II-VI

MATERIALS THAT MATTER

Overview of Coherent Technology

Enabling Next-Generation Networks

IX Forum 13 – December 2019

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FINISAR

is now part of

II-VI

II-VI Expands Compound Semiconductors and Photonic Solutions Platforms Through its Acquisition of FINISAR

A Transformative Combination

II-VI
FINISAR®

$2.6B
Pro Forma Revenue[1]

$650M
Pro Forma EBITDA[1]

70
Locations Worldwide
Diversified Global Footprint

7
Target End Markets

$22B
Addressable Market Size[2]

26K
Total Employees Worldwide

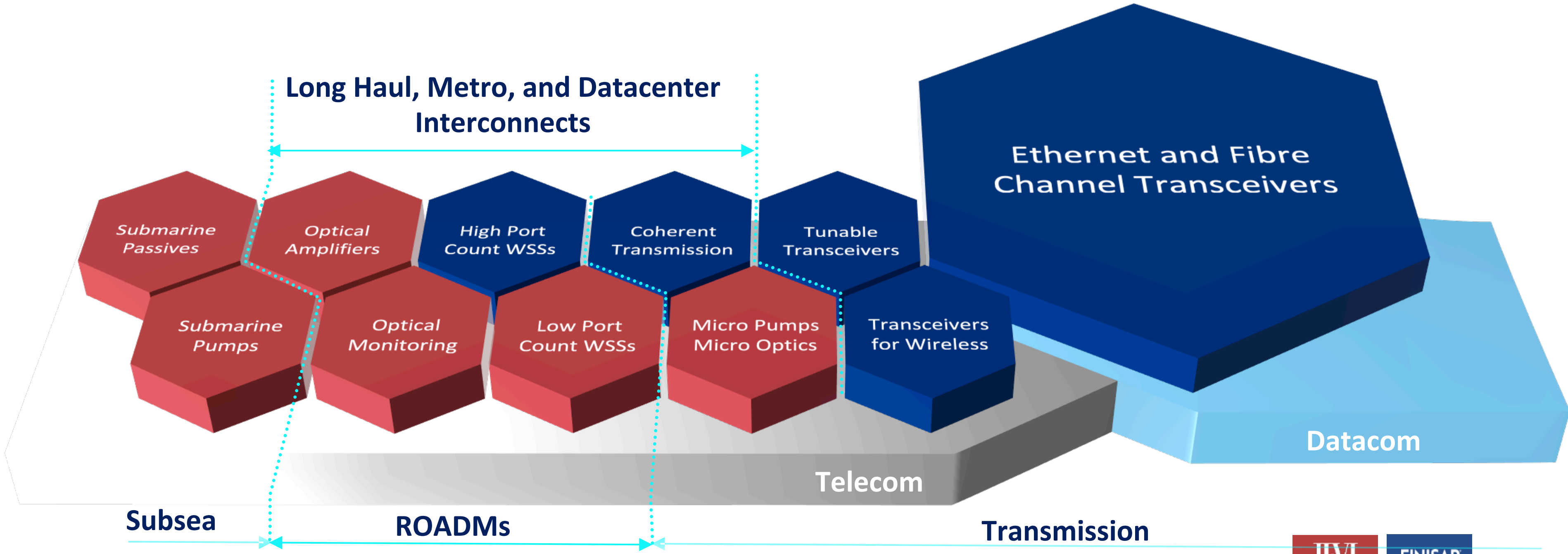
"TWO SIX" Refers to groups **II** and **VI** of the Periodic Table of Elements

Note: Pro forma Revenue and EBITDA represents LTM 06/30/2019 for II-VI and LTM 07/28/2019 for Finisar.

1. Represents LTM 06/30/2019 for II-VI plus LTM 07/28/2019 for Finisar and includes $150mm run-rate synergies for EBITDA. EBITDA excludes amortization of intangibles, the impact of SFAS 123(R) stock-based compensation expense and one-time charges.
2. 2022 estimated market size. Includes 3D Sensing, Power Devices for Automotive and Wireless RF size from Yole, Optical Communications from Lightcounting and Ovum, Industrial Processing, Military, Life Sciences from Strategies Unlimited.

#1 in Optical Communications

A highly complementary and complete portfolio of leading-edge products

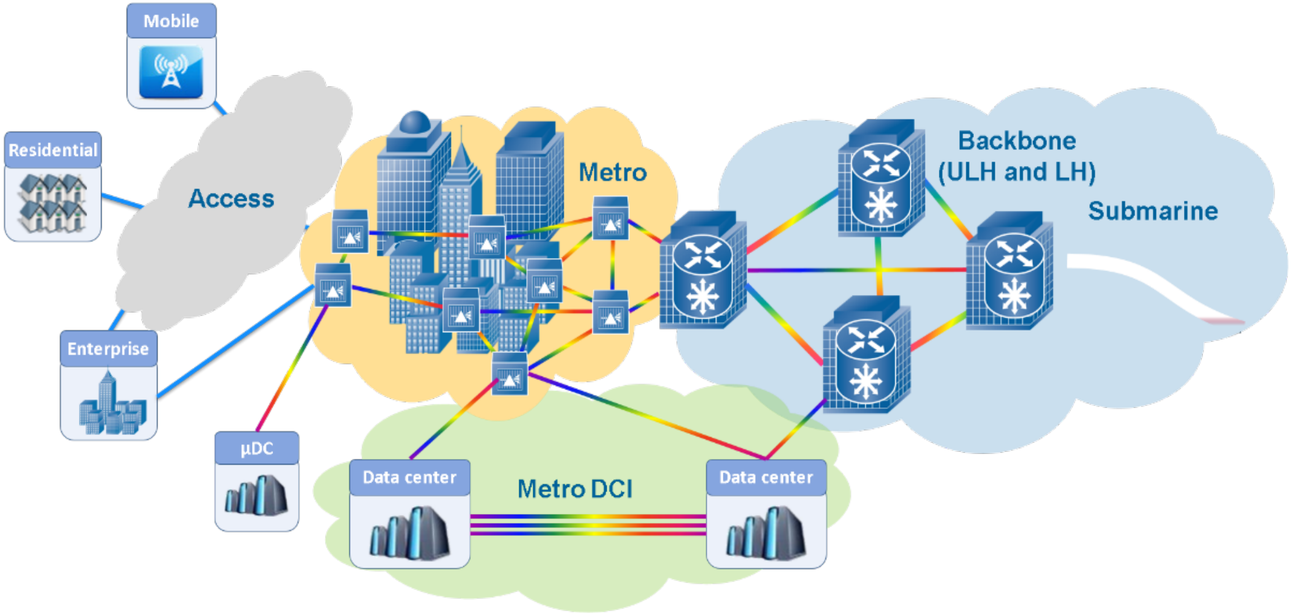


What is the Demand that is Driving Coherent?

- Today's metro/core networks need to support data rates of 100Gbit/s & 200Gbit/s.
- Deployment of 400Gbit/s will start very soon.
- Optics R&D at even higher rates is being launched to support beyond 1Tbit/s.

Achieving these data rates is a difficult problem for traditional data coding streams (RZ/NRZ, etc.)

Coherent technology offers techniques to address the limitations of legacy modulation schemes



DCI in the Network Core and to the Edge

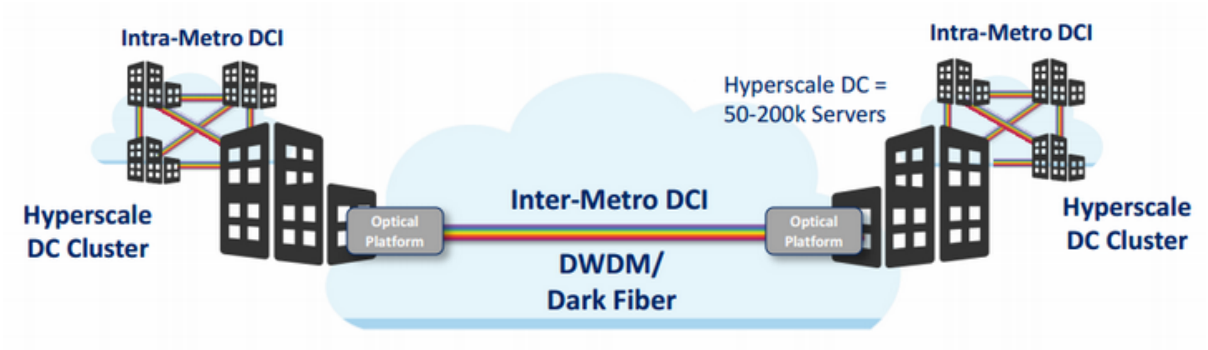
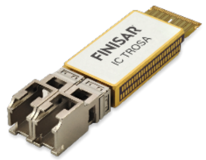


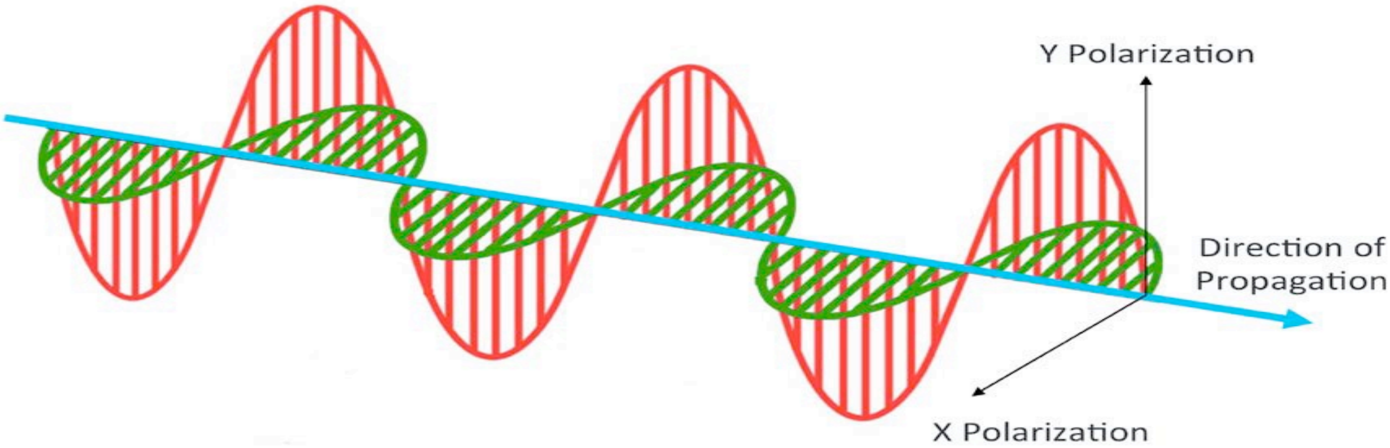
Image: Converge! Network Digest, February 2015

- **Coherent interfaces are capturing the ~100km market at 100G, 200G and 400G data rates.**
  - Direct detection likely lower power/cost for the next few years. E.g., 400GBASE-ER8 modules (40km).
- **Standardization work by OIF 400ZR IA and IEEE P802.3ct Task Force (400GBASE-ZR).**
- **DCI interfaces will take advantage of emerging coherent technologies.**
  - OIF IC-TROSA optical packaging.
  - DSPs based on 7nm CMOS.



Coherent Modulation

"At its most basic, **coherent optical transmission** is a technique that uses **modulation** of the amplitude and phase of the light, as well as transmission across two polarizations, to enable the transport of considerably more information through a fiber optic cable."



Coherent Modulation

What is Coherent: “From a Text Book Point of View”

Light is a transversal electromagnetic wave

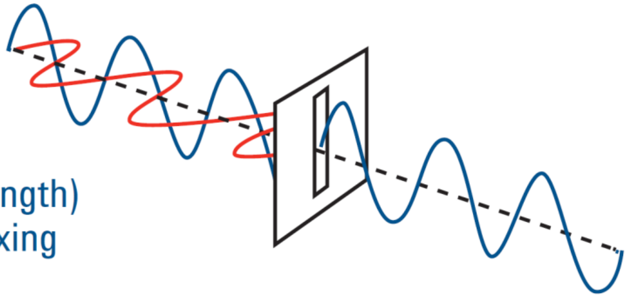
$$\vec{E} = \begin{bmatrix} E_x \\ E_y \end{bmatrix} = \begin{bmatrix} E_x e^{i\phi_x} \\ E_y e^{i\phi_y} \end{bmatrix} e^{i(\omega \cdot t - k \cdot z)} = \begin{bmatrix} I_x + iQ_x \\ I_y + iQ_y \end{bmatrix} e^{i(\omega \cdot t - k \cdot z)}$$

Polarization division multiplexing

Phase modulation

Amplitude modulation

Frequency (wavelength) division multiplexing



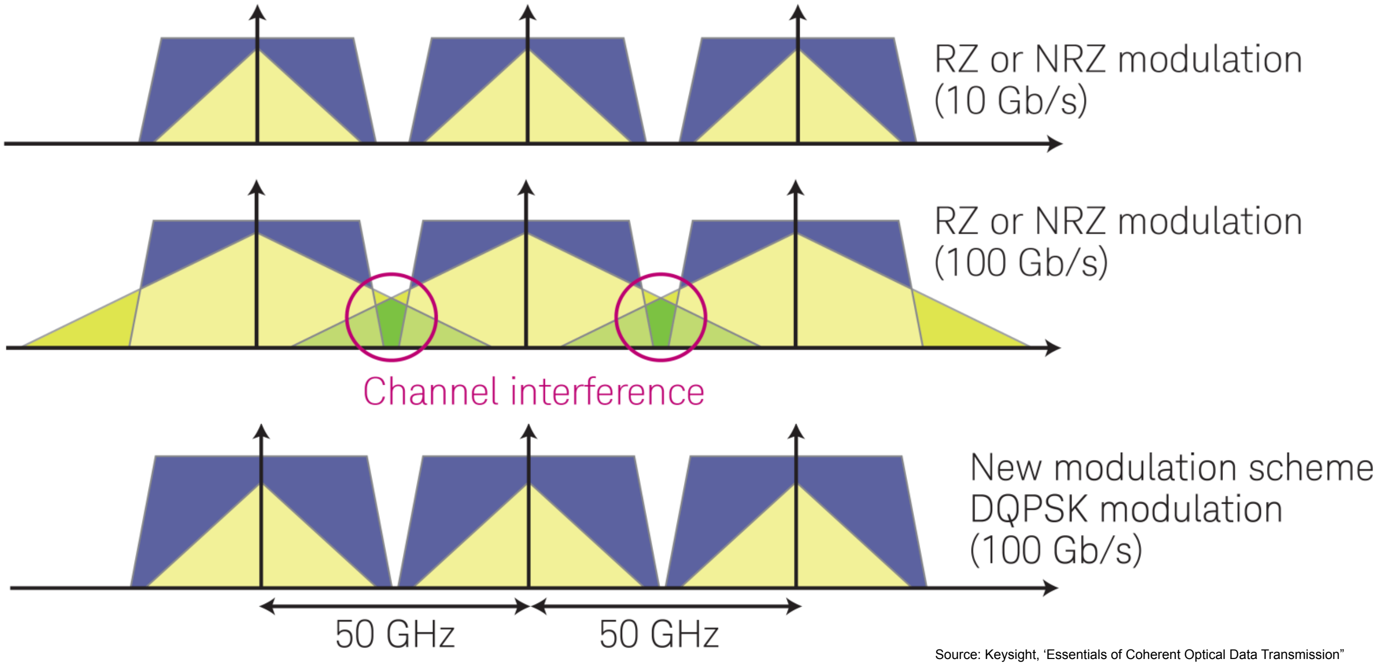
Source: Keysight, ‘Essentials of Coherent Optical Data Transmission”

Why Use Coherent vs. Traditional OOK (RZ/NRZ)

For data rates 40Gbit/s and above traditional (On-Off-Keying: i.e., NRZ/RZ) coding schemes face limits imposed by the high clock rate, bandwidth and channel broadening to fit into the traditional 50GHz DWDM ITU channels.

100Gb/s implemented with NRZ results in channels much greater than 50GHz to fit into the ITU grid

Coherent Modulation reduces bandwidth so that 100Gb/s can be transmitted in the ITU 50GHz grid



Source: Keysight, 'Essentials of Coherent Optical Data Transmission"

Transmitting Symbols Instead of Bits

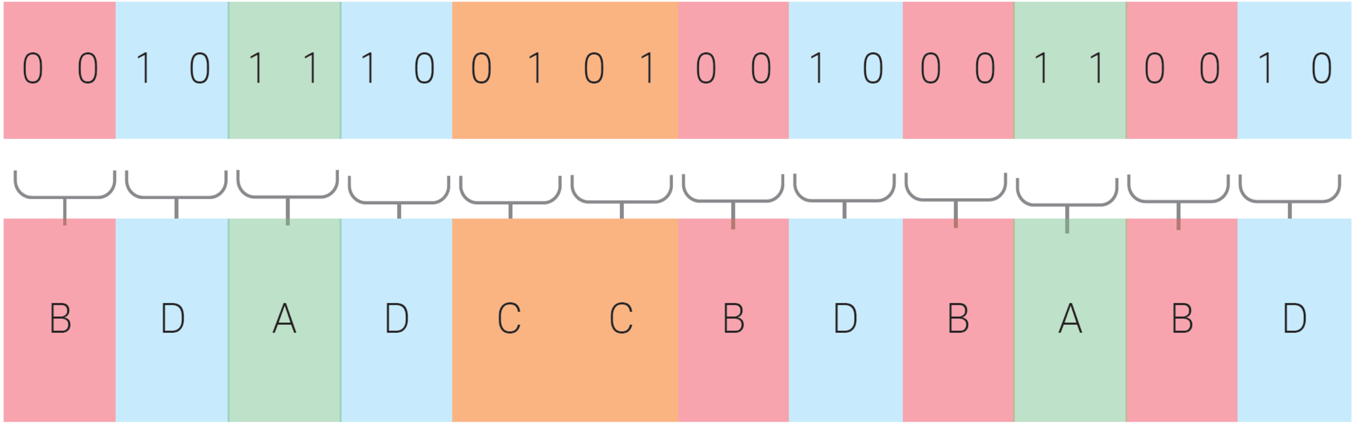
The fundamental drawback of NRZ/RZ modulation is that each channel only transmits one bit of information, one symbol at a time.

Formats like Coherent transmit several bits of information at a time, allowing higher data throughput to be transmitted through the same fiber.

A binary sequence of "1"s and "0"s has been coded into symbols using 2 bits/symbol

Transmitting symbols sends twice the amount of data in the same amount time

Several sequential bits of binary data are coded or mapped to a new "symbol". A stream of these symbols are then transmitted instead of bits on the optical carriers



Source: Keysight, 'Essentials of Coherent Optical Data Transmission"

How do you Transmit Symbols Instead of Bits?

In NRZ and PAM4 types of modulation, we use an Eye Diagram to represent the data being transmitted.

The information is transmitted using the amplitude or intensity of the laser.

This can be viewed on an oscilloscope.

In NRZ and PAM4 information is transmitted using only one parameter.

Eye Diagram of an NRZ Signal

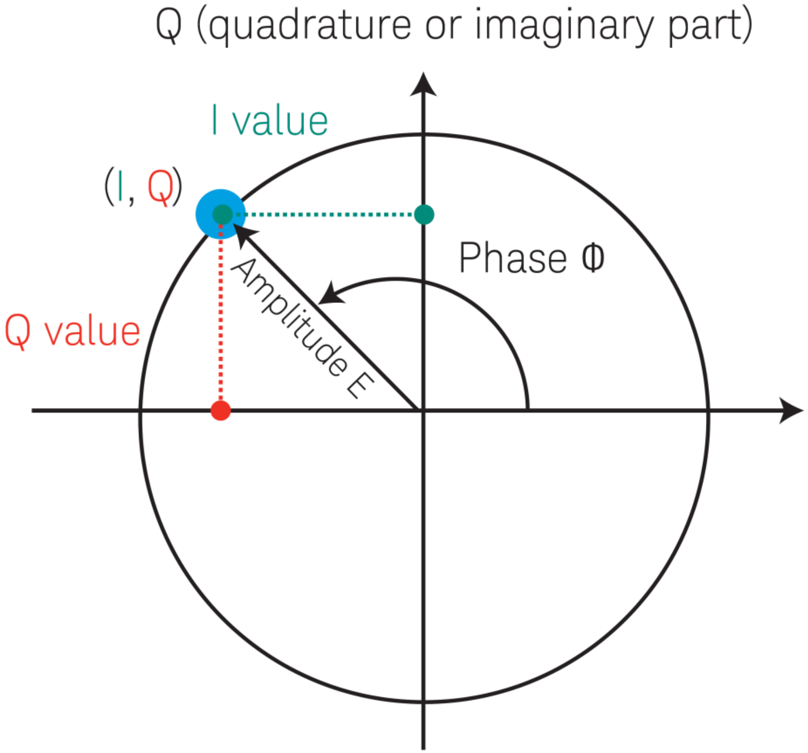
How do you Transmit Symbols Instead of Bits?

Since a light wave is defined by more parameters than just amplitude, we have more dimensions to encode information.

Coherent Modulation uses additional dimensions of a light wave to transmit information.

Every carrier can be described by two parameters:

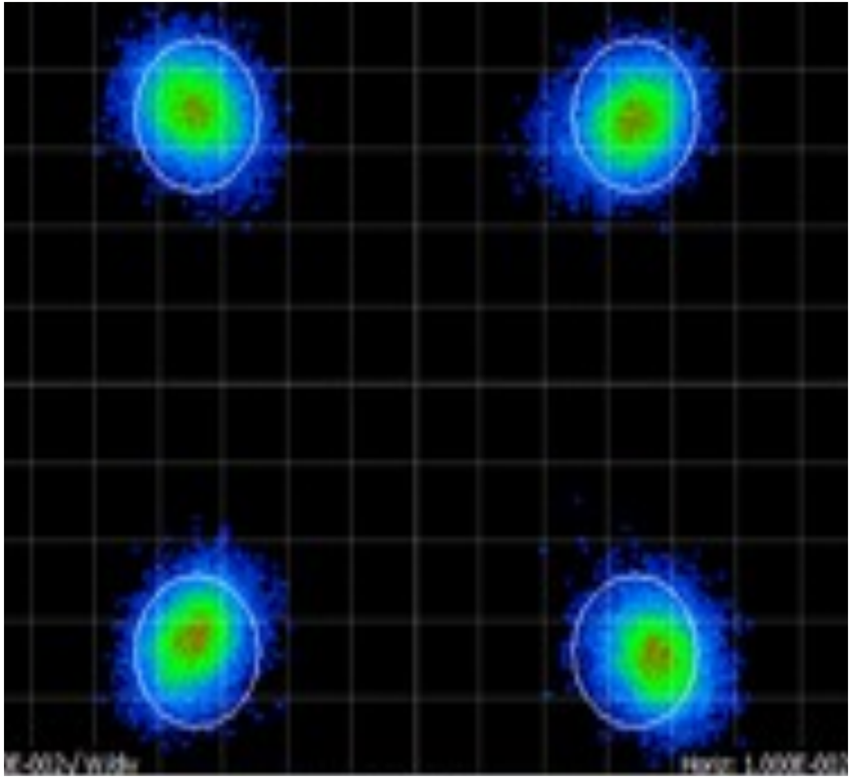
- Amplitude
- Phase



Source: Keysight, 'Essentials of Coherent Optical Data Transmission"

How do you Transmit Symbols Instead of Bits?

Much like NRZ uses an Eye Diagram, complex modulation schemes use a *Constellation Diagram* to represent the data being transmitted



Each symbol being transmitted is encoded using two dimensions:

- Amplitude
- Phase

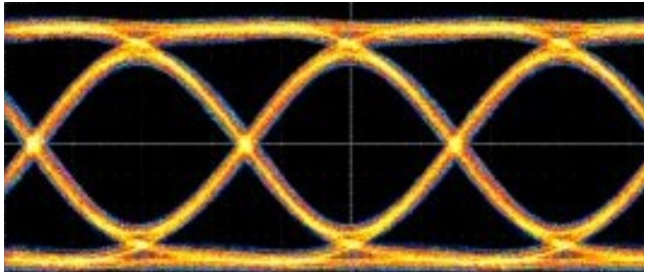
Both parameters carry information to be transmitted.

The constellation diagram is viewed on Modulation Analyzers.

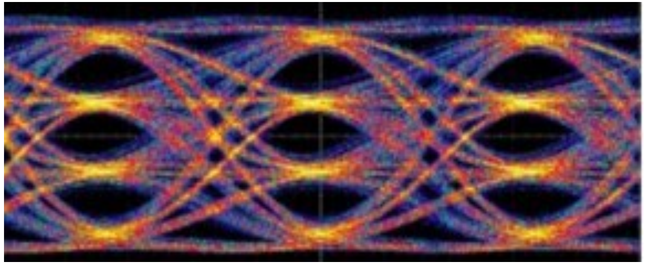
How do you Transmit Symbols Instead of Bits?

In NRZ and PAM4 modulation the amplitude of the laser source is used to encode the data being transmitted.

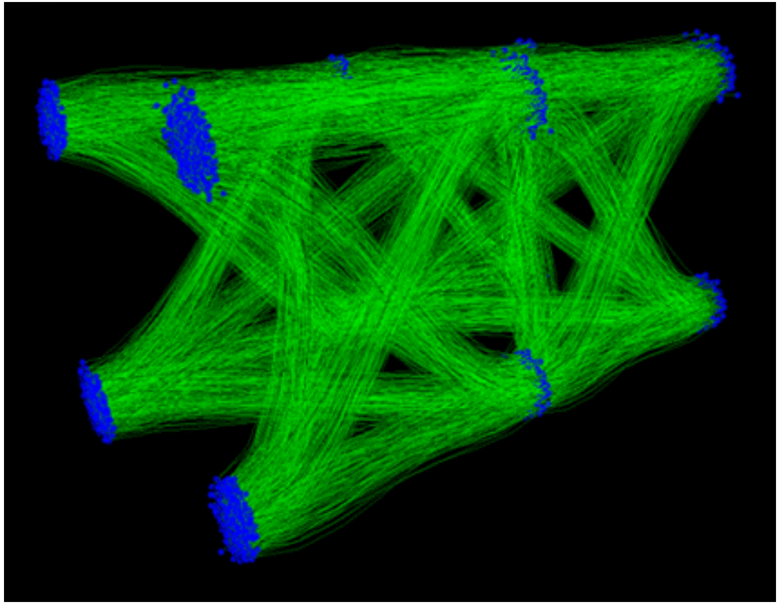
NRZ



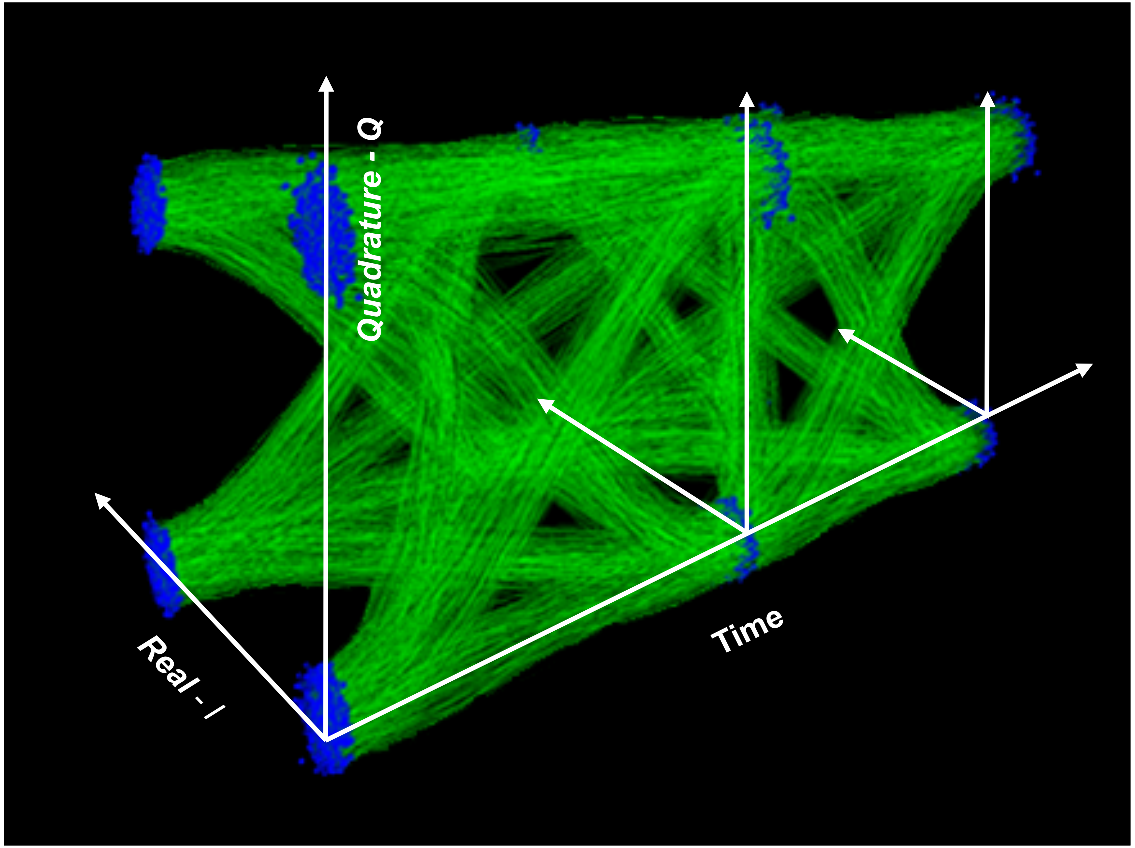
PAM4

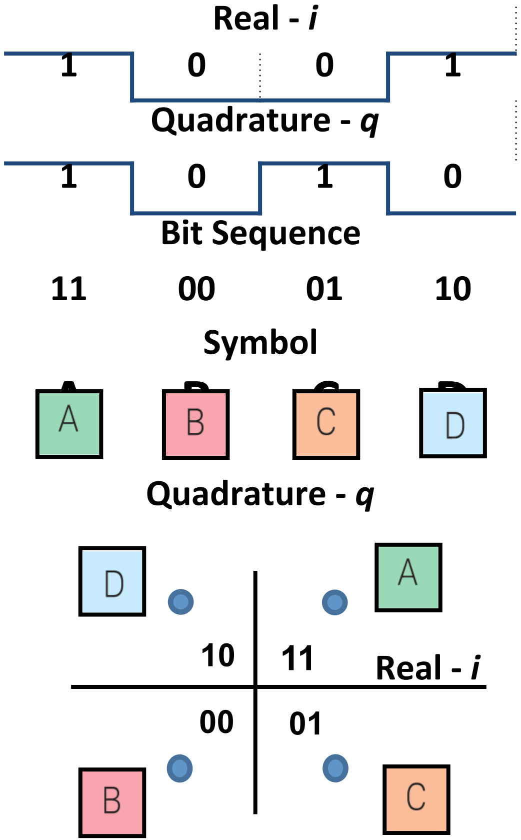


Coherent modulation uses the full characteristics of a light-wave to encode information.

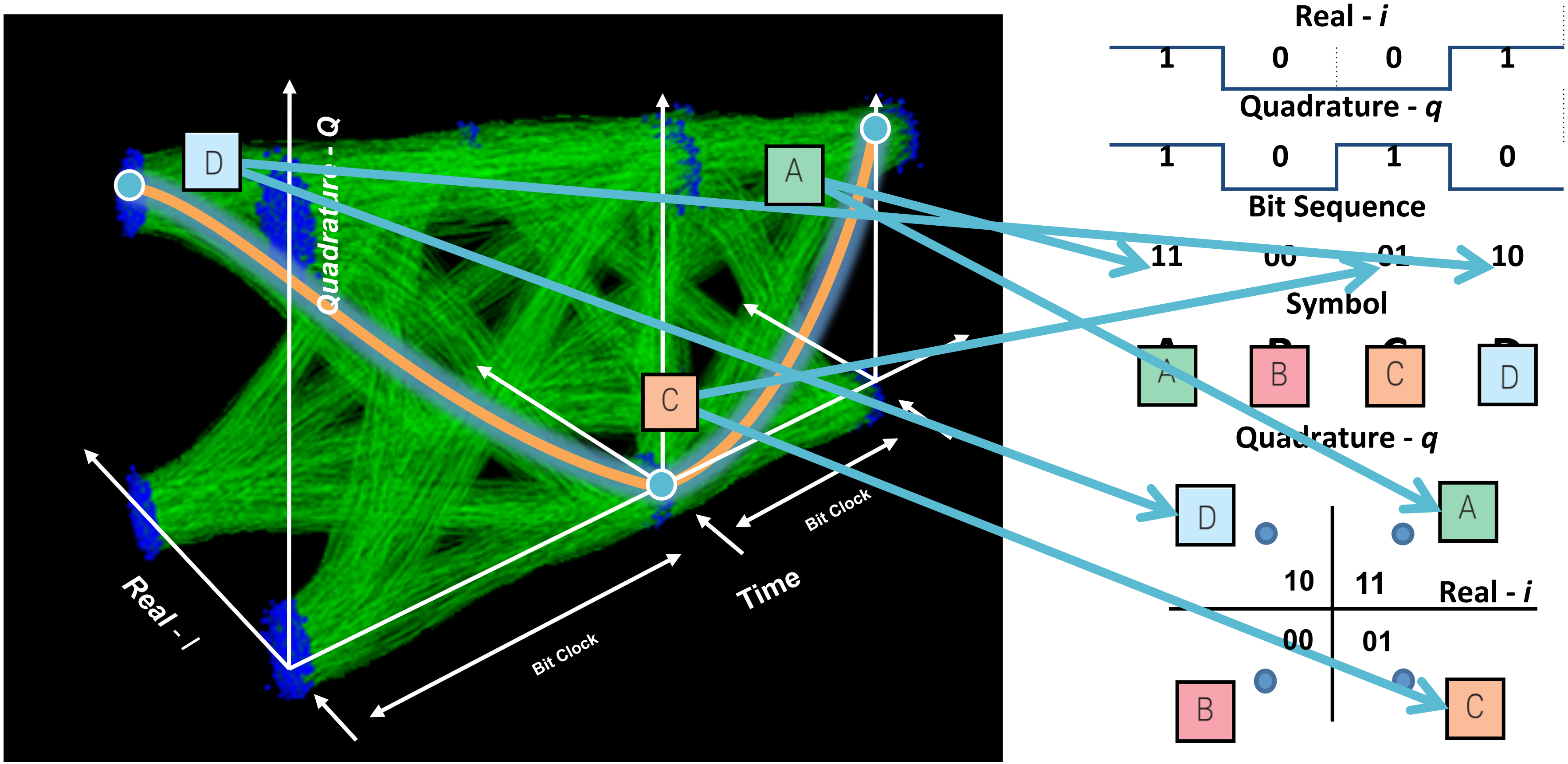


Understanding Constellation Diagrams for QPSK





Understanding Constellation Diagrams for QPSK



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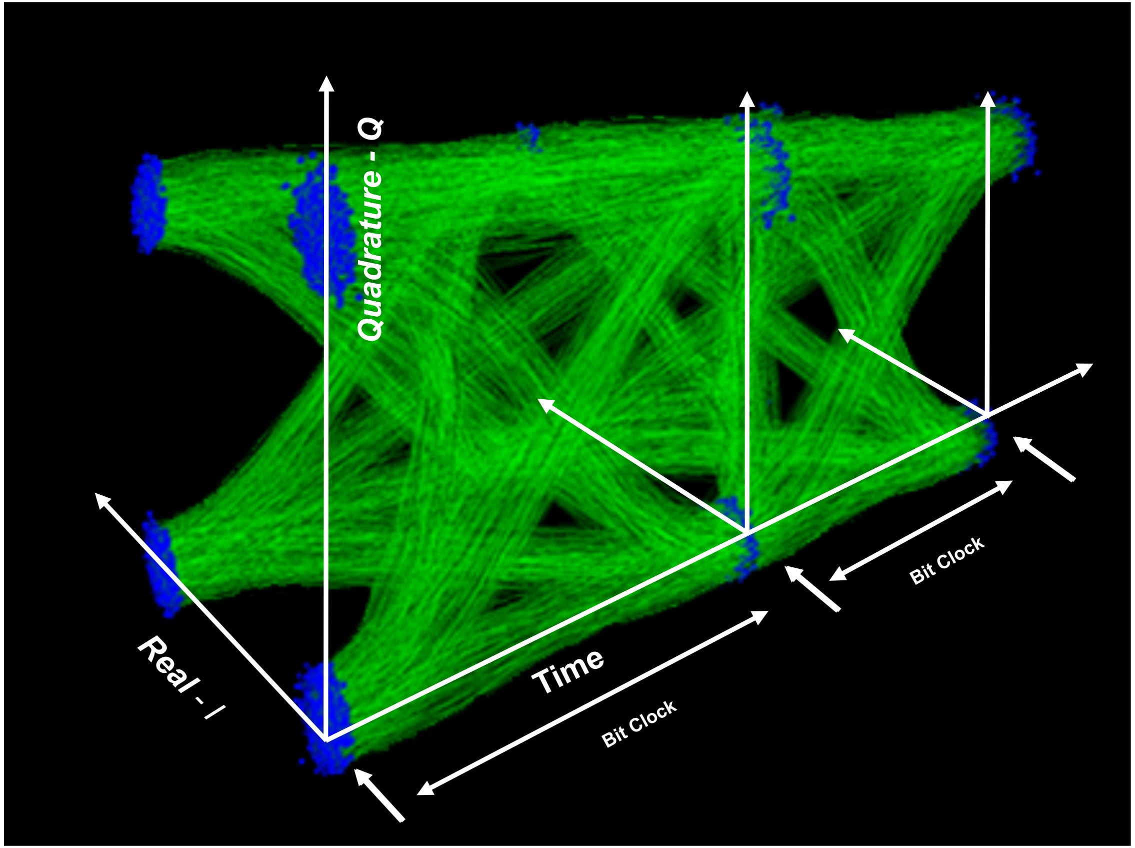

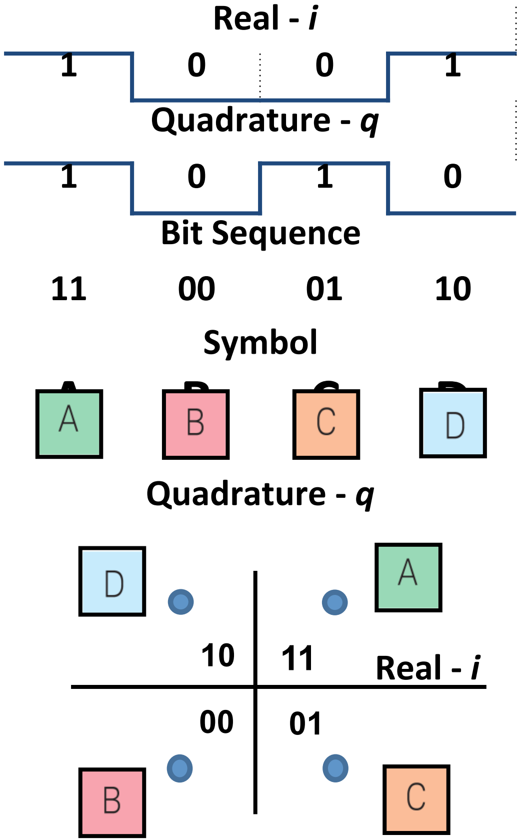

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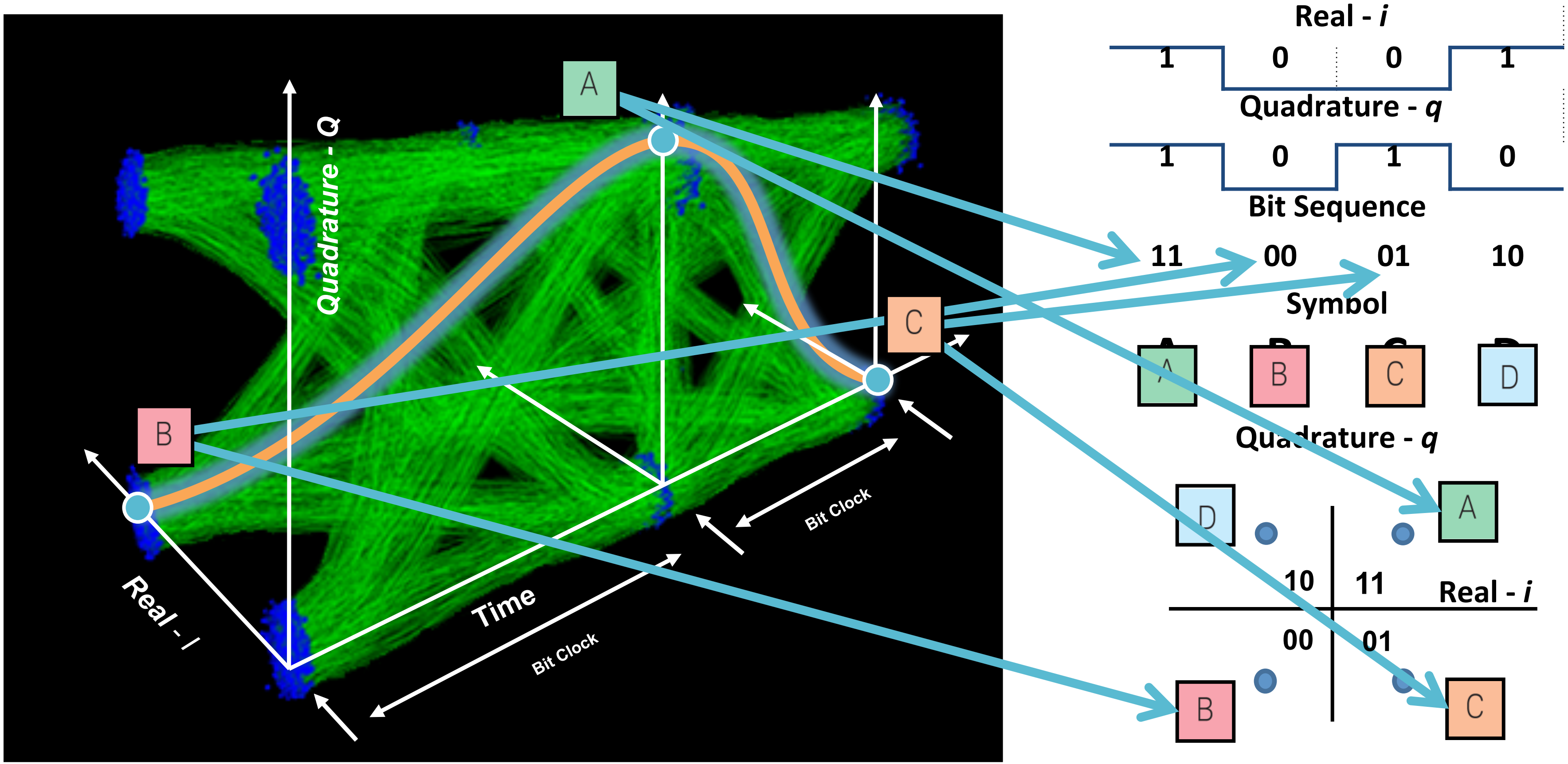
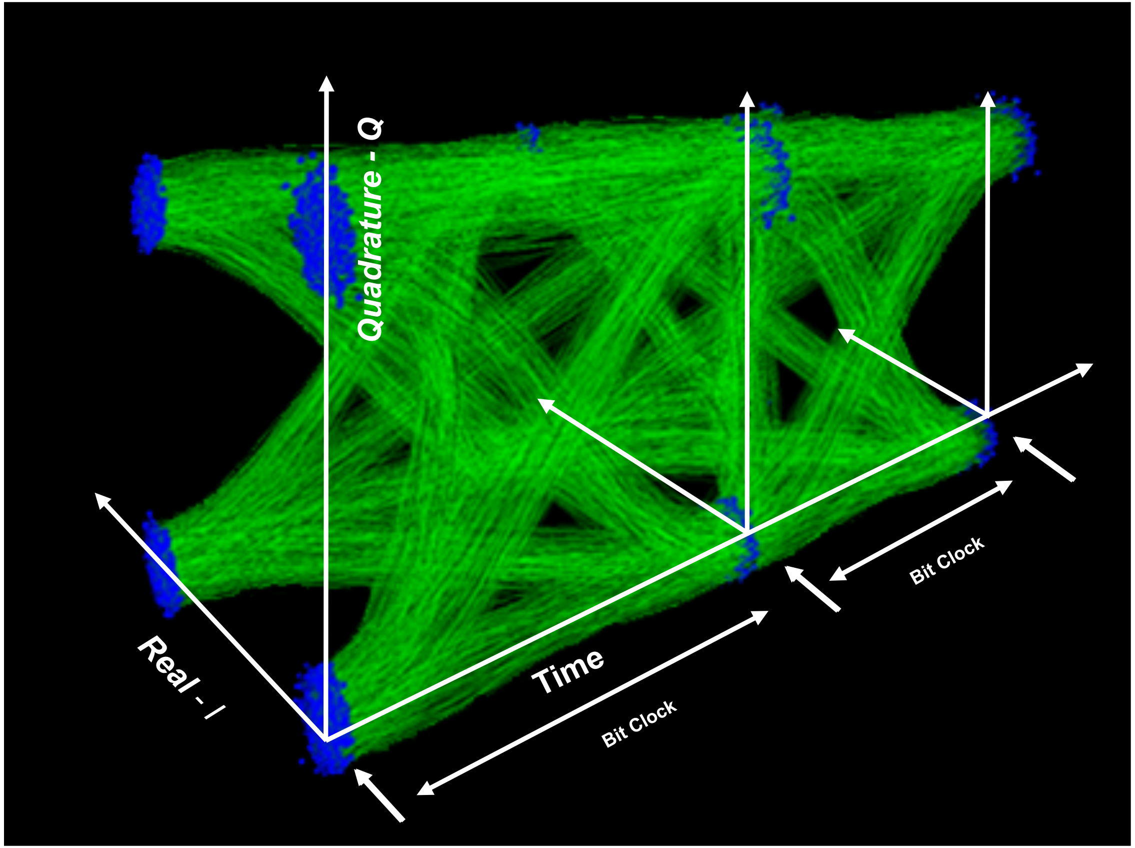
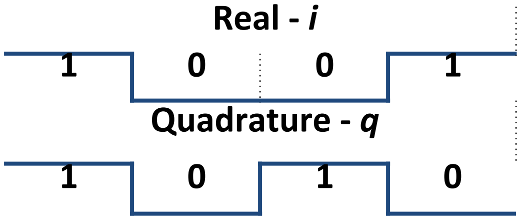


Understanding Constellation Diagrams for QPSK



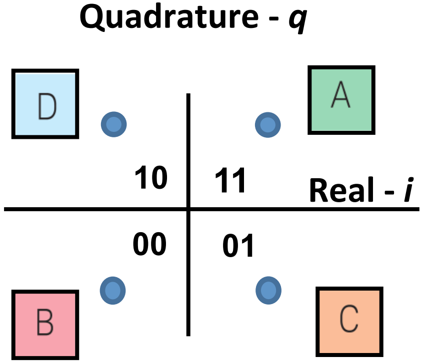


Bit Sequence

11 00 01 10

Symbol

A B C D



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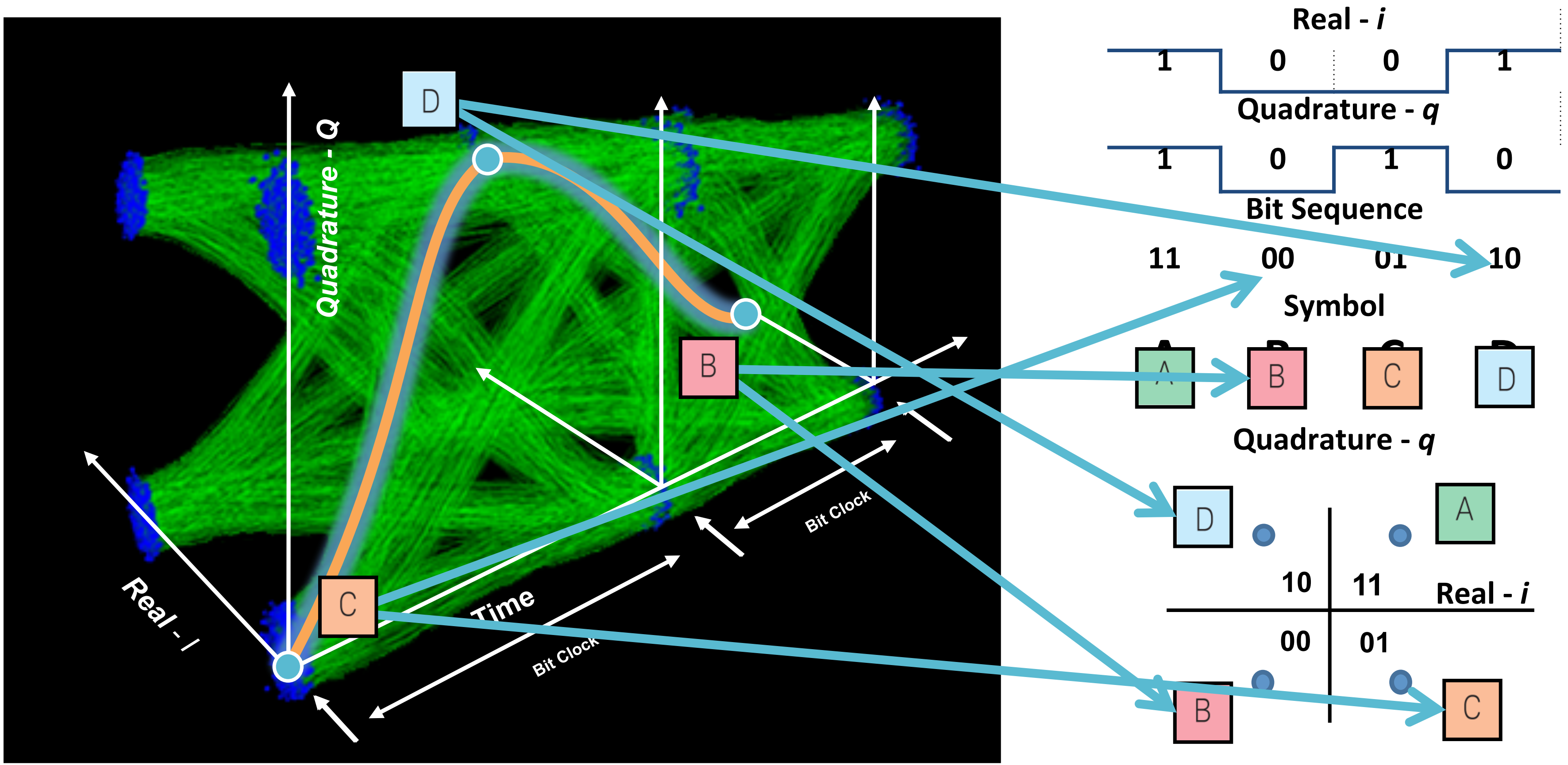
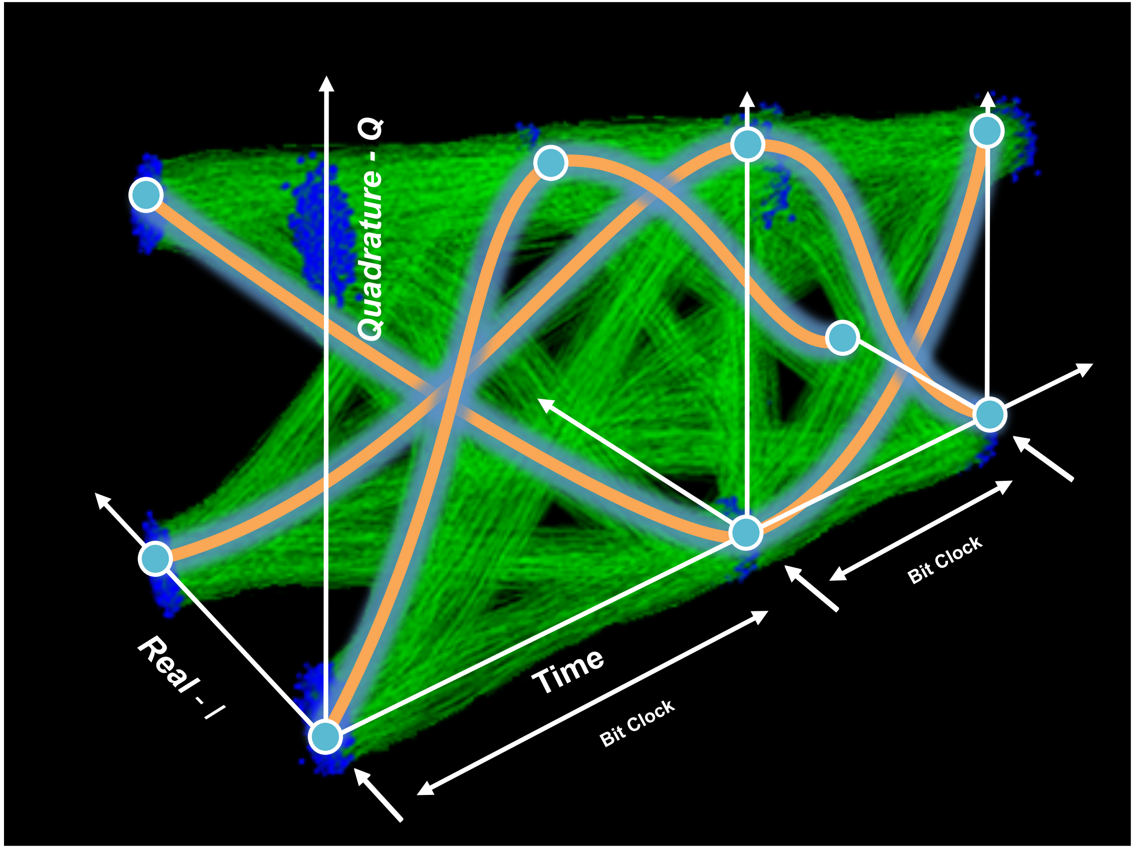
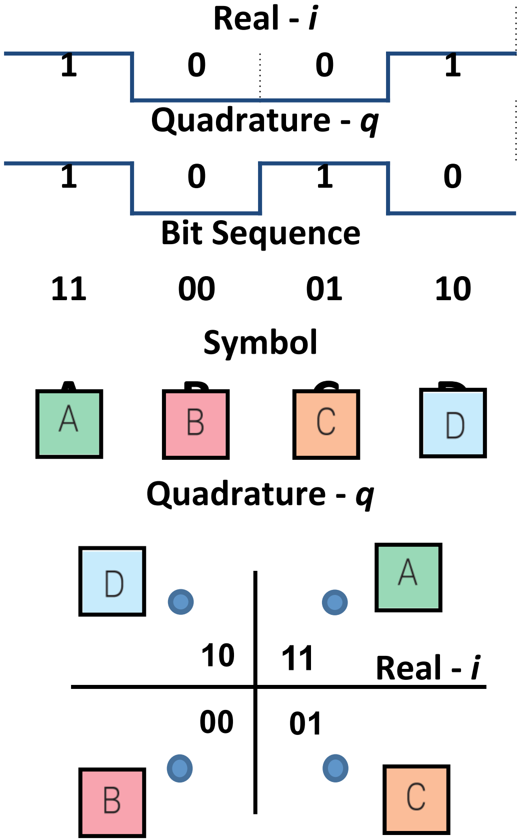


Understanding Constellation Diagrams for QPSK





Bit rate vs. Symbol rate

By using complex modulation schemes, the optical bandwidth needed to send the data can be reduced to fit within the 50GHz ITU Channels

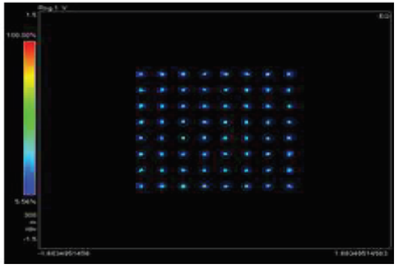
- This means the more bits encoded into one symbol at a given data rate, the greater reduction in the occupied optical bandwidth of the signal

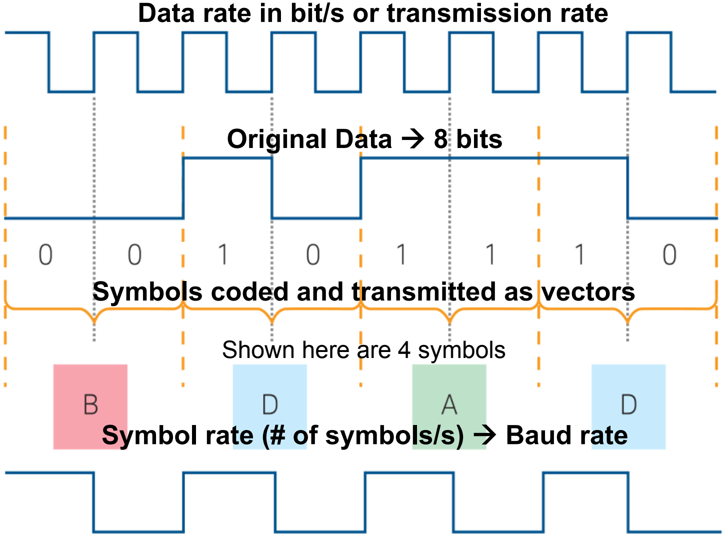
16 QAM Modulation

Using 16 symbols to transmit data reduces the baud rate by a factor of ***4x*** from the bit rate

64 QAM Modulation

Using 64 symbols to transmit data reduces the baud rate by a factor of ***6x*** from the bit rate



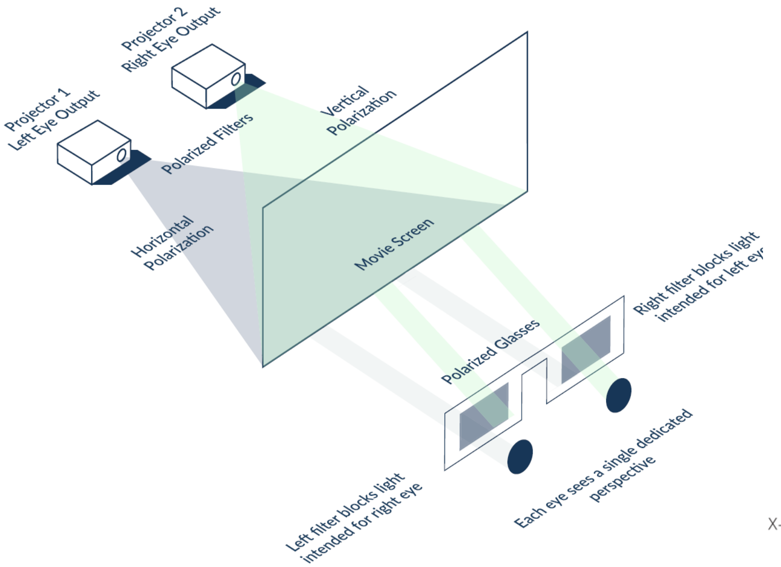


Source: Keysight, 'Essentials of Coherent Optical Data Transmission"

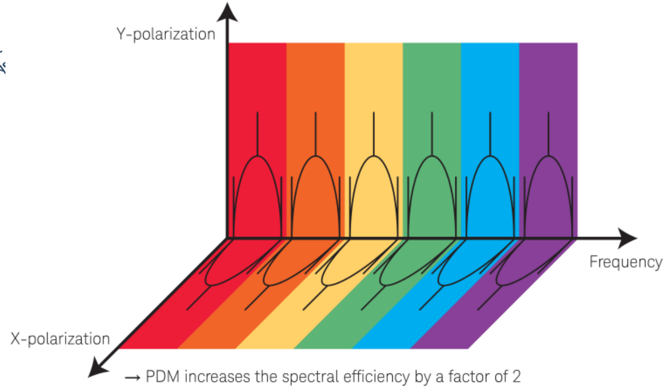
Dual Polarization Multiplexing for Additional Capacity

Polarization Division multiplexing (PDM) uses a second light-wave signal which is orthogonal to the first, to carry independent information. It is transmitted over the same fiber and on the same wavelength.

3D Movies make use of Polarization Multiplexing. The polarized glasses filter out the independent signals for each eye and provide a different picture to create the 3D effect



PDM adds a second channel and doubles the transmission capacity without the need of a second fiber



Source: Keysight, 'Essentials of Coherent Optical Data Transmission"

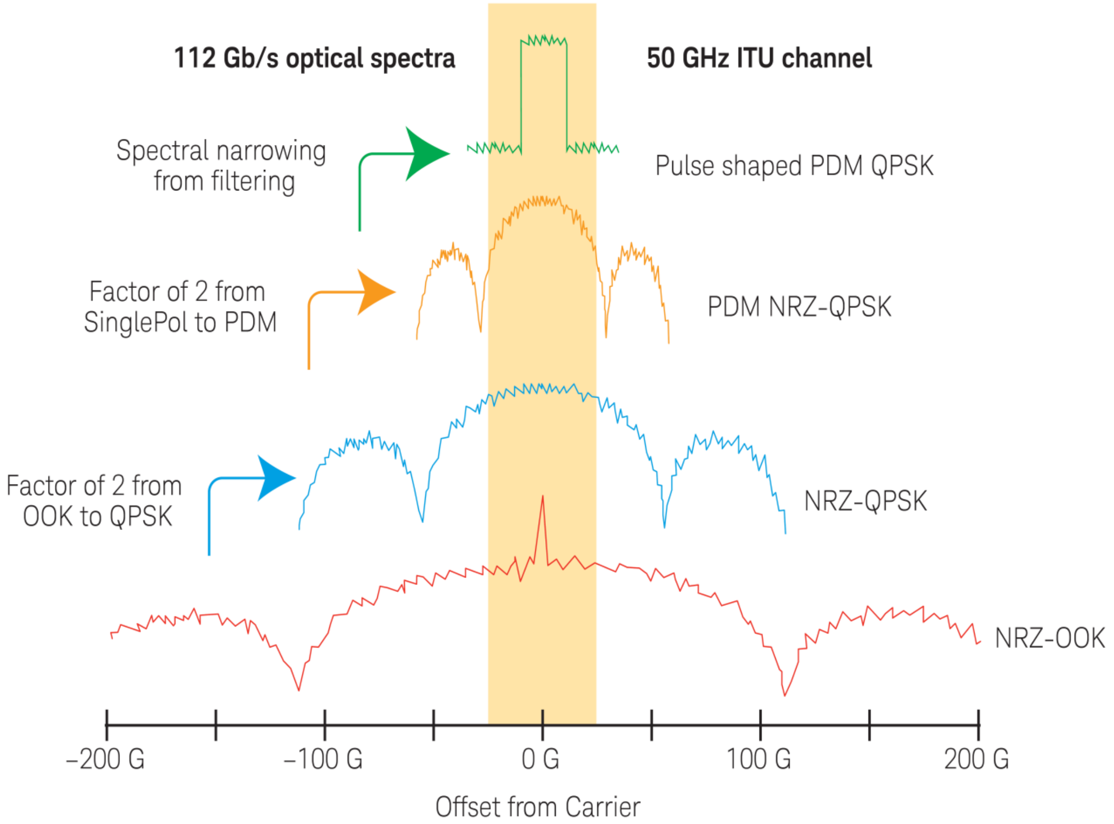
Coherent Modulation – Increases Capacity by Reducing Bandwidth

Coherent Modulation achieves efficiency by encoding data simultaneously in the Polarization, Amplitude, Phase and Frequency portions of the light wave

- At the bottom of the figure, we have the simplest scheme: on-off-keying
- Using Quadrature Phase Shift Keying (QPSK) we can double the data rate in half the spectrum
- Another factor of 2 can be gained through Polarization Division Multiplexing

QPSK plus PDM allows you to transfer 2 x 2 = 4 times more bits at the same time

After further narrowing the occupied spectrum with a filter, 100 Gb/s of data can be sent using PDM-QPSK modulation in a 50 GHz ITU channel



Source: Keysight, 'Essentials of Coherent Optical Data Transmission"

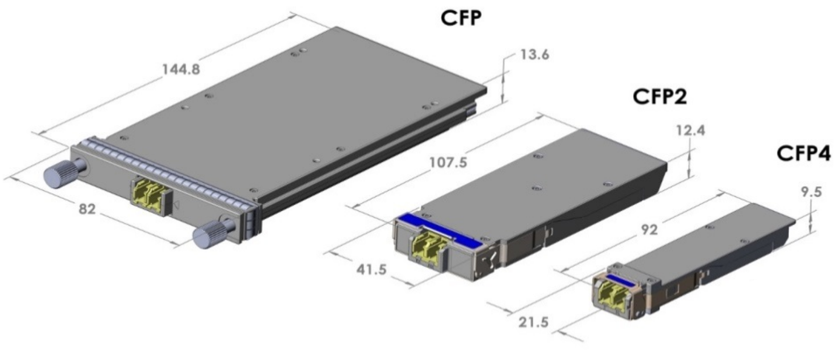
Common Modulation Formats

Format	Polarization	28 GBaud	32 GBaud	40 GBaud	46 GBaud	56 GBaud	64 GBaud
NRZ/PAM2 1 bit per Baud (symbol)	Single Polarization	28 Gb/s	32 Gb/s	40 Gb/s	46 Gb/s	56 Gb/s	64 Gb/s
BPSK 1 bit per Baud (symbol) per polarization	Single Polarization	28 Gb/s	32 Gb/s	40 Gb/s	46 Gb/s	56 Gb/s	64 Gb/s
	Dual Polarization	56 Gb/s	64 Gb/s	80 Gb/s	92 Gb/s	112 Gb/s	128 Gb/s
PAM4 2 bits per Baud (symbol)	Single Polarization	56 Gb/s	64 Gb/s	80 Gb/s	92 Gb/s	112 Gb/s	128 Gb/s
QPSK 2 bits per Baud (symbol) per polarization	Single Polarization	56 Gb/s	64 Gb/s	80 Gb/s	92 Gb/s	112 Gb/s	128 Gb/s
	Dual Polarization	112 Gb/s	128 Gb/s	160 Gb/s	184 Gb/s	224 Gb/s	256 Gb/s

Common Modulation Formats

Modulation format	Polarization	28 GBaud	32 GBaud	40 GBaud	46 GBaud	56 GBaud	64 GBaud
8QAM 3 bits per Baud (symbol) per polarization	Single Polarization	84 Gb/s	96 Gb/s	120 Gb/s	138 Gb/s	168 Gb/s	192 Gb/s
	Dual Polarization	168 Gb/s	192 Gb/s	240 Gb/s	276 Gb/s	336 Gb/s	384 Gb/s
16QAM 4 bits per Baud (symbol) per polarization	Single Polarization	112 Gb/s	128 Gb/s	160 Gb/s	184 Gb/s	224 Gb/s	256 Gb/s
	Dual Polarization	224 Gb/s	256 Gb/s	320 Gb/s	368 Gb/s	448 Gb/s	512 Gb/s
32QAM 5 bits per Baud (symbol) per polarization	Single Polarization	140 Gb/s	160 Gb/s	200 Gb/s	230 Gb/s	280 Gb/s	320 Gb/s
	Dual Polarization	280 Gb/s	320 Gb/s	400 Gb/s	460 Gb/s	560 Gb/s	640 Gb/s
64QAM 6 bits per Baud (symbol) per polarization	Single Polarization	168 Gb/s	192 Gb/s	240 Gb/s	276 Gb/s	336 Gb/s	384 Gb/s
	Dual Polarization	336 Gb/s	384 Gb/s	480 Gb/s	552 Gb/s	672 Gb/s	768 Gb/s

Pluggable Form Factors Suitable for Coherent Transceivers



[mm]	CFP	CFP2	CFP4	OSFP	QSFP	QSFP-DD
Length	144.8	107.5	92.0	100.4	72.4	93.3
Width	82.0	41.5	21.5	22.9	18.4	18.4
Height	13.6	12.4	9.5	13.0	8.5	8.5

Coherent Transmission for DCI Applications

- **Several system OEMs already provide a 1RU transponder for DCI applications, most of which use pluggable 100G/200G Coherent CFP2-ACO optical transceivers.**





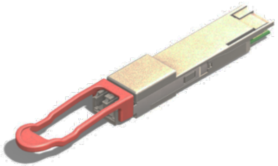



CFP2-ACO

ACO = Analog Coherent Optics
DCO = Digital Coherent Optics

- **Expected coherent transceiver evolution to 400G is driven by improvements in optical packaging and DSP power dissipation:**

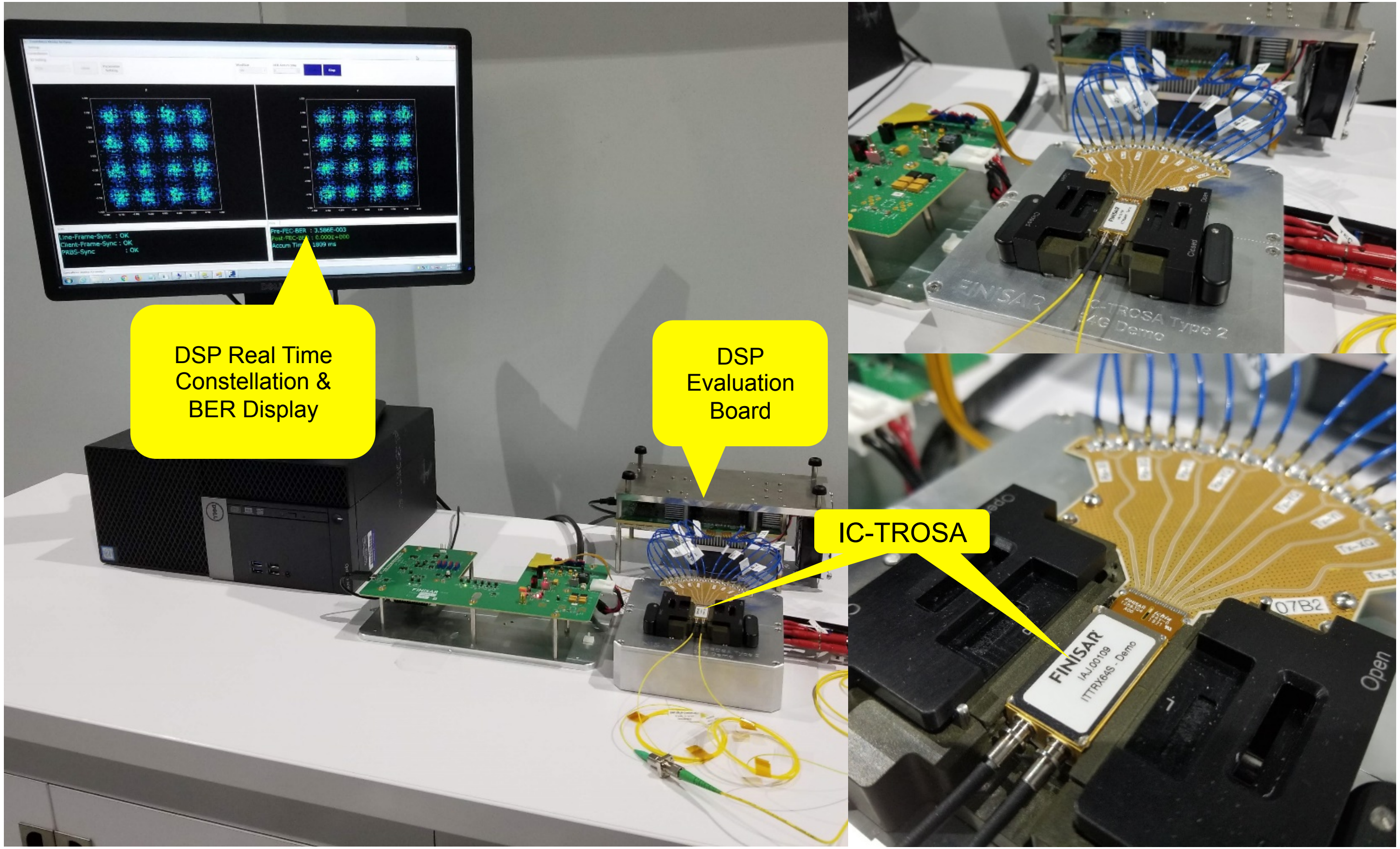
200G CFP2-ACO → **400G CFP2-DCO** → **400G QSFP-DD DCO(*)**



400G DCO transceivers are expected to be plugged directly into switches and routers

(*) Could also be implemented in OSFP.

OFC 2019: 64 GBaud IC-TROSA Demo by II-VI/Finisar



II-VI

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