Outline

- Optical Interface Types
- DSP in Datacom
- Optical Datacom Today
- Next Gen Optical Datacom: 40Gb/s & 100Gb/s
- Beyond 100Gb/s: 400Gb/s & ≥1Tb/s
- DSP in Optical Datacom
Optical Interface Types - Telecom

- Enterprise: 200km transmission (transport)
- Metro: 500km transmission
- Long Haul: 2000km transmission
- Multiple DWDM channels per fiber per ITU-T
- 40Gb/s: OTN or SDH (SONET) per ITU-T (Telcordia)
- 100Gb/s: OTN per ITU-T
- Moderate volume (1Ks to 10Ks)
- High ASPs
- Stringent performance requirements
- DSP advantageous for 40Gb/s
- DSP required for 100Gb/s Metro & Long Haul
- Discussed in detail in the other F3 presentations
- Not discussed in this presentation
Optical Interface Types - Datacom

- 300m / 2km / 10km / 40km data-center, campus and interoffice point to point links
- From a technology standpoint includes Telecom clients for central office links
- Single channel per fiber (gray)
- Mainstream interfaces at 1Gb/s & 10Gb/s
  - high volume (100Ks to 1Ms)
  - moderate performance requirements require no DSP
  - Cost sensitive
- Niche interfaces at 10Gb/s
  - modest volume (10Ks)
  - stringent performance requirements optionally use DSP
- When will DSP become necessary in mainstream optical datacom?
DSP in Datacom

- Voiceband Example
- Wireline Example
- Wireless Example
- Observations
# Voiceband Datacom Example

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>bit rate (b/s)</td>
<td>1200</td>
<td>9600</td>
</tr>
<tr>
<td>Baud (Bd)</td>
<td>600</td>
<td>2400</td>
</tr>
<tr>
<td>bits/symbol</td>
<td>2 (4 state QAM)</td>
<td>4 (16 state QAM)</td>
</tr>
<tr>
<td>channels</td>
<td>1 (unidirectional, split-band over 1 wire pair)</td>
<td>1 (bidirectional, full-band over 1 wire pair)</td>
</tr>
<tr>
<td>DSP</td>
<td>none</td>
<td>Echo cancellation, adaptive equalization and forward error correction (FEC)</td>
</tr>
</tbody>
</table>
## Wireline Datacom Example

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>IEEE standard</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>bit rate (Mb/s)</strong></td>
<td>100</td>
<td>1000</td>
</tr>
<tr>
<td><strong>Baud (MBd)</strong></td>
<td>125</td>
<td>125</td>
</tr>
<tr>
<td><strong>bits/symbol</strong></td>
<td>1 (3 state PAM)</td>
<td>~2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(5 state PAM)</td>
</tr>
<tr>
<td><strong>channels</strong></td>
<td>1 (unidirectional over 2 wire pairs)</td>
<td>4 (bi-directional over 4 wire pairs)</td>
</tr>
<tr>
<td><strong>DSP</strong></td>
<td>4B/5B encoding</td>
<td>Echo cancellation and trellis coding across all channels</td>
</tr>
</tbody>
</table>
## Wireless Datacom Example

<table>
<thead>
<tr>
<th></th>
<th>802.11b (WiFi)</th>
<th>802.11a (WiFi)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>IEEE standard</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>bit rate (Mb/s)</strong></td>
<td>11 (simplex)</td>
<td>54 (simplex)</td>
</tr>
<tr>
<td><strong>Baud (KBd)</strong></td>
<td>1400</td>
<td>208</td>
</tr>
<tr>
<td><strong>bits/symbol</strong></td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>(64 state QPSK x 4 state DQPSK CDMA)</td>
<td>(64 state QAM)</td>
</tr>
<tr>
<td><strong>channels</strong></td>
<td>1</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>(unidirectional, CCK, CSMA/CA full-band)</td>
<td>(unidirectional, OFDM, CSMA/CA full-band)</td>
</tr>
<tr>
<td><strong>DSP</strong></td>
<td>Walsh/Hadamard coding, adaptive rate selection</td>
<td>FFT coding, adaptive rate selection</td>
</tr>
</tbody>
</table>
DSP in Datacom Observation

- DSP is used when the communication channel is close to Nyquist and Shannon limits, and/or channel impairments cause large fractional U.I. symbol degradation.

- Mainstream voiceband, wireline and wireless datacom interfaces reached these limits, and DSP was required to support data rate increases.
Optical Datacom Today

- Mainstream
- Niche
- DSP Use
# Mainstream Optical Datacom

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>bit rate (Gb/s)</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Baud (GBd)</td>
<td>1.25</td>
<td>10.3</td>
</tr>
<tr>
<td>bits/symbol</td>
<td>1 (2 state NRZ)</td>
<td>1 (2 state NRZ)</td>
</tr>
<tr>
<td>channels</td>
<td>1 (unidirectional over 2 fibers)</td>
<td>1 (unidirectional over 2 fibers)</td>
</tr>
<tr>
<td>DSP</td>
<td>8B/10B coding</td>
<td>64B/66B coding</td>
</tr>
</tbody>
</table>
## Niche Optical Datacom

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>bit rate (Gb/s)</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Baud (GBd)</td>
<td>3.1</td>
<td>10.3</td>
</tr>
<tr>
<td>bits/symbol</td>
<td>1 (2 state NRZ)</td>
<td>1 (2 state NRZ)</td>
</tr>
<tr>
<td>channels</td>
<td>4 (unidirectional WDM over 2 fibers)</td>
<td>1 (unidirectional over 2 fibers)</td>
</tr>
<tr>
<td>DSP</td>
<td>8B/10B coding</td>
<td>64B/66B coding, adaptive equalization</td>
</tr>
</tbody>
</table>
DSP in Mainstream Optical Datacom

- Fundamental limits of fiber communication channel
  - Nyquist limit, 60nm window @1310nm: 
    ~20TBaud
  - Capacity limit, 60nm window @1310nm with simple modulation (0.5bits/sec-HZ):
    ~5Tbits/sec
  - Shannon limit in the presence of fiber non-linearity, 60nm window @1310nm (8bits/sec-Hz):
    ~40Tbits/sec
  - Dispersion penalty 25GBaud @1310nm:
    <1.5dB/10km

- Mainstream optical datacom interfaces are far below fundamental fiber channel limits and do not require DSP
DSP in Niche Optical Datacom

- Niche optical datacom interface:
  - 10GE-LRM (DSP based)
  - 10GBb/s (10GBaud) 220m old multi-mode fiber link
  - ~2GHz bandwidth
  - Severe multi-path

- DSP is not fundamentally required for 10Gb/s over old MMF, as it is in the voiceband, wireline, and wireless datacom examples, since a technical alternative (WDM) exits. DSP use is based on potential for lower cost.

- Total R&D investment in 10GE-LRM technology exceeds $100M so positive industry ROI may never happen.

- Could a similar size investment in WDM photonic integration technology produced better financial results?
Next Datacom Rates: 40Gb/s & 100Gb/s

- 40Gb/s WDM SMF Transceiver
- 40Gb/s Serial SMF Transceiver
- 100Gb/s Gen1 WDM SMF Transceiver
- 100Gb/s Gen3 WDM SMF Transceiver
40Gb/s WDM SMF Transceiver
40Gb/s Serial SMF Transceiver

802.3ba PCS MLD
G.707 STL-256.4
G.709 OTL3.4

802.3ba XLAUI
CEI-11G (OIF)

Ethernet (IEEE)
SONET (Telcordia)
SDH (ITU-T)
OTN (ITU-T)

802.3ba 40GE-LR (TBD)
GR-253 OC-768 SR-2
G.693 VSR2000-3R2
G.693 VSR2000-3R2F
100Gb/s Gen1 WDM SMF Transceiver
100Gb/s Gen3 WDM SMF Transceiver

[Diagram showing the block diagram of a 100Gb/s Gen3 WDM SMF Transceiver, including components such as CDR, LD, DML, TIA, PIN, and SMF.]

Lane Coding:
- TX3, TX2, TX1, TX0: Transmitters
- RX3, RX2, RX1, RX0: Receivers

Protocol Standards:
- 802.3ba PCS
- G.709 OTL4.4
- Future Spec (OIF or other)
- CEI-28G (OIF)

Ethernet Standards:
- OTN (ITU-T)

Future Technologies:
- 802.3ba 100GE-LR4
- G.959.1 4I1-9D1F
Observations on 40Gb/s & 100Gb/s

- Defined far below fundamental fiber channel limits to not require DSP
- Mainstream 40Gb/s (4x10G WDM) leverages today’s 10GBaud technology
- Niche 40Gb/s (40G Serial) supports legacy Telecom client interfaces deployed in some carrier central offices
- Mainstream 100Gb/s Ethernet establishes a new signaling rate base technology for the entire datacom industry
  - Ethernet: 26GBaud (4x26Gb/s → 103Gb/s)
  - Telecom: 28GBaud (4x28Gb/s → 112Gb/s)
  - Infiniband: 25Gbaud (N x 25Gb/s)
  - FiberChannel: 28Gbaud (28Gb/s)
- Key technology required for high volume, low cost 40Gb/s & 100Gb/s is high yield photonic integration
Photograph of a monolithic InP transmitter PIC comprising four O-band DFB lasers and an AWG with 24.5nm channel spacing. The chip size is 1.1 x 2.4 mm. (CyOptics Inc.)
Beyond 100Gb/s: 400Gb/s & >1Tb/s

- 400Gb/s SMF WDM Transceiver
- 400Gb/s SMF Transceiver Alternatives
- >1Tb/s SMF Transceiver Alternatives
400Gb/s SMF WDM Transceiver
400Gb/s SMF Transceiver Alternatives

- SMF WDM Transceiver alternative requires extension of 100Gb/s WDM PIC and 25GBaud I/O technology, but no new fundamental technology and no DSP

- Electrical I/O Alternative to 25GBaud NRZ
  - 8x50Gb/s (25GBaud PAM4)
  - Requires DSP

- Optical Complex Modulation Alternative 1
  - 8x50Gb/s (25GBaud (D)QPSK)
  - May require DSP

- Optical Complex Modulation Alternative 2
  - 4x100Gb/s (25GBaud DP-QPSK)
  - Requires DSP
≥1Tb/s SMF Transceiver Alternatives

- What is the likely ≥1Tb/s rate?
- 1Tb/s is a small 2.5x rate jump from 400Gb/s so is unlikely to justify investment or meet bandwidth growth demands.
- 1.2Tb/s is possible, but a 3x jump from 400Gb/s is not a traditional datacom data rate step.
- A likely ≥1Tb/s rate is 1.6Tb/s
- Possible optical approach: 64x25Gb/s DMLs (directly modulated lasers); requires very high yield PICs, does not require DSP
- Alternate optical approach: 16x25GBaud DP-QPSK MLs (modulated lasers); requires DSP
- Electrical I/O is unlikely to be 64 NRZ lanes; any multi-level encoding to give 32 or 16 lanes requires DSP
DSP in Optical Datacom - Conclusions

■ Today mainstream interfaces up to 10Gb/s do not require DSP

■ Next Gen mainstream interfaces at 40Gb/s & 100Gb/s do not require DSP

■ Beyond 100Gb/s, 400Gb/s could be based on extended 100Gb/s technology and not require DSP

■ Beyond 400Gb/s, 1.6Tb/s is the likely next rate and will require DSP