The Convergence of Optical and Electronic Solutions for Future Network Challenges

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Protecting the Signal
-- in the DWDM Backbone

PMD: low polarization mode dispersion in cabled fiber & dispersion compensation modules.
- OFS holds fundamental IP for controlling PMD in cabled fiber

Chromatic Dispersion:
slope compensation modules for wide band matching of all fiber types
- OFS has ~50% global share for dispersion comp modules, key IP in DCF and FBG technologies

Attenuation: EDFA and Raman amplifiers; cabled fiber with low loss;
- OFS has ~50% global market share in erbium doped fiber for amplifiers

Balancing act between maximizing OSNR and minimizing non-linearity
What’s driving 100G in the backbone transport network?

- Carriers recently began deploying 40G technology in the photonic core and for video delivery in the metro
- However IEEE P802.3ba will standardize 40 and 100Gbps transceivers for the short reach in the LAN
IEEE P802.3ba Adopted Objectives

- Support full-duplex operation only
- Preserve the 802.3 / Ethernet frame format utilizing the 802.3 MAC
- Preserve minimum and maximum FrameSize of current 802.3 standard
- Support a BER better than or equal to $10^{-12}$ at the MAC/PLS service interface
- Provide appropriate support for OTN
- Support a MAC data rate of 40 Gb/s
- Provide Physical Layer specifications which support 40 Gb/s operation over:
  - at least 100m on OM3 MMF
  - at least 10m over a copper cable assembly
  - at least 1m over a backplane
- Support a MAC data rate of 100 Gb/s
- Provide Physical Layer specifications which support 100 Gb/s operation over:
  - at least 40km on SMF
  - at least 10km on SMF
  - at least 100m on OM3 MMF
  - at least 10m over a copper cable assembly

Single-channel transport; 40km is maximum reach considered!
### Variety of Optical Transceiver Technologies Employed

<table>
<thead>
<tr>
<th>Speed (Gbps)</th>
<th>Reach</th>
<th>Medium</th>
<th>Baud Rate (GBaud)</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>&gt; 100 m</td>
<td>MMF</td>
<td>10</td>
<td>parallel</td>
</tr>
<tr>
<td>100</td>
<td>&gt; 100 m</td>
<td>MMF</td>
<td>10</td>
<td>parallel</td>
</tr>
<tr>
<td>40</td>
<td>&gt; 10 km</td>
<td>SSMF</td>
<td>10</td>
<td>CWDM</td>
</tr>
<tr>
<td>100</td>
<td>&gt; 10 km</td>
<td>SSMF</td>
<td>25</td>
<td>CWDM</td>
</tr>
<tr>
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<td>25</td>
<td>CWDM</td>
</tr>
</tbody>
</table>

MMF = multi mode fiber; SSMF = G.652 single mode fiber
Lowest cost 10Gbps transmission in the Data Center uses IEEE 10GBASE-SR VCSEL transceivers and Laser-Optimized (OM3 and OM4) MMF.
100 Gbps Ethernet – IEEE 802.3ba

- Support a MAC data rate of 40Gb/s operation over at least 100m on OM3 MMF
- Support a MAC data rate of 100Gb/s operation over at least 100m on OM3 MMF

The high bandwidth of laser-optimized MMF supports cost-reduced, low power parallel Tx & Rx for high speed interconnects
What’s driving 100G in the backbone transport network?

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- Therefore ITU must standardize 100G in OTN
- Carriers optical transport requirements:
  - Tight channel spacing (50 GHz) is desirable for efficient use of the amplifier band, as well as making enough λ’s available for mesh routing
  - Strong filtering from cascaded ROADMbs requires spectrally efficient transmission
  - Need backbone 800 to 1200 km for regional mesh networks and up to 2000km for ultra-long haul networks
100 Gbps Backbone DWDM

→ Strong desire to reduce the Baud rate for 100Gbps by factor of 4x to 28 GBaud
  
  • 2 bits / symbol with (D)QPSK
  • 2 polarizations per channel
  • Coherent equalization de-multiplexes polarizations and improves CD and PMD tolerance

Research papers have shown the ability to compensate many impairments, such as chromatic dispersion and polarization mode dispersion, trading off Tx and Rx complexity and cost and power.

However the sensitivity to non-linearity becomes more severe, and much work remains in this area – major area of focus at GaTech.

Conference papers and press release demos generally use a 50 GS/s storage scope and off-line processing.
Should we Protect the Signal?  
... or Clean it up at the Receiver?

- The power of coherent equalization proposed for 100G transmission requires the availability of very high speed A/D converters, with absolutely huge data transfer requirements from A/D to the DSP.
  - Strong PMD compensation requires 2x oversampling.

<table>
<thead>
<tr>
<th></th>
<th>20 GS/sec production</th>
<th>1.25 W</th>
<th>40 Gbps</th>
<th>2x over-sampling</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 bit A/D (need 4)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30 GS/sec demo</td>
<td>1.25 W</td>
<td>6 W</td>
<td>100 Gbps</td>
<td>1x sampling</td>
</tr>
</tbody>
</table>

- Compensation of CD requires > 250 FIR taps.

- Prediction: the first generation of coherent 100G systems will have only modest PMD and CD compensation capability.

- Question: Are per-channel solutions with very high power dissipation “green”?  
  - Alternative: Full band optical compensation and low PMD fiber cable consume no power regardless of channel count.
Conclusions

- Various technologies will be used to accomplish 100Gbps transmission in different network segments and link distances.

- Electronic processing after coherent detection offers many advantages, especially for legacy networks, but at the cost of $$ and power.

- Electronic processing is most cost effective for lower numbers of DWDM channels.

- Reducing optical impairments in the design of the transmission line remains the “green” option with the lowest power consumption for a loaded network.
Back Up Slides
PMD Tolerance of Modulation Formats from Alcatel-Lucent IEEE contribution

### DGD Tolerance vs Modulation Format

<table>
<thead>
<tr>
<th>Modulation Format</th>
<th>DGD (1.5 dB Penalty)</th>
<th>&lt;DGD&gt; (1.5 dB Margin, 4E-5 outage)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRZ-OOK</td>
<td>41%</td>
<td>14%</td>
</tr>
<tr>
<td>RZ-OOK</td>
<td>51%</td>
<td>17%</td>
</tr>
<tr>
<td>Duobinary</td>
<td>30%</td>
<td>10%</td>
</tr>
<tr>
<td>NRZ-DPSK</td>
<td>47%</td>
<td>16%</td>
</tr>
<tr>
<td>RZ-DPSK</td>
<td>52%</td>
<td>17%</td>
</tr>
<tr>
<td>NRZ-DQPSK</td>
<td>101% **</td>
<td>34% **</td>
</tr>
<tr>
<td>RZ-DQPSK</td>
<td>108% **</td>
<td>36% **</td>
</tr>
</tbody>
</table>

- All data are simulated and hold for an OSNR-limited transmission system
- Measured data depend on exact pulse (eye) shape and receiver characteristics
- All <DGD> data given for 4E-5 outage probability $\rightarrow$ DGD = 3x<DGD>
- All data given for BER 1E-3 (FEC limit)
- All data given as percentage of the bit period!