OPTICAL NETWORK SCALING
SPATIAL AND SPECTRAL SUPERCHANNELS

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AND MANY OTHERS
• Interface rates available up to 200 Gb/s per carrier
• How do we get to Terabit channels?
• WDM systems available up to ~20 Tb/s, saturating at ~50 Tb/s
• How can we scale to Petabit capacities?
SCALING LINE INTERFACE RATES

Physical dimensions

- Space
- Time
- Polarization
- Frequency
- Quadrature

- 100-Gbaud not widely supported by electronics
- Intolerant to CD (~R²) and PMD (~R)
- Doesn’t scale WDM spectral efficiency

CD: Chromatic dispersion
PMD: Polarization-mode dispersion

[Winzer et al., ECOC 2005]
SCALING LINE INTERFACE RATES

Space

Polarization

Physical dimensions

Time

Quadrature

• 100-Gbaud not widely supported by electronics
• Intolerant to CD (~R²) and PMD (~R)
• Doesn’t scale WDM spectral efficiency

⇒ Exploit phase dimension (2x parallelization)
SCALING LINE INTERFACE RATES

Polarization multiplexing lowered symbol rates to ~10 Gbaud (40G) and ~25 Gbaud (100G)

- Can use fast (CMOS) A/D converters
- Digital coherent (intradyne) detection
SCALING LINE INTERFACE RATES

Current state of research:
• 856-Gb/s PDM-16-QAM (107-Gbaud)

[G. Raybon et al., ECOC (2013)]
**DIGITAL COHERENT DETECTION**

**2x2 MULTIPLE-INPUT MULTIPLE-OUTPUT (MIMO)**

- Digital polarization de-rotation
- Digital frequency & phase locking
- Digital impairment compensation

**PBS**

**Fiber**

**Signal 1**

**Signal 2**

**A_{xx}x + A_{xy}y**

**A_{yx}x + A_{yy}y**

**2 x 2 MIMO DSP engine**

**MIMO DSP:** Multiple-input multiple-output digital signal processing
MODERN OPTICAL TRANSPONDERS
LOTS OF DIGITAL PROCESSING

[Diagram showing various components and processes in a modern optical transponder, including ADCs, DACs, DSPs, FEC encoders, and decoders.

FEC: Forward error correction
PDM: Polarization-division multiplexing
DSP: Digital signal processing
DAC: Digital-to-analog converter
ADC: Analog-to-digital converter

[Doerr et al., OFC 2009]

Monolithic Silicon Coherent Receiver

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Constellation Size Versus Symbol Rate

- **PDM 512-QAM**
  - 3 GBaud (27 Gb/s)
  - [Okamoto et al., ECOC’10]

- **PDM 256-QAM**
  - 4 GBaud (32 Gb/s)
  - [Nakazawa et al., OFC’10]

- **PDM 64-QAM**
  - 21 GBaud (128 Gb/s)
  - [Gnauck et al., OFC’11]

- **PDM 16-QAM**
  - 80 GBaud (320 Gb/s)
  - [Raybon et al., PTL’12]

- **PDM QPSK**
  - 107 GBaud (224 Gb/s)
  - [Raybon et al., PTL’12]

ADC & DAC resolution vs. Bandwidth

- **16-QAM**
  - 80 GBaud (320 Gb/s)
  - [Raybon et al., PTL’12]
**TERABIT INTERFACES AND BEYOND**

**OPTICAL SUPERCHANNELS**

- **Space**
  - Polarization
- **Frequency**
  - Time
  - Quadrature

**Physical dimensions**

1. **1 Tb/s** (2 subcarriers) 16-QAM
   - 5.2 bit/s/Hz
   - 3200 km transmission
   - [Raybon et al., IPC’12]

2. **1 Tb/s** (4 subcarriers) 16-QAM
   - 5.0 bit/s/Hz
   - 2400 km transmission
   - [Renaudier et al., OFC’12]

3. **1.5 Tb/s** (8 subcarriers) 16-QAM
   - 5.7 bit/s/Hz
   - 5600 km transmission
   - [Liu et al., ECOC’12]

4. **1.2 Tb/s** (24 subcarriers) QPSK
   - 3 bit/s/Hz
   - 7200 km transmission
   - [Chandrasekhar et al., ECOC’09]

**Electronics complexity**

**Optics complexity**
DWDM Superchannel

- Cohesive spectral entity
- *Parallelization* requires *integration*
SUPERCHANNEL TRANSPONDER INTEGRATION

SPECTRAL SUPERCHANNEL

[H. Yamazaki et al., Opt. Ex. 19, B69 (2011)]

10 x 14.25 GBd PDM-QPSK Transmitter

[F. A. Kish et al., JSTQE 17, 1470 (2011)]
SUBCARRIER ADD/DROP IN SUPERCHANNELS
AN OPTO-ELECTRONIC INTERFEROMETER

[P. J. Winzer, J. Lightwave Technol. 1775 (2013)] (earlier patents by Taylor, Morita, Winzer)
SUBCARRIER ADD/DROP IN SUPERCHANNELS
AN OPTO-ELECTRONIC INTERFEROMETER

[S. J. Winzer, J. Lightwave Technol. 1775 (2013)] (earlier patents by Taylor, Morita, Winzer)
OPTICAL NETWORKS SCALING CHALLENGES IN A NUTSHELL

- Interface rates available up to 200 Gb/s per carrier
- How do we get to Terabit channels?
- WDM systems available up to ~20 Tb/s, saturating at ~50 Tb/s
- How can we scale to Petabit capacities?
THE (LINEAR) SHANNON LIMIT
SPECTRAL EFFICIENCY VS. SIGNAL-TO-NOISE RATIO

• For every bit of higher spectral efficiency, ~3 dB more SNR are needed
  [C. E. Shannon, BLTJ (1948)]

⇒ 16-QAM turns out to be a good compromise

\[ SE = \log_2 (1 + \text{SNR}) \]
APPROACHING SHANNON IN OPTICS
4D, CODED MODULATION, SHAPING, MAP DETECTION

Spectral efficiency [b/s/Hz]

Required SNR per bit [dB]

Constellation shaping
256-QAM
64-QAM
16-QAM
4-QAM

Coded modulation
Over-filtering & MAP

ISI: Inter-symbol interference; MAP: Maximum a posteriori
THE NONLINEAR NEAR SHANNON LIMIT
COMMERCIAL WDM PRODUCT NEEDS

Transmission distance [km]
Spectral efficiency [b/s/Hz]

WDM Experiments
Products

Commercial WDM needs ca. 2016 ... 2018
30 ... 60% traffic growth per year

Current WDM products

NL Shannon limit

<2x

[R.-J. Essiambre et al., J. Lightwave Technol. 28(4), 662-701 (2010)]
BETTER FIBER: NOT A LONG-TERM SOLUTION

Capacity is fairly insensitive to (heroic!) improvements of fiber loss, nonlinearity, or dispersion.

- Improving single-mode fiber is not a long-term solution

PHYSICAL DIMENSIONS IN USE TOMORROW

~100x

- Polarization
- Frequency
- Time
- Quadrature

Integration

WDM with polarization multiplexing

~5x

Loss [dB]

Wavelength [nm]

1300 1360 1460 1530 1565 1625

O E S C L

1260 1360 1460 1530 1565

0.3 0.6 0.9 1.2

0 1

100x

Integration

Space

Physical dimensions

Courtesy: X. Liu
RELIABLE MODE DIVISION MULTIPLEXING

ESSENTIAL INGREDIENTS

1. MIMO processing of all modes (both polarizations)

2. Coherent detection of any complete orthogonal set of modes (both orthogonal polarizations, any basis)

3. Selective excitation of any complete orthogonal set of modes (both orthogonal polarizations, any basis)

[Winzer and Foschini, Proc. OFC, OThO5 (2011)]
HOW TO PERFORM SELECTIVE EXCITATION
UNITARY TRANSFORM INTO (ANY COMPLETE) BASIS

[R. Ryf, et.al., JLT 30(4), 2012]

[H. Bülow et al., ECOC2011 (Tu.5.B);
N. Fontaine et al. ECOC 2012 (Th.2.D.6)]

[R. Ryf et al., PTL, 1973 (2012)]
Deploying $M$ parallel paths is better than using multiple regenerators. *But: $M$ systems cost $M$ times as much & consume $M$ times the energy.*

$\Rightarrow$ Cost/bit (or energy/bit) remains constant

*Integration* is key to scale capacity in parallel systems.
SUPERCHANNEL TRANSPONDER INTEGRATION

SPECTRAL SUPERCHANNEL

SPATIAL SUPERCHANNEL

[S. Randel, OFC 2013, Tutorial OW4F.1]
TRANSPONDER INTEGRATION
MULTI-CORE FIBER INTERFACING

OPTICAL AMPLIFIER INTEGRATION
OPTICAL AMPLIFIER INTEGRATION

SOME EXAMPLES

Multimode-pumped Er doped

[Core- and cladding-pumped 7-core]

[SOA array]

[K. S. Abedin et al., Opt. Ex. 19, 16715 (2011)]

[H. Takahashi et al., ECOC, Th.3.C.3 (2012)]

[K. S. Abedin et al., Opt. Ex. 20, 20191 (2012)]

Few-mode doped & Raman

[Y. Yung et al., ECOC 2011]

[E. Ip et al., ECOC 2011]

[R. Ryf et al., ECOC 2011]

[M. Salsi et al., ECOC 2012]

[M. H. Hu et al., OAA, OWB3 (2006)]
SDM WAVEGUIDE INTEGRATION
SDM RESEARCH HAS STARTED WITH FIBERS
MULTI-CORE AND FEW-MODE

[B.Zhu et al., ECOC 2011] [K.Imamura et al., ECOC 2011] [Sakaguchi et al., OFC 2012]

[T. Hayashi et al., ECOC 2011] [H. Takara et al., ECOC 2012]

[R. Ryf et al., OFC 2012] [M. N. Petrovich et al, ECOC 2012] [C. Cia et al., Sum. Top. 2012]
VERY IMPRESSIVE TRANSMISSION RESULTS
BEYOND THE SINGLE-MODE SHANNON LIMIT

![Graph showing transmission distance vs. aggregate spectral efficiency with data points and lines indicating NL Shannon limit and Experiments, single-mode.]

- [Takara, ECOC 2012]
- [Liu, ECOC 2011]
- [Sakaguchi, OFC 2012]
- [Ryf, OFC 2013]
- [Gnauck, ECOC 2012]
- [Chandrasekhar, ECOC 2011]
- [Takahashi, ECOC 2012]
USE OF SPATIAL PATHS FOR NETWORKING?
THE ANSWER LIES IN THE PHYSICAL LAYER

- The benefits of SDM come through integration
- Integration typically comes at the cost of impairments
  - ... such as crosstalk
- Crosstalk can be accommodated by MIMO processing
  - MIMO requires detection of all cross-talking channels
  ➔ Forces the use of spatial superchannels

MIMO DSP: Multiple-input multiple-output digital signal processing

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CONCLUSIONS

• Optical transport has run out of physical dimensions
  • Need parallelism in frequency or space → Superchannels

• Parallelism in frequency
  • Spectral superchannels to reach Terabit/s interface rates
  • Multi-band systems as a stop-gap solution to capacity crunch

• Parallelism in space
  • Spatial superchannels to reach Petabit/s fiber capacities

• Integration is essential to reduce cost per bit
  • Transponders, optical amplifiers, ROADM, connectors/splices, fiber
  • Integration eventually leads to crosstalk and the need for MIMO

• A smooth upgrade path from existing infrastructure is essential
  • Start with parallel deployed fiber strands
  • Mixed fiber and mixed technologies
  • Leverage existing components at telecom wavelengths