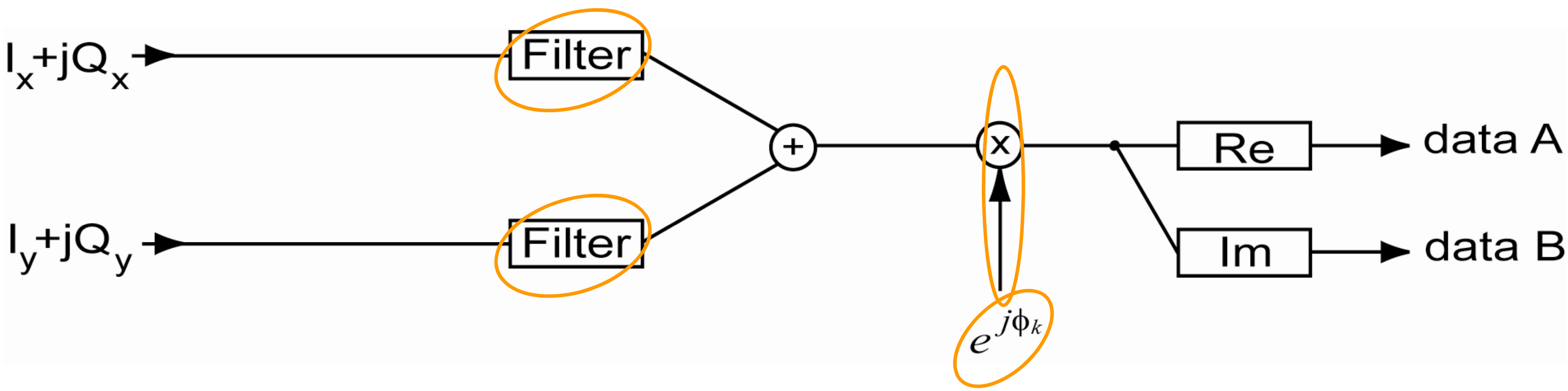
Recent progresses on digital signal processing (DSP) make it that signal can be detected with a free-running LO and with two sets of receivers with orthogonal SOP, so that the information (albeit randomly distributed on the two polarisation components) is detected.



DSP for coherent detection

Using linear digital signal processing is possible

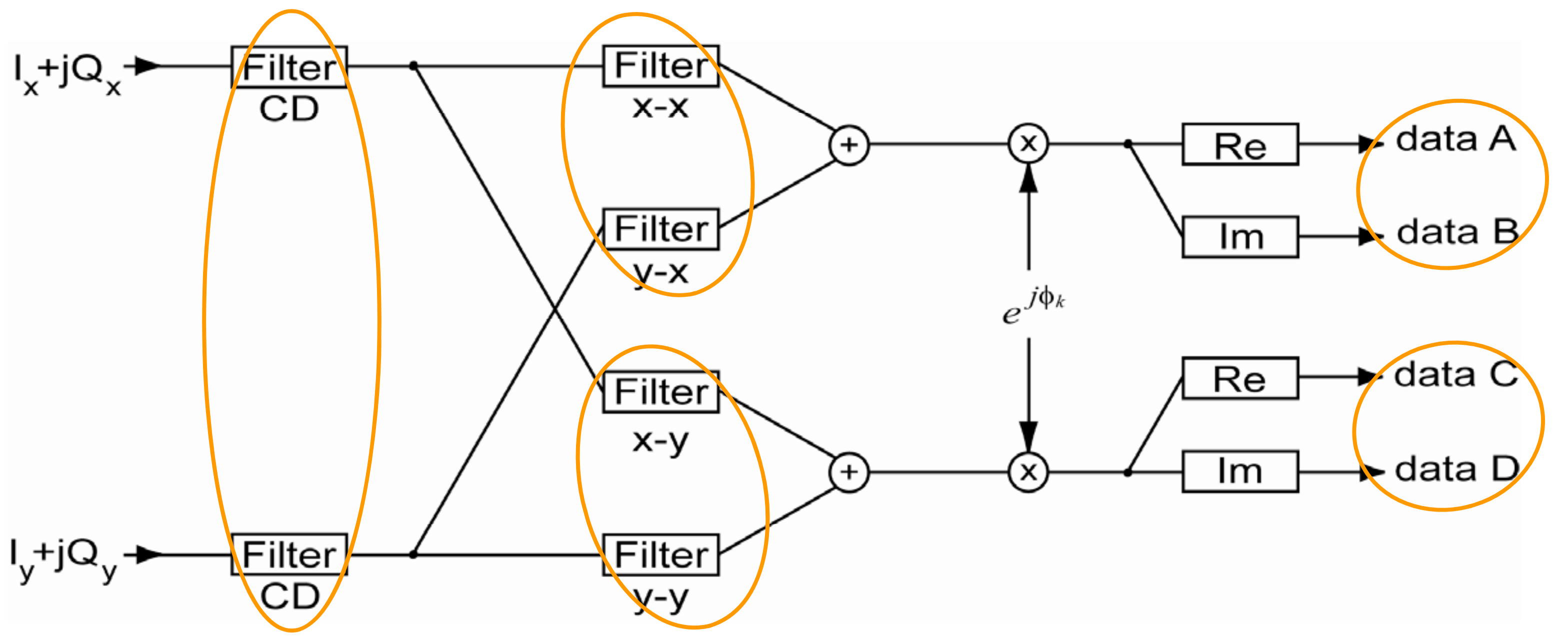
- to properly "re-shuffle" the information from the two polarisation components
- to remove the **phase error** induced by the fact that the LO is not locked to the transmitter laser



DSP for coherent detection: Side advantages

DSP enables:

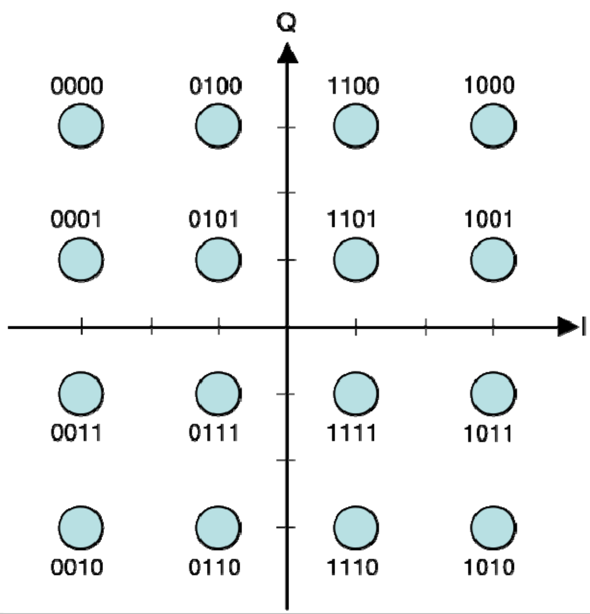
- Digital polarisation tracking (adaptive digital filters , e.g. FIR, which can be used to compensate for PMD)
- Digital polarisation tracking can be easily extended to detect two orthogonal polarisations each carrying data (double bit-rate with Pol-Mux)
- Chromatic dispersion compensation(FIR)



Coherent detection and higher-order modulation formats

Besides QPSK (2 bits per symbol), and Pol-Mux QPSK (4 bits per symbol with two polarisations), coherent detection enables the use of higher-order modulation formats such as M-QAM where both the in-phase and quadrature components of the optical carrier are modulated to transmit $\log_2(M)$ bits per symbol per polarisation

- M-QAM can be generated using the dual parallel MZM configuration (also referred to as an optical IQ-modulator) where each MZM is driven by a multi-level signal
- QPSK generated using an IQ-modulator is equivalent to 4-QAM, i.e. the in-phase and quadrature components are modulated by binary signals
- Using 16-QAM the spectral efficiency can be doubled compared to QPSK since four bits per symbol can be transmitted
- Using Gray coding ensures that neighbouring constellation points differ by only one bit which minimizes BER



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Performance costs and benefits of different modulation formats

	Scheme	Tx com-plexity	Rx com-plexity	Receiver sensitivity	CD tolerance	PMD tolerance	Nonlinear tolerance	Filtering tol. Spectral eff.
Direct detection	NRZ-OOK	Low	Lowest	Poor	Low	Low	Lowest	Low
Direct detection	RZ-OOK	Moderate	Low	Moderate	Lowest	Moderate	Low	Lowest
Direct detection	DPSK	Moderate	Moderate	Good	Moderate	Moderate	Moderate	Moderate
Direct detection	DQPSK	High	Quite high	Good	Moderate	High	Moderate	Rather good
Coherent detection and DSP	QPSK	High	High	Very good	Very high	Very high	Moderate?	Rather good
Coherent detection and DSP	Pol-Mux QPSK	Very high	Very high	Very good	Very high	Very high	Moderate?	Good
Coherent detection and DSP	16-QAM	High	High	Moderate	Very high	Very high	?	Very good
Coherent detection and DSP	Pol-Mux 16-QAM	Very high	Very high	Moderate	Very high	Very high	?	Very good

Summary

- Digital Data Modulation and basics of modulation formats
- Amplitude Shift Keying transmitters and receivers
- Phase Shift Keying transmitters and receivers (differential detection)
- Coherent detection with DSP

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