Optical (Long-Haul) Transport of 100 Gigabit Ethernet

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Example: The Internet2 Network
Remote Locations with Routers that have 100 GbE Interfaces
How to Transport 100 GbE between Routers?

Distances 1,000-3,000 km

Old fibers with high Polarization-Mode Dispersion (PMD) ???
How to Transport 100 GbE between Routers?

Optical Add/Drop Switching Nodes
(= Optical Bandpass Filters)
Serial vs Parallel Transport

Serial PHY
- All information transported on one wavelength
- Higher spectral efficiency
- Higher total transport capacity in a WDM system, resulting in lower $$$/bit
- Complexity in high-speed transponder implementation
- Physical transmission constraints depending on symbol rate
- Could use multi-level modulation formats and/or both polarizations of light to reduce baud rate

Parallel PHY
- All information transported over multiple lanes (fibers, wavelengths, etc.)
- Lower baud rate per lane
- Fewer transmission constraints on physical layer
- Complexity in multi-lane implementation & management (e.g., Virtual Concatentation VCAT, Link Capacity Adjustment Scheme LCAS, etc.)
What is the Total Capacity per Fiber Link?

100 Gb/s to ~300 Gb/s ???
→ Parallel Transport of 100 GbE might be more cost-efficient ...

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What is the Total Capacity per Fiber Link?

~400 Gb/s to ~10 Tb/s ???

→ Serial Transport of 100 GbE will be more cost-efficient ...
What are the (Likely) Bit Rates?

**100 Gigabit Ethernet**
- IEEE 802.3ba standard
- MAC rate = 100.000 Gb/s
- 3.125% overhead due to 64B/66B PCS encoding
- PCS-encoded line rate = 103.125 Gb/s

**“100 Gigabit OTN”**
- ITU-T G.709 standard (OTN = Optical Transport Network)
- OPU4 payload rate ~104 Gb/s
- 7% overhead due to framing and Forward Error Correction (FEC)
- OTU4 line rate ~112 Gb/s

- Single-mode fiber PHY = parallel = 4 wavelengths @ 25.78 Gb/s
- Max. 40-km reach, single-channel fiber links, no optical amplification (OEO)

- Single-mode fiber PHY = serial = 1 wavelength @ 112 Gb/s but at lower baud rate...
- Longer spans, multi-channel fiber links (WDM), optical amplification, etc.
What are the Promising Options for ~112 Gb/s Serial Transport?

**56 Gbaud per wavelength**
- 2 bits per symbol
- Single polarization
- Advanced phase modulation format (Differential Quadrature Phase-Shift Keying, DQPSK)

  - “Advanced 40G technology”
  - Technology & components available today!

**28 Gbaud per wavelength**
- 4 bits per symbol
- Dual polarization
- DQPSK/QPSK with polarization-multiplexing & coherent detection

  - Coherent receiver main challenge, first introduction of 40G coherent Rx expected in 2008, not yet ready for 100G (very fast A/D converters & DSP with 1 Tb/s throughput required)!

- Lower tolerance to chromatic dispersion, PMD, optical filtering ... (similar to today’s 40G systems)

- Higher tolerance to chromatic dispersion, PMD, optical filtering ...
# 100G Hero Experiments

<table>
<thead>
<tr>
<th>When</th>
<th>Experiment</th>
<th>Reach</th>
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<tbody>
<tr>
<td>ECOC 2005</td>
<td>107-Gb/s binary ETDM Tx &amp; OTDM Rx</td>
<td>–</td>
<td>Alcatel-Lucent</td>
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<tr>
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<td>10x107-Gb/s NRZ transmission (0.7 b/s/Hz)</td>
<td>400 km</td>
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<td>100-Gb/s DQPSK generation</td>
<td>–</td>
<td>KDDI+NICT+Sumitomo</td>
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<td>100-Gb/s binary ETDM Rx</td>
<td>–</td>
<td>HHI+Siemens+Micram</td>
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<td>OFC 2006</td>
<td>100-Gb/s binary OOK ETDM Tx and ETDM Rx</td>
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<tr>
<td></td>
<td>10x107-Gb/s RZ-DQPSK transmission (0.7 b/s/Hz)</td>
<td>2,000 km</td>
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<tr>
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<td>140x111-Gb/s PDM-CSRZ-DQPSK transmission (2.0 b/s/Hz)</td>
<td>160 km</td>
<td>NTT</td>
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<tr>
<td>ECOC 2006</td>
<td>10x107-Gb/s NRZ-DQPSK transmission + ROADMs (1.0 b/s/Hz)</td>
<td>1,200 km</td>
<td>Alcatel-Lucent</td>
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<tr>
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<td>10x107-Gb/s NRZ transmission (0.5 b/s/Hz)</td>
<td>480 km</td>
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<td>10x111-Gb/s PDM-RZ-DQPSK transmission (2.0 b/s/Hz)</td>
<td>2,375 km</td>
<td>CoreOptics+Siemens</td>
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<td>204x111-Gb/s PDM-CSRZ-DQPSK transmission (2.0 b/s/Hz)</td>
<td>240 km</td>
<td>NTT</td>
</tr>
<tr>
<td>OFC 2007</td>
<td>107-Gb/s O/E Rx (photodetector &amp; electrical demux)</td>
<td>–</td>
<td>Alcatel-Lucent</td>
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<tr>
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<td>80x107-Gb/s NRZ-VSB transmission (1.0 b/s/Hz)</td>
<td>510 km</td>
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<td></td>
<td>8x107-Gb/s PDM-RZ-DQPSK transmission + ROADMs (2.0 b/s/Hz)</td>
<td>1,280 km</td>
<td>Alcatel-Lucent</td>
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<tr>
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<td>30x100-Gb/s OFDM transmission + ROADMs (1.0 b/s/Hz)</td>
<td>1,300 km</td>
<td>NTT</td>
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- Spectral efficiency @ 10 Gb/s = 0.1 or 0.2 b/s/Hz
- Spectral efficiency @ 40 Gb/s = 0.4 (or 0.8) b/s/Hz
107 Gb/s NRZ-DQPSK on 100-GHz grid over 1,200 km and 6 ROADMs

- High spectral efficiency, 1 bit/s/Hz, (100-GHz channel spacing)
- No polarization multiplexing, full ETDM
- Reconfigurable optical add/drop multiplexers (ROADMs)
  - Placed every 200 km, adjacent channels dropped and re-inserted
- 1,200-km reach with six ROADMs
- 2,000-km reach without ROADMs

P.J. Winzer et al.,
OFC 2007 PD paper
ECOC 2006 PD paper