Optical Transport Innovations for High Capacity Networks

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How To Increase Capacity of Transport Networks?

Two Main Leverages…

- Higher Bit Rate Wavelengths
- More Wavelengths per Fiber

…and Two Key Questions

- Does Distance have a Role?
- Super-Fast Dumb Pipe or Transport Network able to Interact?

Higher Bit Rate Wavelengths

Simply Faster?!?

- All Transmission Effects scale with Channel's bit-rate:
  - **CD Tolerance** scales as the Square of Bit Rate
    (800ps/nm @ 10G → 50ps/nm @ 40G)
  - **PMD Tolerance**, **OSNR** Requirement, **Bandwidth** and Unregenerated **Reach** scale Linearly with Bit Rate
    (10ps @ 10G → 2.5ps @ 40G)

- Transition between 2.5Gbps and 10Gbps has introduced the use of **FEC** coding

- Transition to 40Gbps, 100Gbps, 1,000Gbps cannot be supported only by more powerful coding
  - Increase Complexity of **Modulation Schema** and **Optical Receiver** to provide an effective answer: **CP-DQPSK**

CP-DQPSK Modulation Details

- CP: Coherent Polarized
  - Leverages on Polarization Multiplexing to transmit with Lower Baud Rate (e.g. 40Gbps as 10GBaud)
  - Leverages on Coherent Detection and Electronic Post-Processing to provide high tolerance to PMD and CD
- DQPSK: Differential QPSK
  - Differential operating mode provides required system robustness against Laser Cycle Slips
  - Laser Cycle Slips can be caused by ASE, Laser Phase Noise and XPM (induced by 10G IM/DD channels)
  - Even w/o 10G channels ASE and Laser Phase Noise can cause Laser Cycle Slips

Coherent Optical Transmission Benefits

High **Chromatic Dispersion (CD)** Robustness

- Can avoid Dispersion Compensation Units (DCUs)
- No need to have precise Fiber Characterization
- Simpler Network Design

High **Polarization Mode Dispersion (PMD)** Robustness

- High Bit Rate Wavelengths deployable on all Fiber types
- No need for “fancy” PMD Compensator devices
- No need to have precise Fiber Characterization

Low **Optical Signal-to-Noise Ratio (OSNR)** Needed

- More capacity at greater distances w/o OEO Regeneration
- Possibility to launch lower per-channel Power
- Higher tolerance to Channels Interferences

Can CP-DQPSK Resolve All Our Problems?

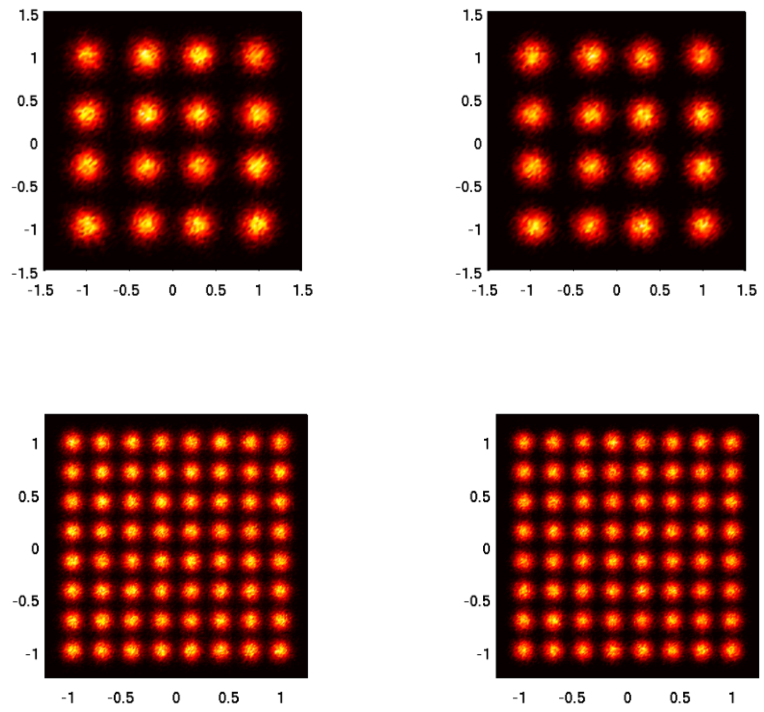
- 40Gbps Wavelengths
  - 20Gb/s ADC Required @ Receiver
  - Optical Bandwidth of ~10GHz
- 100Gbps Wavelengths
  - 50Gb/s ADC Required @ Receiver
  - Optical Bandwidth of ~25GHz
- 1,000Gbps Wavelengths
  - 500Gb/s ADC Required @ Receiver
  - Optical Bandwidth of ~250GHz

→ Need Extra "Complexity" to address 1,000Gbps Wavelengths

Beyond 100G: Higher-level Modulation Formats

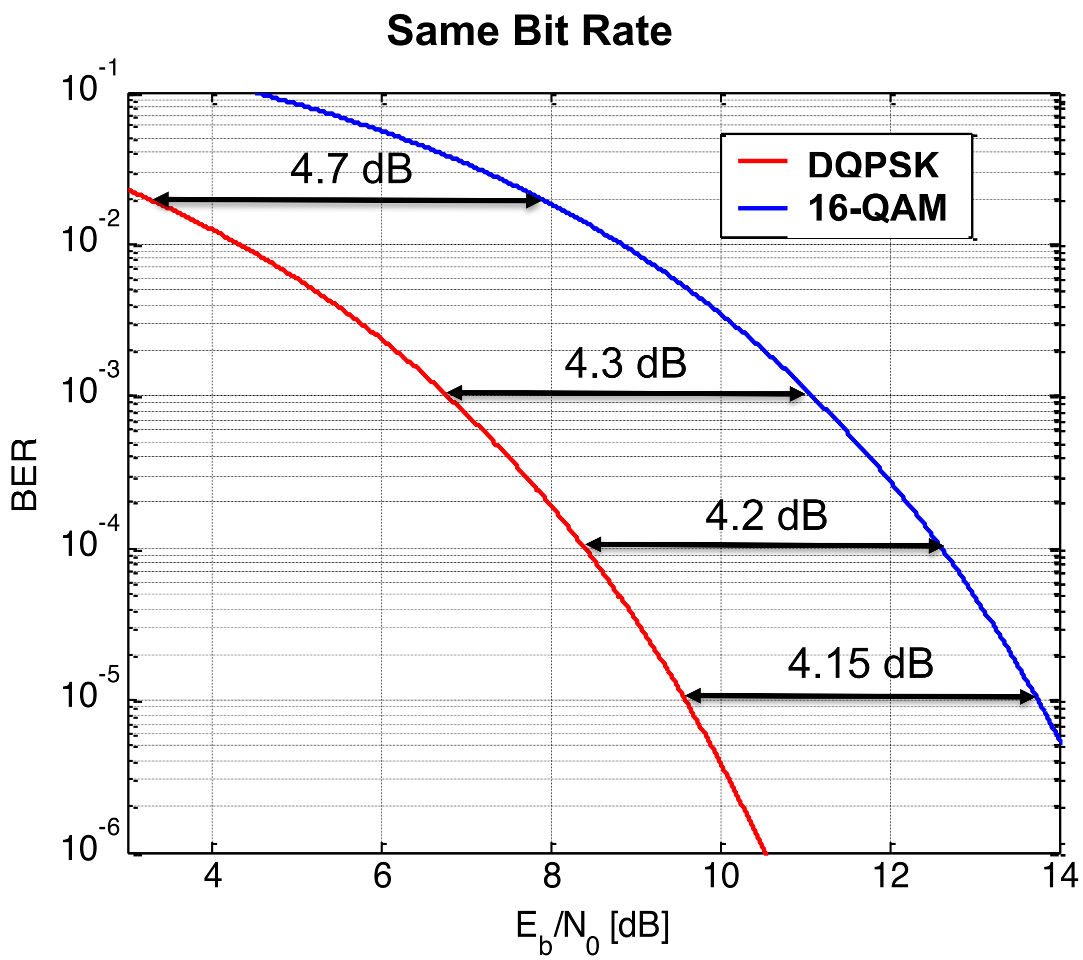
Scattering diagram for CP-16QAM (4+4bit/symbol)

Scattering diagram for CP-64QAM (8+8bit/symbol)



X-pol Y-pol

CP-16QAM vs. CP-DQPSK



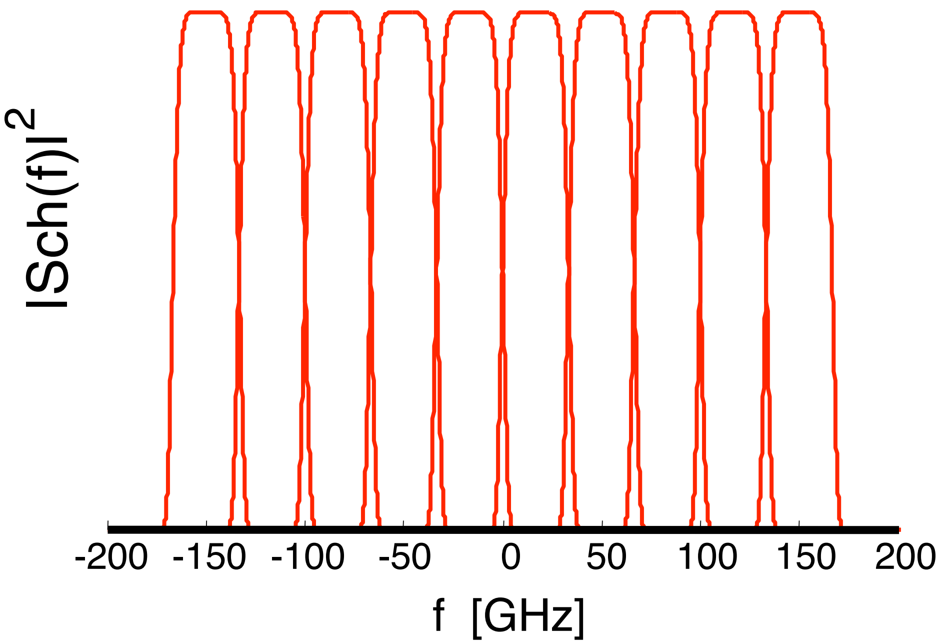
OSNR Gain of CP-DQPSK vs. CP-16QAM is:

- 4 dB comparing at **Constant Bit-Rate**
- 7 dB comparing at **Constant Baud-Rate**

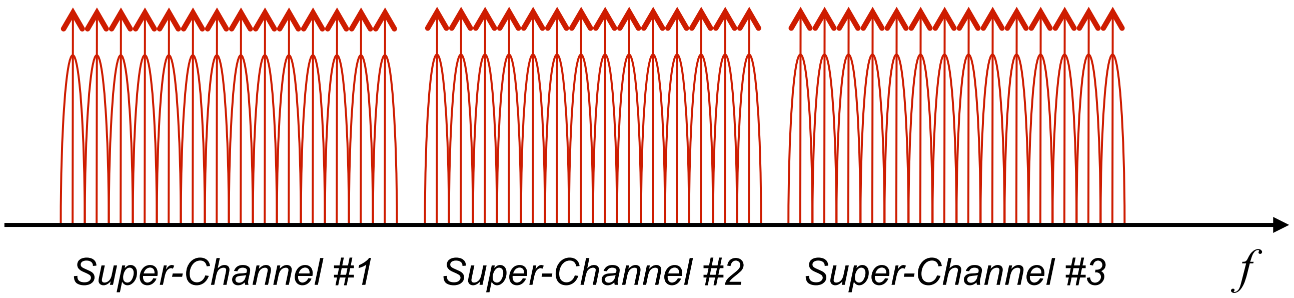
Need a Solution which would NOTsacrifice Reach: **Super-Channel**

The Terabit Super-Channel

- Information distributed over a few Sub-Carriers spaced as closely as possible forming a 1,000Gbps Super-Channel
- Each Sub-Carrier transporting a lower Bit Rate, compatible with current ADCs and DSPs

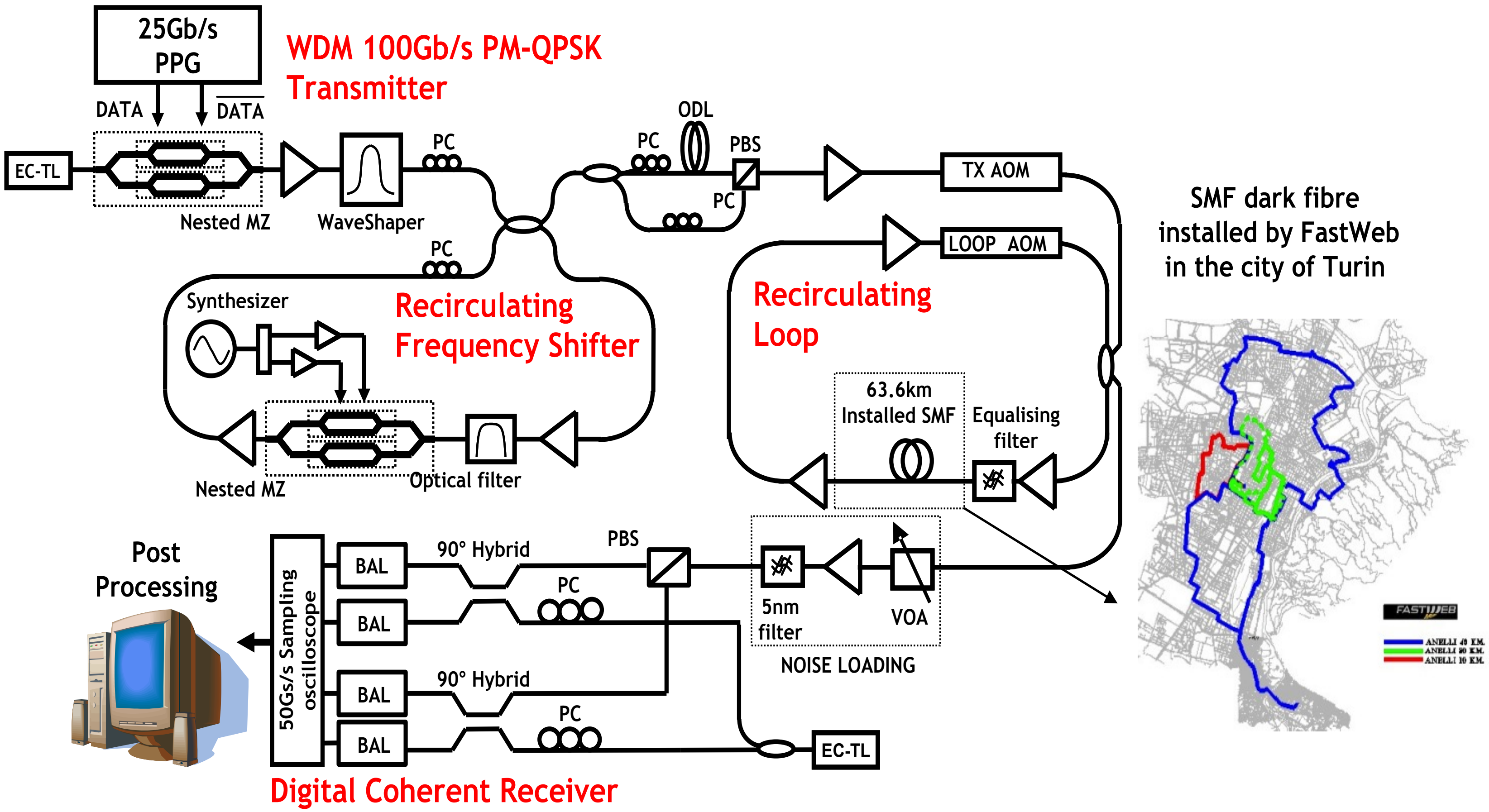


10x 100Gbit/s Sub-Carriers close-to-Baud-rate spaced

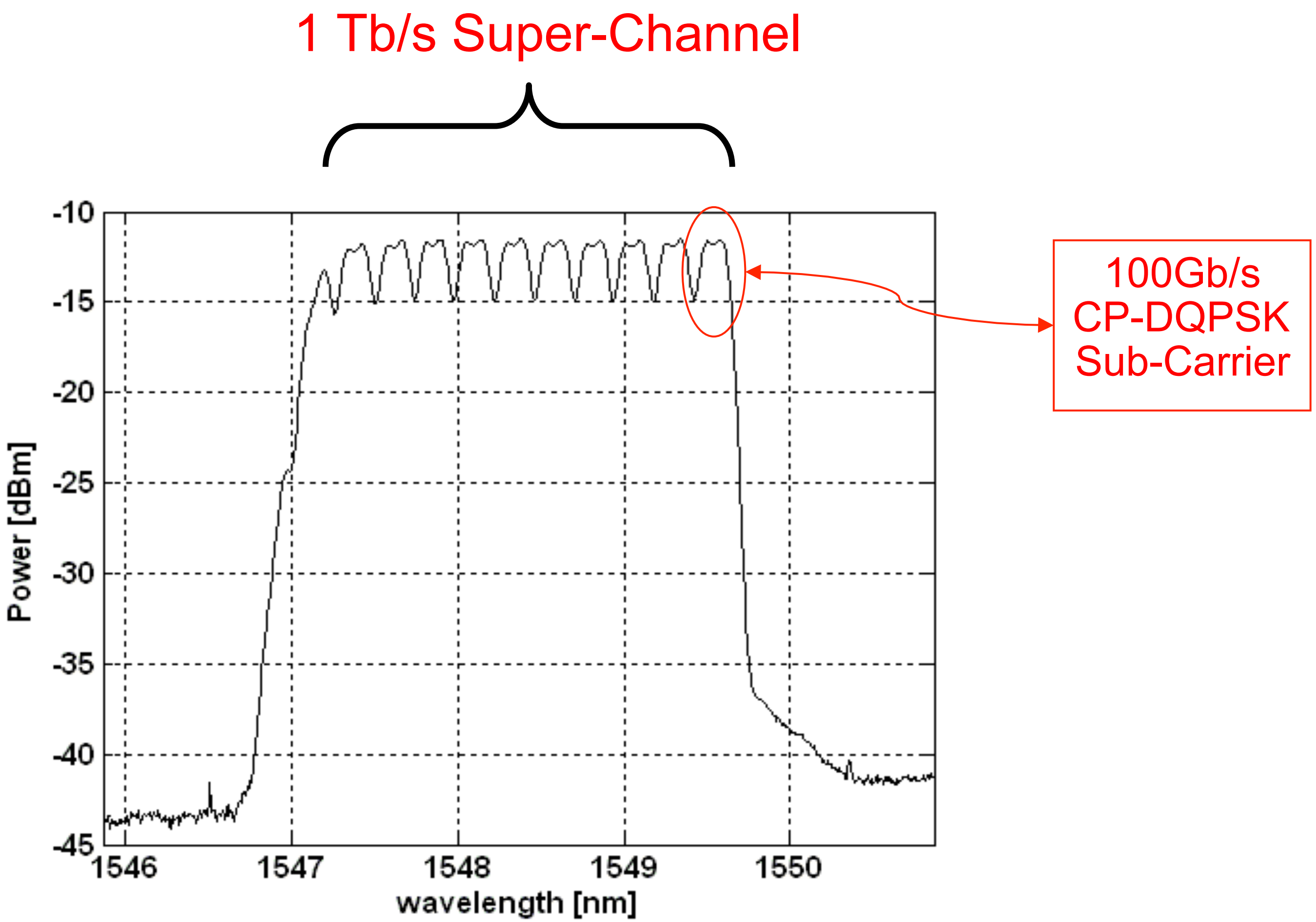


Terabit Super-Channel Experiment: Setup

OFC 2010: *"Investigation of the Impact of Ultra-Narrow Carrier Spacing on the Transmission of a 10-Carrier 1Tb/s Superchannel"*

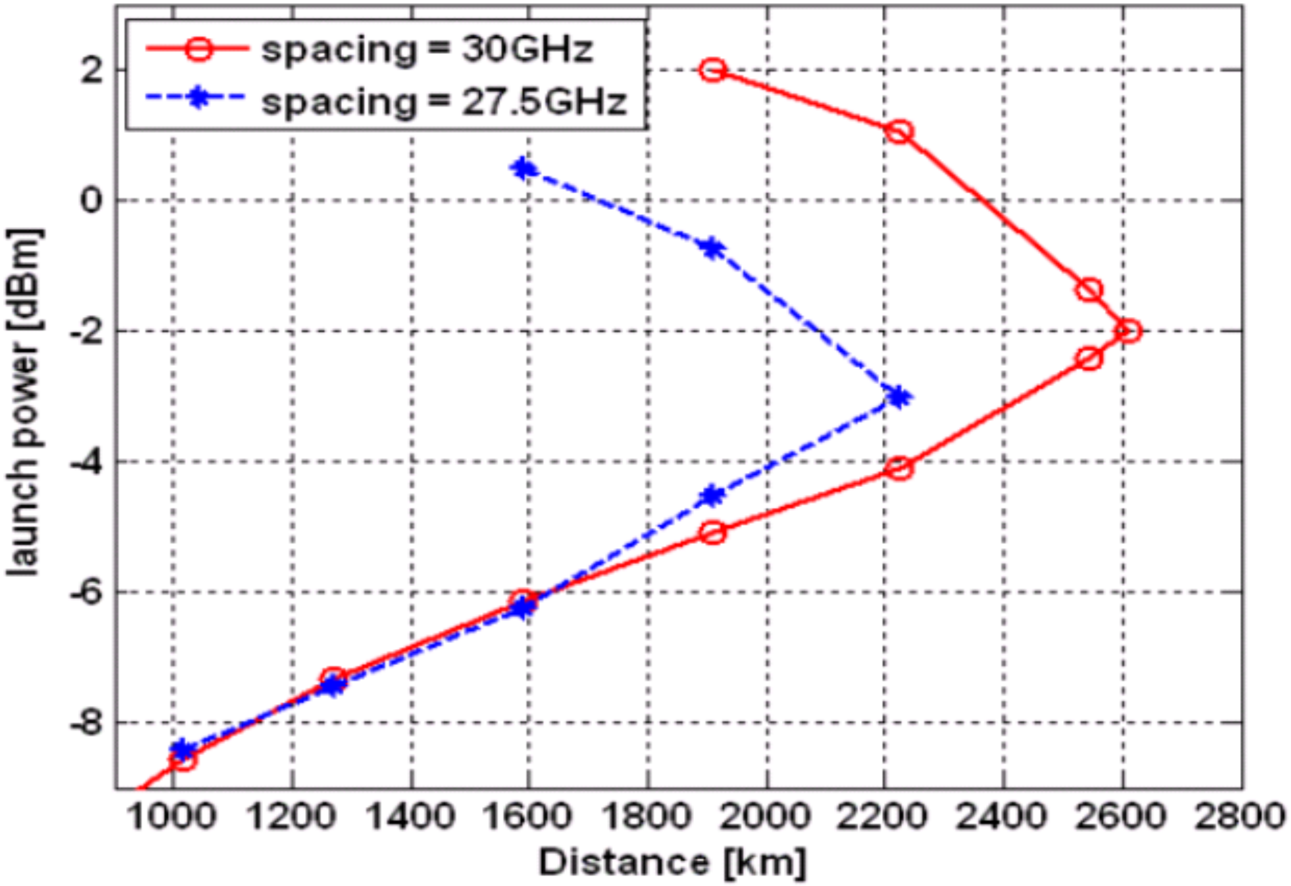


Terabit Super-Channel Experiment: Spectrum



Terabit Super-Channel Experiment: Results

→ 41 spans at BER=3e-3 with spacing 1.2
→ 35 spans at BER=3e-3 with spacing 1.1



Examples of Terabit Super-Channel

- Sub-Carrier spacing: 1.2 times the Baud Rate
- Different approaches for 1,000Gb/s:

  CP-QPSK: 10 Sub-Carriers at 111 Gbit/s each

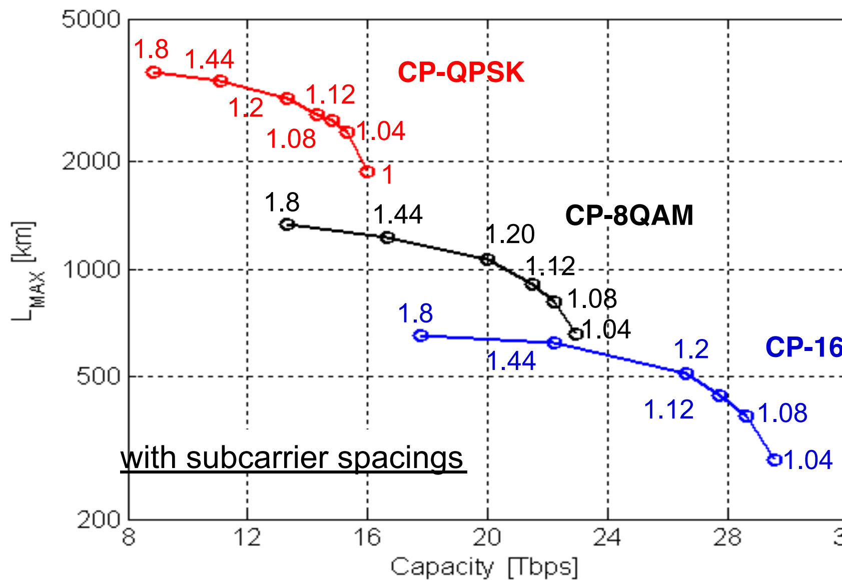
  back-to-back sensitivity 12 dB

  CP-8QAM: 8 Sub-Carriers at 138.75 Gbit/s each

  back-to-back sensitivity 16.1 dB

  CP-16QAQM: 5 Sub-Carriers at 222 Gbit/s each

  back-to-back sensitivity 19.1 dB



- System Configuration:

  Span of 90km each (ITU-T G.652)

  Span Insertion Loss: 25dB

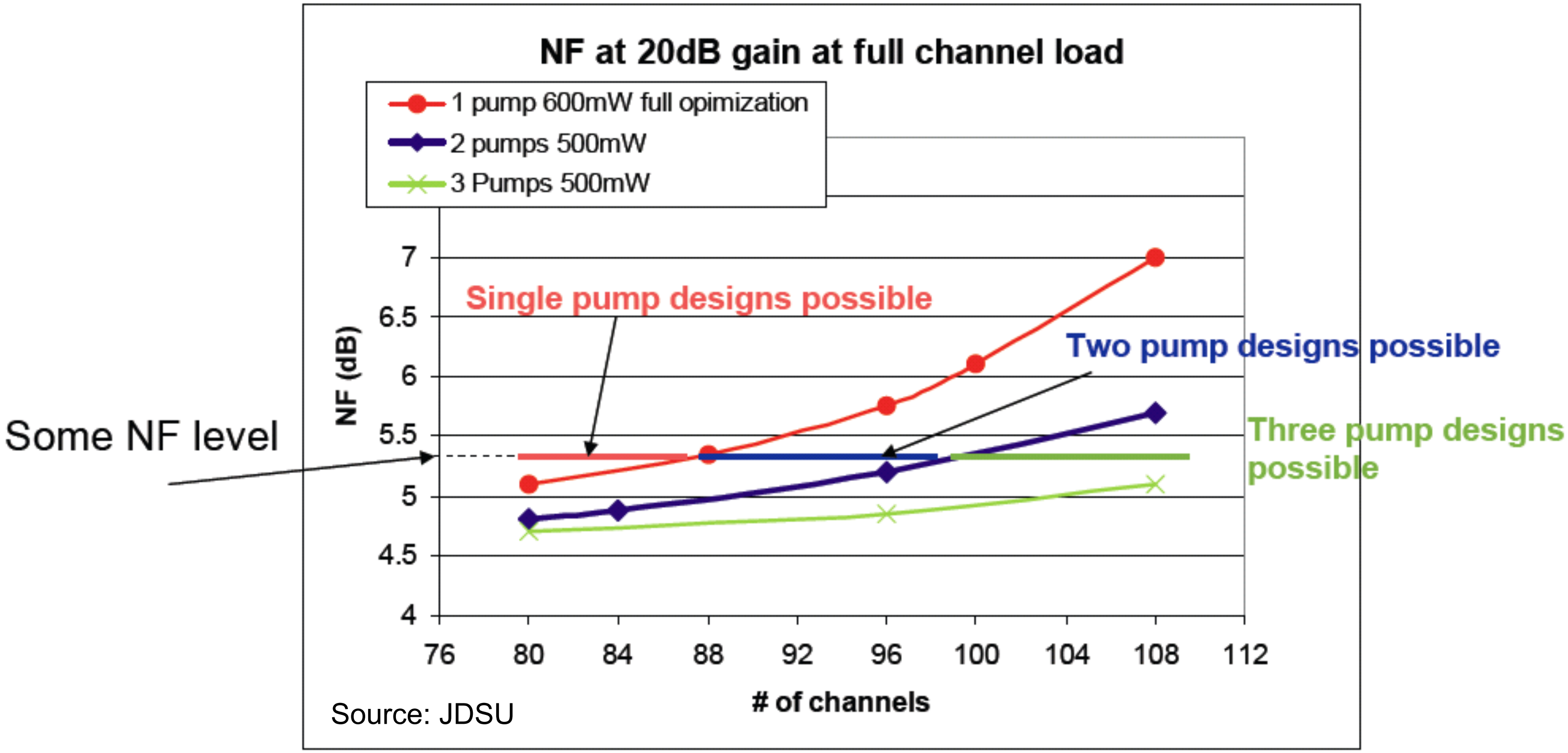
More Wavelengths per Fiber

How Much Optical Spectrum Can Be Used?

- Virtually all the DWDM Systems deployed in the world leverage on the C-band part of the Optical Spectrum (1530nm – 1560nm)
- L-band Systems are available and have been selectively deployed
- Systems which can combine C-band and L-band on the same fiber pair are available
- Reference number of Wavelength in the C-band is 80 @ 50GHz Channels Spacing

- Would it be Possible / Practical to do more?

EDFA Performances vs. Channel Count

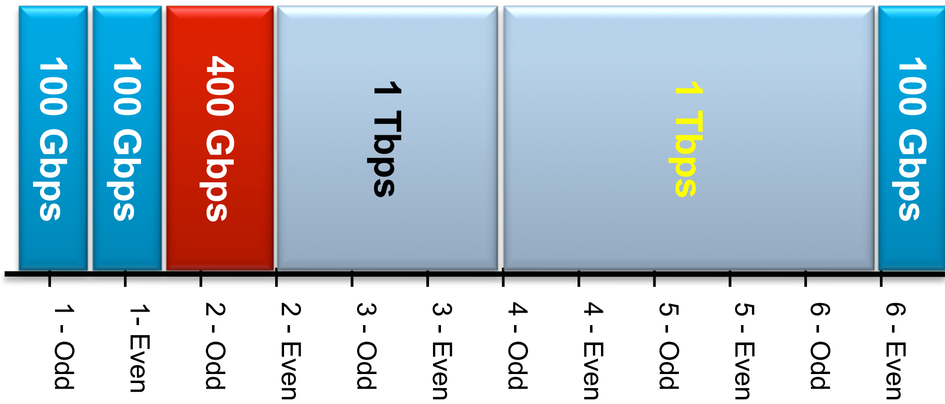


- 80Chs @ 50GHz Spacing in the C-Band is NOT a Physical limit
- There is the possibility to grow the Channel Count to 96Chs or more
- Additional Channels add Complexity (Power Consumption, Space, Cost) to the Amplifier

And My Two Questions?

Does Distance Has a Role?

- Not all the Systems are created equal
- Different Modulation Formats allows to trade Capacity for Reach
- A **Flex Spectrum DWDM System** removes ANY restrictions from the Channels Spacing and Modulation Format point of view
  - Possibility to mix very efficiently wavelengths with different Bit Rates on the same system
  - Allows scalability to higher per-channel Bit Rates
  - Allows maximum flexibility in controlling non-linear effects due to wavelengths interactions (XPM, FWM)
  - Allows support of Alien Multiplex Sections through the DWDM System



Fully Flexibility & Switching @ DWDM Layer

Remotely re-configure wavelengths in any Color and any Direction on ALL Nodes without re-wiring ANY fiber.

Rapidly reconfigure bandwidth

Capitalize on changes in network demand and transitory events

Tunability	Zero-Touch Photonic Layer				DWDM-Aware CP
Wavelength is a routing element and can be SW Provisioned and Changed remotely	**Omni-Directional** De-couple Add/Drop entry point from the Line direction facing the Network	**Colorless** Decouple the Add/Drop port from the wavelength (SW Provisioning and Protection)	**Contentionless** Remove any constraint on Node Add/Drop Capacity & Wavelength	**Flex Spectrum** Enable system to Transport & Switch any Modulation Format and any Bit Rate	Fully automated End-to-End SW provisioning taking into account DWDM specific parameters

GMPLS DWDM-Aware (WSON) Benefits

Automatic Network Discovery

- Node, Link, Network changes

Automatic A-Z Provisioning

- Fast Lambda set up, No pre-planned traffic, Bandwidth on demand

Routing Algorithm DWDM Aware

- Linear (Power, OSNR) and Non-Linear (CD, PMD, FWM, SPM) impairments management

Optical Restoration

- Rapid network re-arrangement, Protection path recovery
- Network Optimization

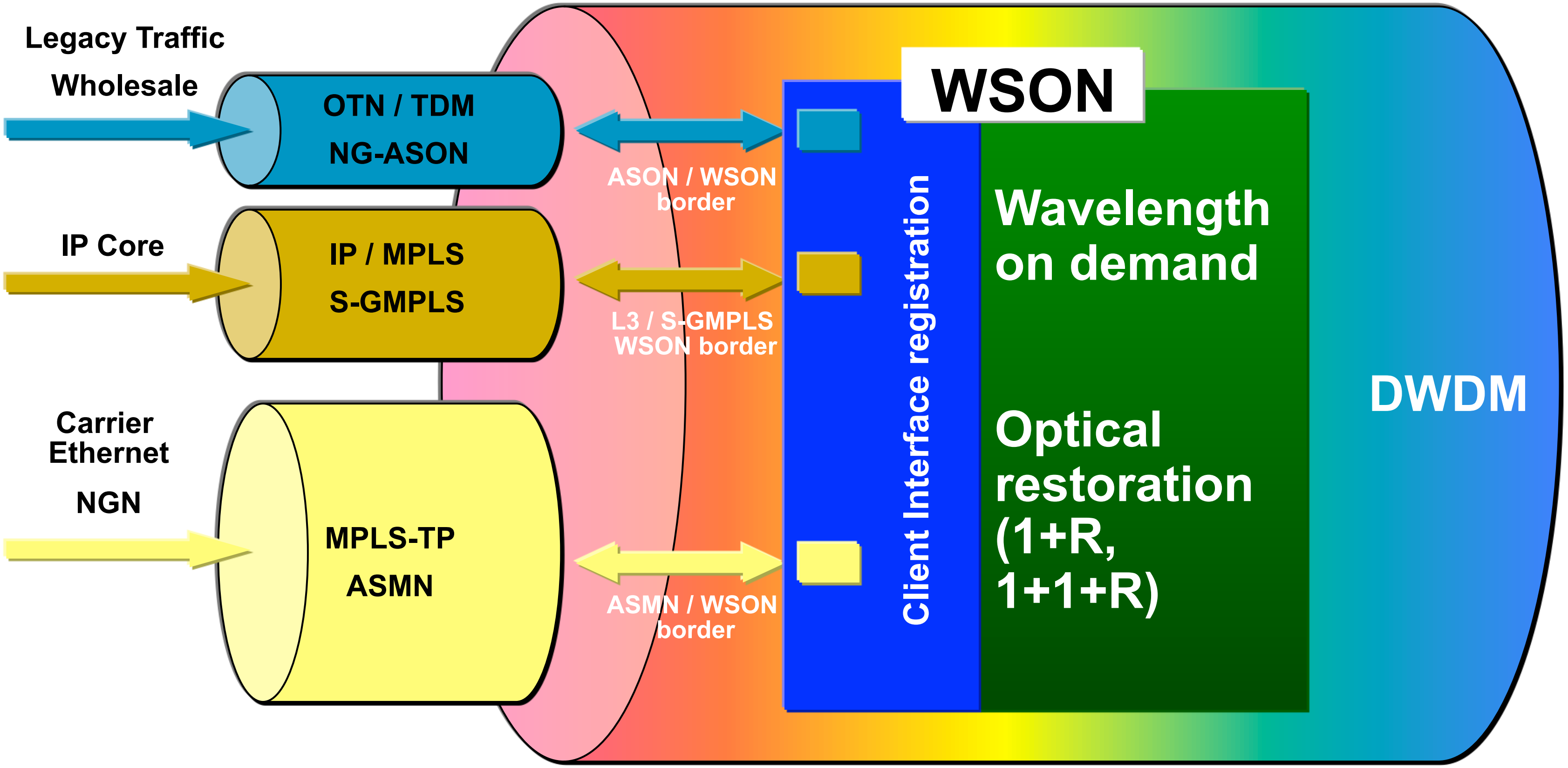
Extensions to IPoDWDM

- Router/Switch G.709 Interface Visibility
- Manageability – Virtual Transponder, NLAC, Inventory, Provisioning

Conclusions

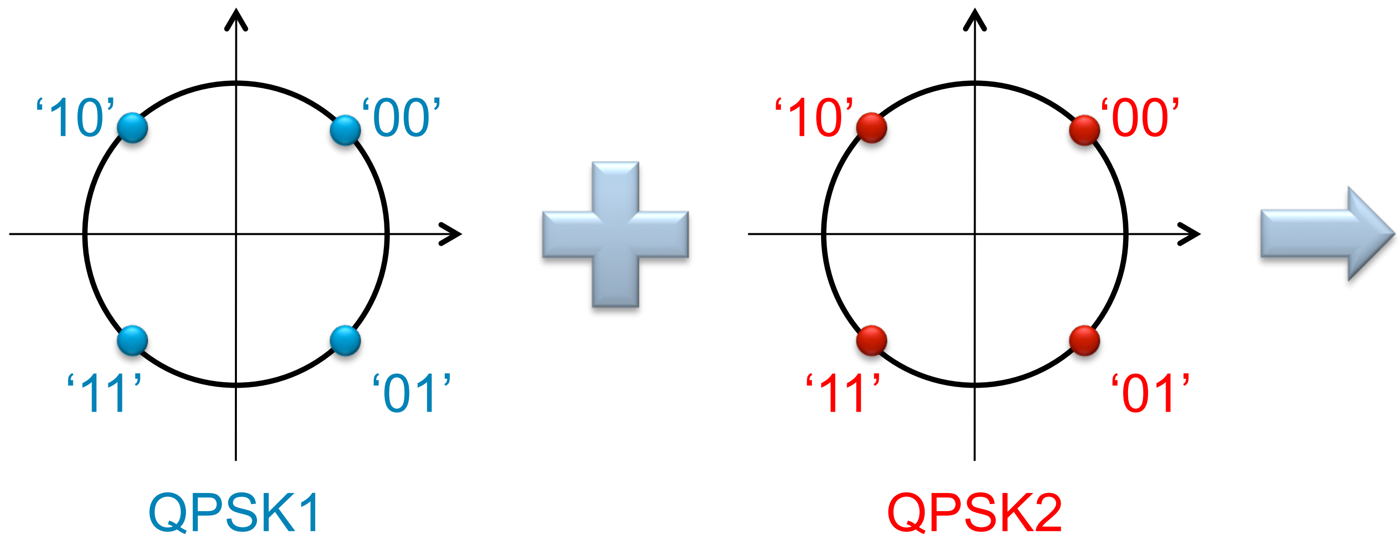
- Coherent Optical Transmission allows today to support 40Gbps wavelengths → 3.2Tbps (80chs @ 40G each) over 3,000Km
- Evolution of FEC and DSP Chips will allow transport of 100Gbps wavelengths at about the same Distance → 8.0Tbps over >2,500Km
- 1,000Gbps per wavelength will require yet another "technology migration" to be usable but is expected to allow about 12.0Tbps over >1,500Km

Control Plane Definition & Interaction



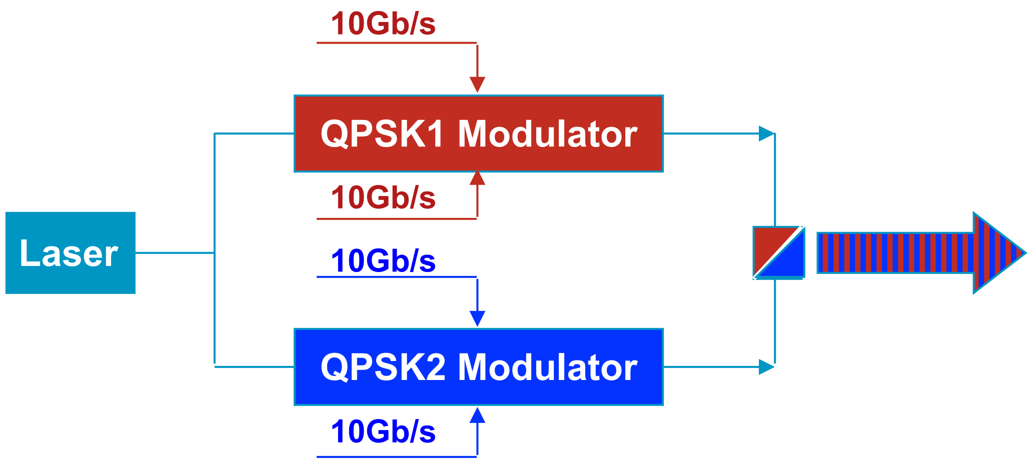
- WSON = Wavelength switched optical network
- ASON = Automatically Switched optical network
- ASMN = Automatically switched MPLS-TP network

Dual Polarization QPSK: Transmitter



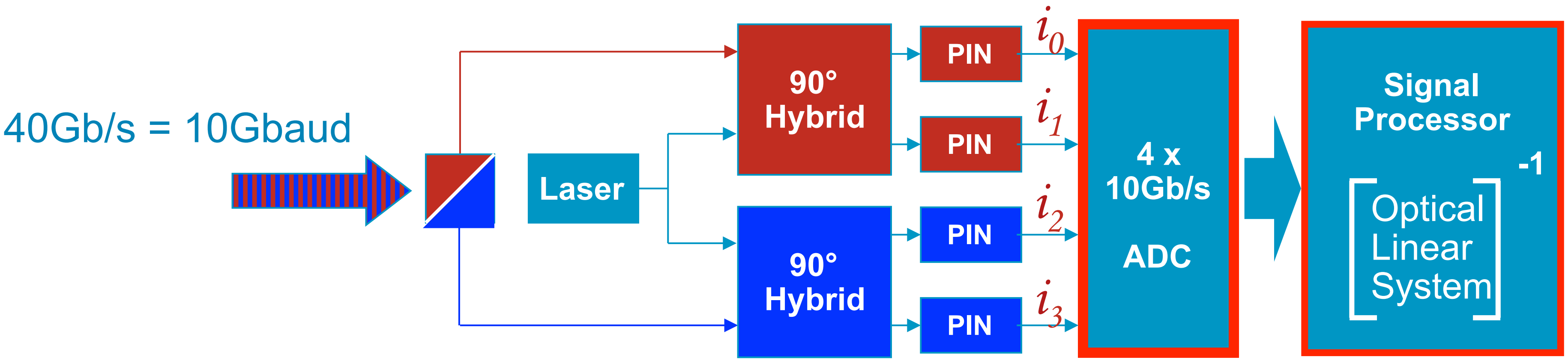
2+2bit/symbol

e.g. 40Gb/s Capacity with a 10Gb/s Optical Bandwidth



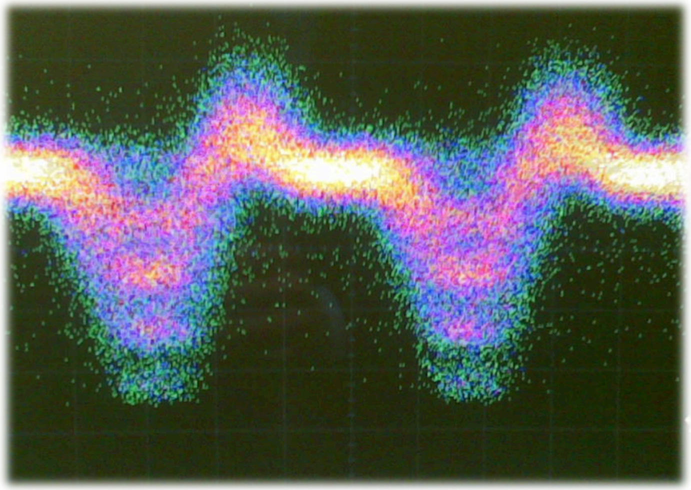
40Gb/s = 10Gbaud

Dual Polarization QPSK: Coherent Detection & Post-Processing



- RX **Laser** behaves as Local Oscillator to provide a Polarization reference
- **90° Hybrid**:
  - Converts Phase modulation in Amplitude modulation
  - Provides In-Phase and Quadrature information Φ (i_0, i_1)
- **Signal Processor**:
  - Calculates the Inverse Optical System Matrix
  - Recovers Polarization
  - Compensates CD and PMD electronically

The "Price" To Pay



40Gbps CP-QPSK Signal

10Gbps NRZ Signal