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Introduction to New Modulation Formats

27 March 2017

Traditional Power Modulation

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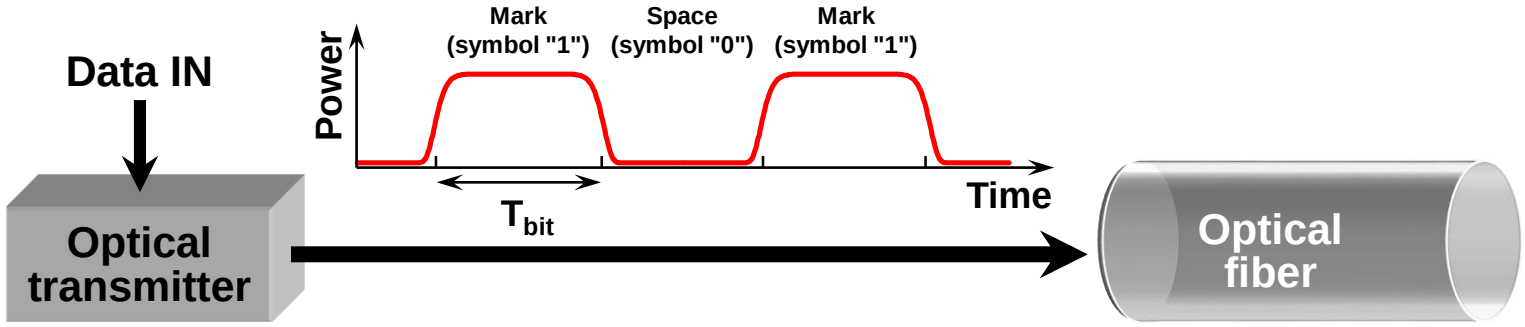
- Optical data transport started with the simplest (and therefore cheapest) digital coding schemes: On/Off-Keying (OOK).
- Modulated physical parameter: amplitude (power) of the optical wave
- Detection is carried out by a simple photodetector that detects fluctuations in the power level hitting the receiver (direct detection).
- Each transmitted symbol takes two values: low optical power level (digital 0) or high optical power level (digital 1).
- Each transmitted symbol can be encoded with one bit (binary digit):
  - 0 for low optical power level
  - 1 for high optical power level



Symbol Rate and Bit Rate

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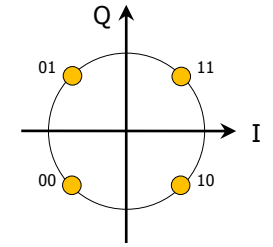
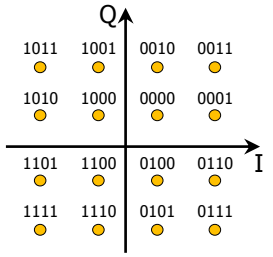
- In the case of traditional two-level power modulation (e.g. OOK/ASK), the symbol rate is equal to the bit rate.
  - E.g. 10 giga symbols per second = 10 Gbit/s
- In telecommunication theory, baud is the unit of the symbol rate.
  - E.g. 10 giga symbols per second = 10 Gbaud
- Current and midterm opto-electronics technologies are limited to about 64 Gbaud. In order to transmit 100 Gbit/s per wavelength, more bits per symbol are required.

Solution: multi-level modulation format

- Example # 1: Four-level modulation format
  - Symbols can take 4 different values (e.g. 0, 1, 2 and 3).
  - 2 bits are encoded in one symbol (00, 01, 10 and 11).
- Example # 1: Sixteen-level modulation format
  - Symbols can take 16 different values (e.g. 0 to 15).
  - 4 bits are encoded in one symbol (0000 to 1111).



QPSK



16QAM

100G Implementation With QPSK Modulation Format

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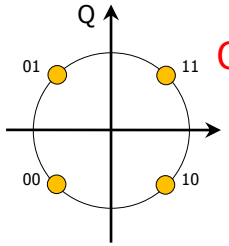
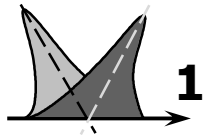
25 Gbaud opto-electronics	Four-level modulation Format (QPSK)	Polarization Multiplexing (PM)

25 Gbaud



QPSK

50 Gbit/s



100 Gbit/s

- Using opto-electronics components (available since 2010) delivering 25 giga symbols per second (Gbaud).
- Using four-level modulation format:
  - Quadrature Phase Shift Keying (QPSK)
    - Two bits are encoded in one symbol (see figure above).
  - Doubles the number of bits per second (from 25 Gbaud to 50 Gbit/s)
- Multiplexing two orthogonal states of optical polarization
  - Polarization Multiplexing (PM)
  - Doubles the number of bits per second (from 50 to 100 Gbit/s).

➔ PM-QPSK modulation format for building 100 Gbit/s data stream starting from 25 Gbaud opto-electronics and using different multiplexing dimensions (modulation level and polarization).

200G Implementation With 16QAM Modulation Format

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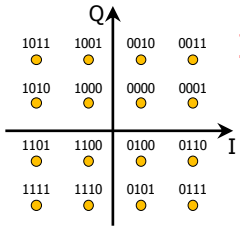
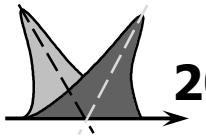
25 Gbaud opto-electronics	Sixteen-level modulation Format (16QAM)	Polarization Multiplexing (PM)

25 Gbaud



16QAM

100 Gbit/s



200 Gbit/s

- Using opto-electronics components (available since 2010) delivering 25 giga symbols per second (Gbaud).
- Using sixteen-level modulation format:
  - Sixteen-level Quadrature Amplitude Modulation (16QAM)
    - Four bits are encoded in one symbol (see figure above).
  - Quadruples the number of bits per second (from 25 Gbaud to 100 Gbit/s)
- Multiplexing two orthogonal states of optical polarization
  - Polarization Multiplexing (PM)
  - Doubles the number of bits per second (from 100 to 200 Gbit/s).

➔ PM-16QAM modulation format for building 200 Gbit/s data stream starting from 25 Gbaud opto-electronics and using different multiplexing dimensions (modulation level and polarization).

400G Implementation

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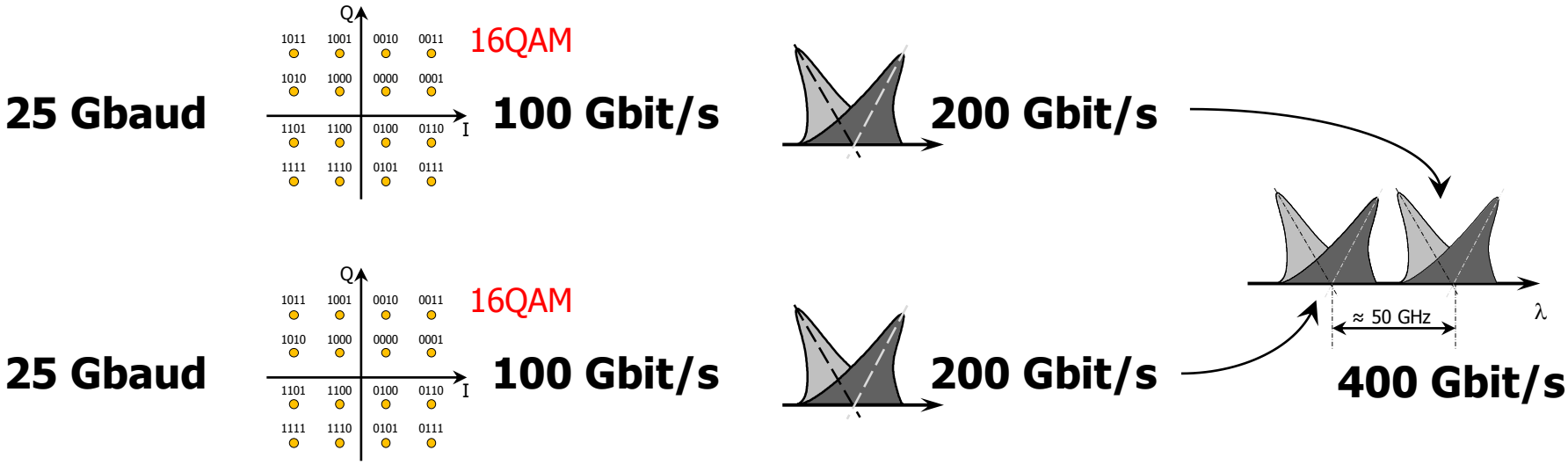
25 Gbaud opto-electronics	Sixteen-level modulation Format (16QAM)	Polarization Multiplexing (PM)	Dual-carrier implementation



- In the most common approach, a 400G optical channel is "simply" the combination of two optical carriers, each supporting a 200 Gbit/s data stream and using the PM-16QAM modulation format.

➔ 400G dual-carrier implementation
(Generally-used acronym: DC-PM-16QAM)

➔ Three multiplexing dimensions (modulation level, polarization, wavelength) are combined to go from 25 giga symbols per second to 400 Gbit/s.

100/200/400G Implementations

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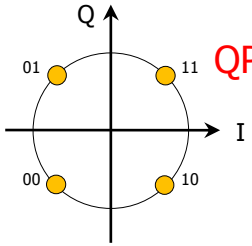
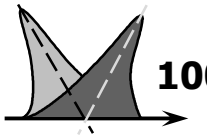
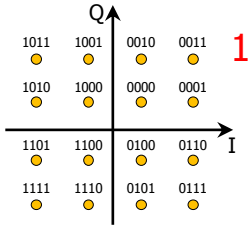
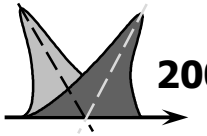
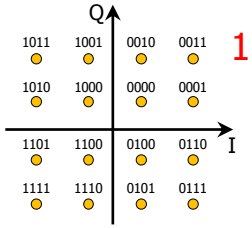
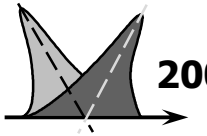
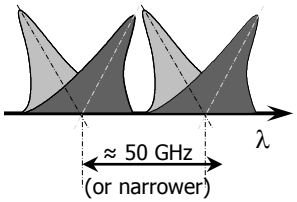
	25 Gbaud opto-electronics	Multi-level modulation format	Polarization Multiplexing (PM)	Dual-carrier implementation
100G PM-QPSK	**25 Gbaud**	 QPSK **50 Gbit/s**	 **100 Gbit/s**	
200G PM-16QAM	**25 Gbaud**	 16QAM **100 Gbit/s**	 **200 Gbit/s**	
400G DC-PM-16QAM	**25 Gbaud**	 16QAM **100 Gbit/s**	 **200 Gbit/s**	 **400 Gbit/s**

N-level modulation format + Coherent detection + Digital signal processing

Additional Modulation Formats

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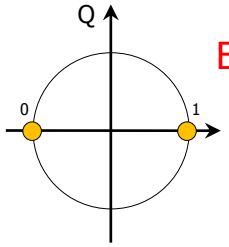
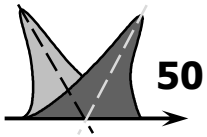
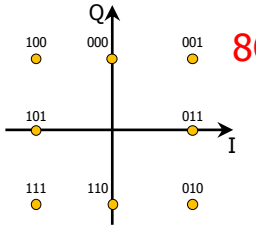
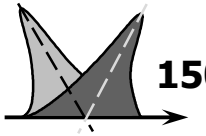
	25 Gbaud opto-electronics	Multi-level modulation format	Polarization Multiplexing (PM)	Dual-carrier implementation
50G PM-BPSK	**25 Gbaud**	 BPSK **25 Gbit/s**	 **50 Gbit/s**	
150G PM-8QAM	**25 Gbaud**	 8QAM **75 Gbit/s**	 **150 Gbit/s**	

- BPSK (1 bit per symbol): More robust to OSNR and nonlinearities due to longer inter-symbol distances compared to QPSK.
- 8QAM (3 bits per symbol): Can be seen as a good trade-off between capacity and reach as it enabled (in 2015) about 1,400 km reach, covering about 80% of the circuit lengths in a typical US backbone network (Source: AT&T / Acacia at OFC 2015)

Constellation Plots for Various-Order Modulation Formats

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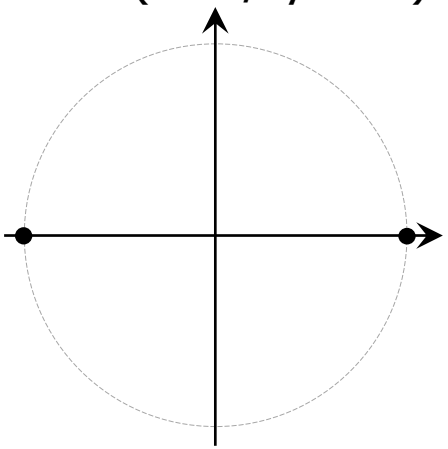
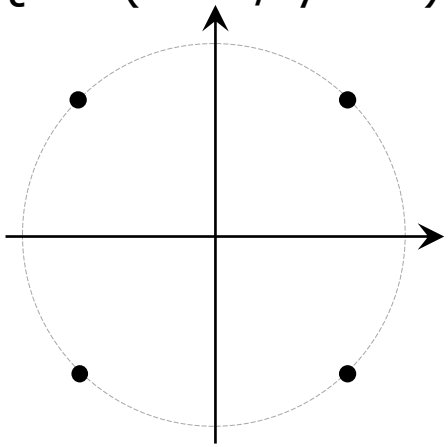
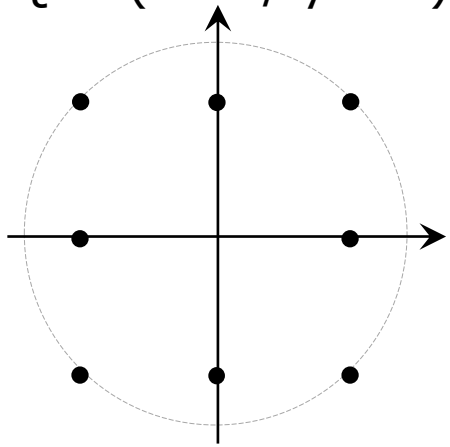
BPSK (1 bit/symbol)



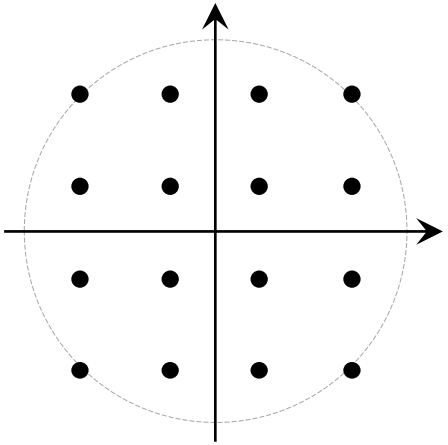
QPSK (2 bits/symbol)



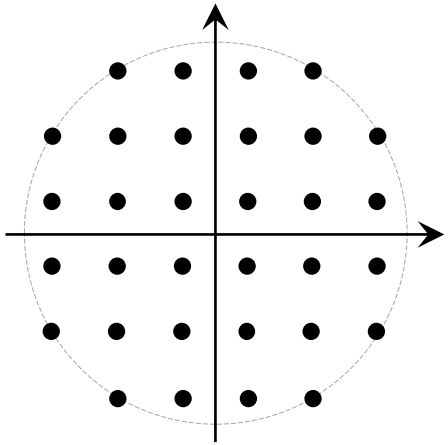
8QAM (3 bits/symbol)



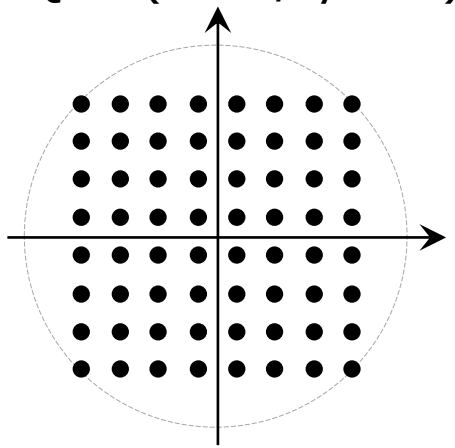
16QAM (4 bits/symbol)



32QAM (5 bits/symbol)



64QAM (6 bits/symbol)



Practical Implementation With 30 Gbaud Opto-Electronics

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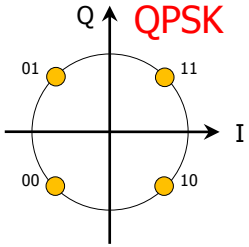
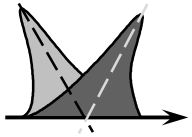
Number of transported bits (**X Gbit/s**) obtainable starting from 32 Gbaud (: 32 Gsymbols per second) opto-electronics and using different multiplexing dimensions

Multi-level modulation format	Polarization Multiplexing (PM)	Optical carrier multiplexing

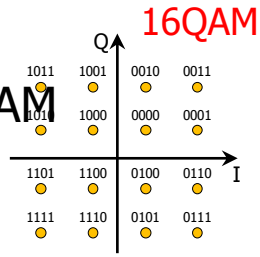
- PM-QPSK

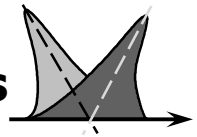
32 Gbaud 

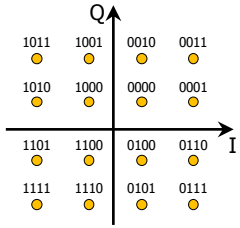
64 Gbit/s  **128 Gbit/s**

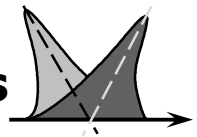
Larger than 100 Gbit/s as it accounts for Soft-Decision Forward Error Correction (SD-FEC) overhead

- DC PM-16QAM

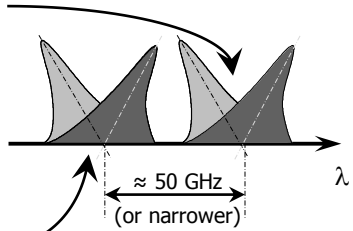
32 Gbaud 

128 Gbit/s  **256 Gbit/s**

32 Gbaud 

128 Gbit/s  **256 Gbit/s**

Dual-carrier implementation



512 Gbit/s

For 400 Gbit/s payload

A Few More Words About Coherent Technology

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- QPSK and 16QAM modulation formats were introduced in optical communications only a few years ago while they have been used in radio communications since the 60s.
  Also more complex modulation formats are commonly used in radio (e.g. 64QAM).

- Optical direct detection does no longer work with QPSK or 16QAM as both phase and amplitude need to be detected.
  ➔ Use of coherent detector (recent innovation in optical communications, but used since several decades for FM radio)

- Year after year, multiple improvements:
  - More powerful Digital Signal Processing (DSP) with smaller node CMOS technology and higher transistor count
  - Pre-transmission signal processing/shaping
  - New modulation technologies, (e.g. probabilistic constellation shaping)
  - Narrower linewidth laser sources

A Few More Words About Coherent Technology

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- *Super channels* are made of a concatenation of, e.g., 200G carriers (built with PM-16QAM modulation format) with carrier spacing equal to or smaller than 50 GHz.
- There is no fundamental limit (except the system spectrum) to the super channel bit rate.
  - 1 Tbit/s super channel is made of, e.g., 5 x 200G carriers.
  - 3 Tbit/s super channel is made of, e.g., 15 x 200G carriers.
  - Note: 400G channels built upon two 200G carriers are "mini" super channels.

Multiple Symbol Rate x Modulation Scheme Combinations

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Symbol Rate (Gbaud)	Modulation Scheme	Symbol Rate minus Overhead (Gbaud)	Bits per symbol	Effective Bit Rate per Polarization (Gbit/s)	Optical States of Polarization	Effective Carrier Bit Rate (Gbit/s)
32	PM-BPSK	25	1	25	2	50
32	PM-QPSK	25	2	50	2	100
32	PM-8QAM	25	3	75	2	150
32	PM-16QAM	25	4	100	2	200
32	PM-64QAM	25	6	150	2	300
43	PM-8QAM	33	3	100	2	200
64	PM-QPSK	50	2	100	2	200
64	PM-8QAM	50	3	150	2	300
64	PM-16QAM	50	4	200	2	400
64	PM-64QAM	50	6	300	2	600

Multiple Symbol Rate x Modulation Scheme Combinations

Optical Cloud Infra

Symbol Rate (Gbaud)	Modulation Scheme	Symbol Rate minus Overhead (Gbaud)	Bits per symbol	Effective Bit Rate per Polarization (Gbit/s)	Optical States of Polarization	Effective Carrier Bit Rate (Gbit/s)
32	PM-16QAM	25	4	100	2	200
43	PM-8QAM	33	3	100	2	200
64	PM-QPSK	50	2	100	2	200

200G carrier rate can be achieved via (at least) 3 different combinations.

- From PM-16QAM to PM-QPSK, the inter-symbol distance inside the constellation increases ➔ Higher optical signal-to-noise ratio and lower sensitivity to noise/distortion
- From 32 to 64 Gbaud, symbol duration gets shorter and the energy per symbol is smaller ➔ Reduced receiver sensitivity
- Practically speaking, lower-order modulation format exhibits longer reach (e.g. 200G carriers with PM-8QAM / 43 Gbaud go further than with PM-16QAM / 32 Gbaud).

PAM4
4-Level Pulse Amplitude Modulation

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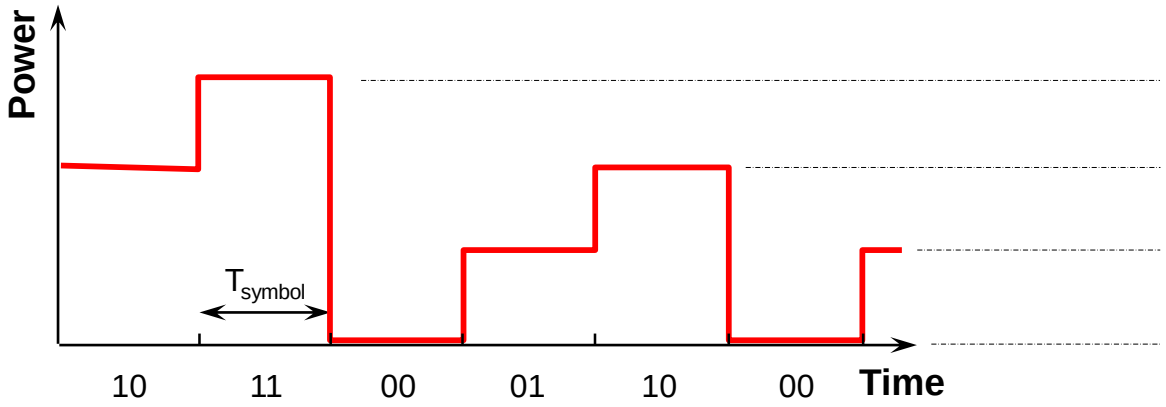

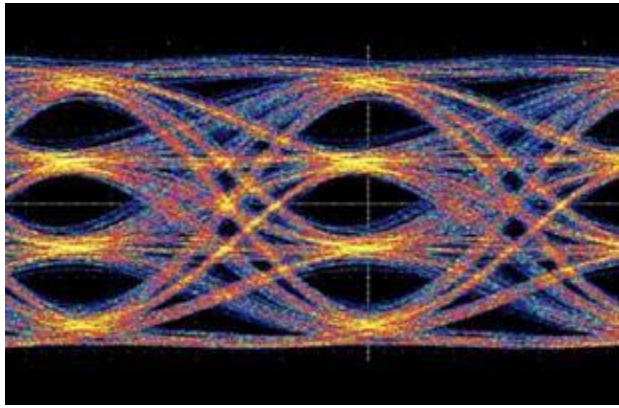

- Four-level modulation format
  - Symbols can take 4 different values (e.g. 0, 1, 2 and 3).
  - 2 bits are encoded in one symbol (00, 01, 10 and 11).
  - For example, a 56 Gbit/s PAM4 signal is transmitted at 28 Gbaud symbol rate.

- Direct detection is used, together with digital signal processing techniques similar to those used for coherent detection (see example on next slide).

- Promoted for 100G and beyond optical pluggable transceivers for both intra data center and short (< 80 km) inter data center interconnect.

PAM4
Digital Signal Processing

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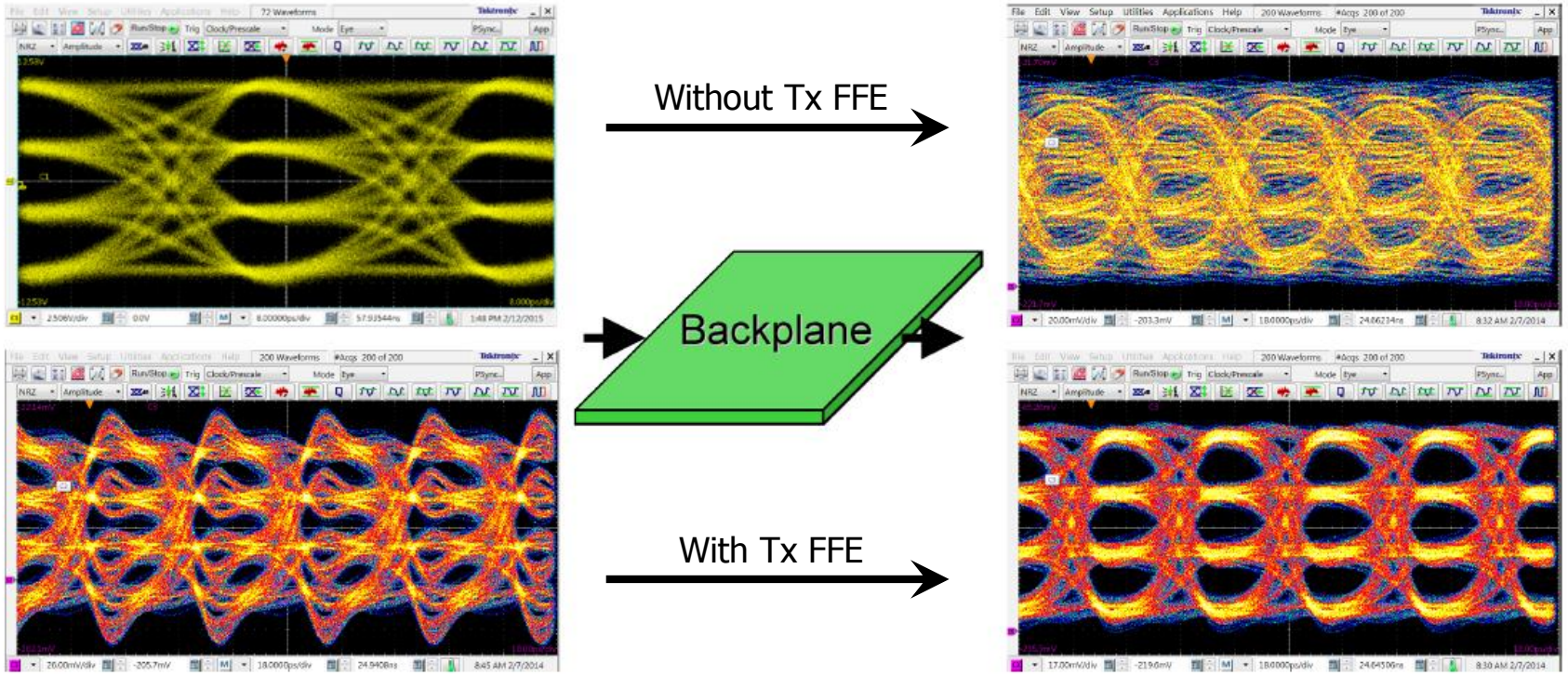
PAM4 eye diagrams prior to and after propagating through a backplane

- Top without transmitter Feed-Forward Equalization (FFE)
- Bottom, with transmitter FFE



PAM4 Ecosystem

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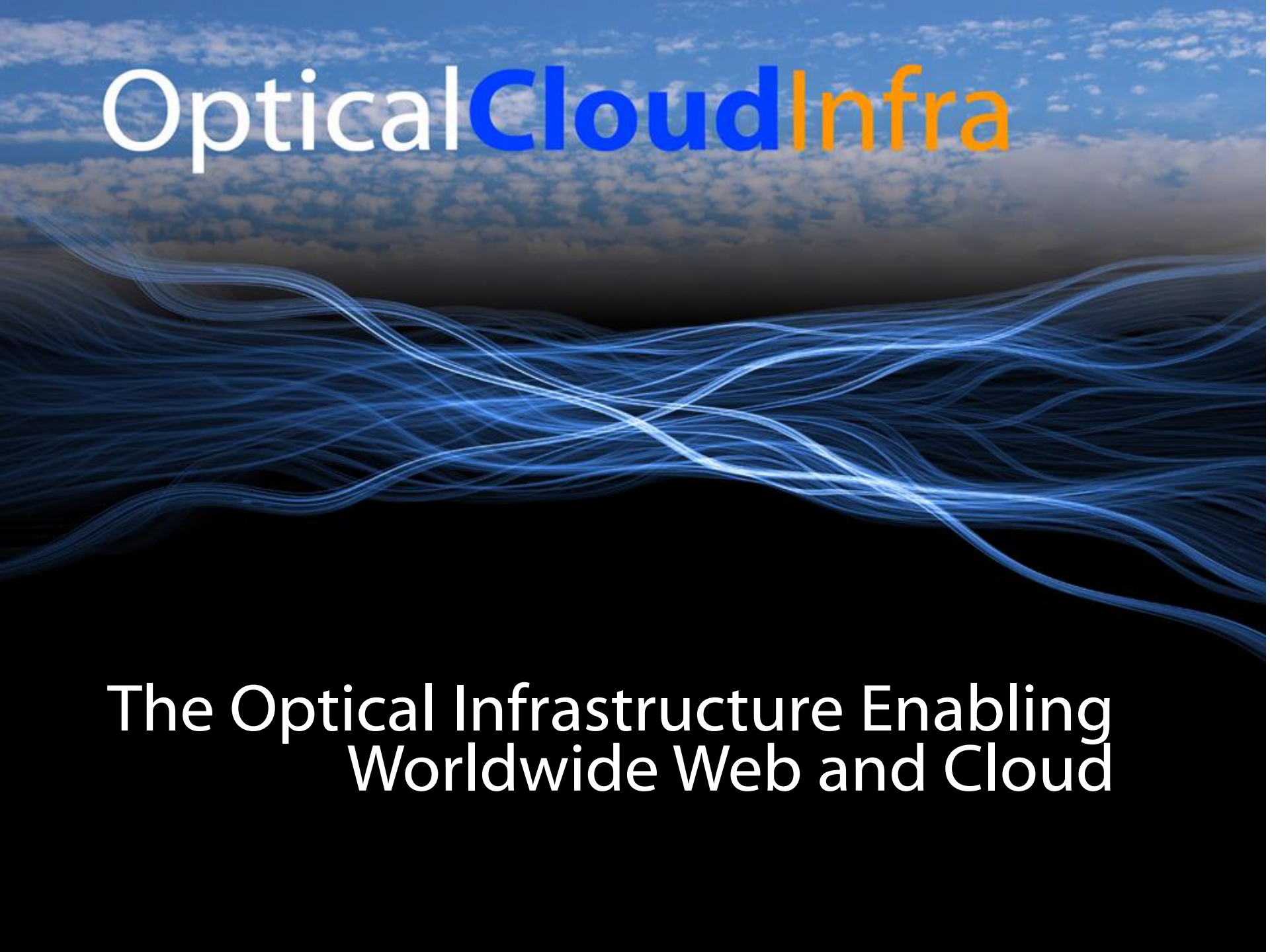
- PAM4 chips based on CMOS technology with two channels of 50 Gbit/s PAM4 (2 x 50 Gbit/s) was available in 2015.
- PAM4 chips with a single channel of 100 Gbit/s (1 x 100 Gbit/s) was available in 2016.
- 100G PAM4 QSFP28 module was announced in March 2017.



The Optical Infrastructure Enabling Worldwide Web and Cloud