• Why spectral efficient DWDM for 100G?
• DWDM spectral efficiency advancement over the last 10 years
  — 10G/20G/40G Modulation techniques review
• Optical modem structure and cost implications
• Conclusion
Spectral-efficient parallel PHY lowers cost on both fiber infrastructure and transceivers.
How many 100GbE can a single-mode fiber support (in C-band)?

<table>
<thead>
<tr>
<th>Spectral Efficiency (bit/s/Hz)</th>
<th># 100GbE Links</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0</td>
</tr>
<tr>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>0.3</td>
<td>0</td>
</tr>
<tr>
<td>0.4</td>
<td>0</td>
</tr>
<tr>
<td>0.5</td>
<td>0</td>
</tr>
<tr>
<td>0.6</td>
<td>0</td>
</tr>
<tr>
<td>0.7</td>
<td>0</td>
</tr>
<tr>
<td>0.8</td>
<td>0</td>
</tr>
<tr>
<td>0.9</td>
<td>0</td>
</tr>
<tr>
<td>1.0</td>
<td>0</td>
</tr>
</tbody>
</table>

- (10G/12.5GHz, 20G/25GHz) Today's capacity
- (10G/25GHz, 20G/50GHz)
- (10G/50GHz, 20G/100GHz)
- (10G/100GHz, 20G/200GHz)
Two extremes on the spectrum

Need to find an optimum point in the middle

10Gb/s x10
- Poor spectral efficiency
- Cumbersome fiber management
- Lower cost on 10 transceivers
- Low cost on fiber infrastructure

100Gb/s x1
- Good spectral efficiency
- Simple fiber management
- Higher cost on 1 transceiver
- High cost on fiber infrastructure

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Historical view: 40G upgrade on 10G infrastructure?

- **6 dB more OSNR must be overcome**
  (> 6 dB if dispersion map is not optimized)
  - NRZ→ RZ: 1~2 dB OSNR gain $\$
  - OOK→ DPSK: 3 dB OSNR gain $\$
  - RS FEC→ BCH FEC: 3 dB OSNR gain $\$

- **Accumulated PMD must be low**
  - New fibers with PMD < 0.1~0.2 ps/km$^{1/2}$ must be used $\$
  - Highly reliable PMD compensators needed $\$

- **Chromatic dispersion maps must be compatible** (requires pre-compensation and tunable post-compensation) $\$

*OPVISTA*
Optical Power Spectra and Pulse Shapes of various modulation formats

NRZ  RZ (50%)  RZ(67%)=CSRZ  Duobinary  RZ-DPSK
10, 20, 40 & 100 Gb/s DWDM Spectral Efficiency Trend

(*) VSB and polarization multiplexing methods not included

Real deployment (10G)

Real deployment (40G)
Different System Considerations between Metro/Regional Networks and Long-Haul Systems

- **Metro/regional networks**
  - Standard (old and new) single-mode fibers dominate
  - Erbium-doped fiber amplifiers dominate
  - A mixture of different data rates and protocols (not just carrying 100GbE)
  - Many dynamic add/drops, ingress and egress nodes often change to cause different accumulated chromatic dispersion and PMD (cannot always be pre-calculated as in LH systems)
  - Transponders are dispersed all over the (ring) network → Cannot use polarization-interleave or –multiplexing techniques to increase spectral efficiency as in LH systems
  - Very cost-sensitive
<table>
<thead>
<tr>
<th></th>
<th>NRZ</th>
<th>RZ (50%, 33%, 67% (CSRZ))</th>
<th>Duobinary</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TX</strong></td>
<td>DFB → driver</td>
<td>DFB → DATA → CLK → BPF</td>
<td>DFB → precoder → LPF</td>
</tr>
<tr>
<td></td>
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<tr>
<td></td>
<td>TIA/AGC</td>
<td>TIA/AGC</td>
<td>TIA/AGC</td>
</tr>
<tr>
<td><strong>RX</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>RZ-DPSK</td>
<td>RZ-DQPSK</td>
<td></td>
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</tr>
<tr>
<td><strong>TX</strong></td>
<td><img src="image1" alt="RZ-DPSK TX diagram" /></td>
<td><img src="image2" alt="RZ-DQPSK TX diagram" /></td>
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<tr>
<td><strong>RX</strong></td>
<td><img src="image3" alt="RZ-DPSK RX diagram" /></td>
<td><img src="image4" alt="RZ-DQPSK RX diagram" /></td>
<td></td>
</tr>
</tbody>
</table>
Today’s Relative Transceiver Cost Comparison

* The ratios could change by 2009/2010, driven by volume

* Fiber infrastructure cost should be considered separately

The best spectral efficiencies are based on published results with no polarization interleaving and multiplexing
Conclusion

- Today’s 10G DWDM spectral efficiency can only support 4~8 100GbE links, and must be improved

- Parallel PHY allows 100GbE to be transported in an incumbent fiber plant

- For both 10Gx10 and 20Gx5
  - Fiber infrastructure cost is far lower than that for serial PHY
  - Transceiver cost has the advantage of much higher volume than that of serial PHY
  - Today’s discrete technology can comfortably improve the spectral efficiency to 0.4~0.6 bit/sec/Hz
  - By 2009/2010, it is feasible to reach a spectral efficiency of 0.8~1 bit/sec/Hz (with binary modulation)


[22] B. Zhu, et al, “6.4 Tb/s (160×42.7 Gb/s) transmission with 0.8 bit/s/Hz spectral efficiency over 32×100km of fiber using CSRZ-DPSK format,” PD19, OFC 2003.
[26] A. H. Gnauck, et al, “Spectrally efficient (0.8b/s/Hz) 1-Tb/s (25×42.7 Gb/s) RZ-DQPSK transmission over 28 100-km SSMF spans with 7 optical add/drops,” Th4.4.1, ECOC 2004.
[29] A. H. Gnauck, et al, “2.5 Tb/s (64×42.7 Gb/s) transmission over 40×100km NZDSF using RZ-DPSK format and all-Raman-amplified system,” Post-deadline paper FC2, OFC 2002.