100G: Opportunities and challenges, and enabling technologies

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2008.10
- 100G market driver-Applications
- Progress of 100G standard
  - 100G standard area
  - IEEE802.3ba 100GE
  - ITU SG15 OTN
  - OIF
- 100G transport challenge
- 100G key technology
  - FEC
  - Dispersion compensation
  - Optical PMD compensation
  - Electrical equalization
  - Coherent detection
  - Modulation format
- Summary
100G market drivers

- Consumer VOD, IPTV, HDTV
- Peer to peer video
- Internet gaming
- High speed computing<br>&lt; 2km
- Computing and Storage<br>Server networks<br>&lt; 100m
- 10-40km: Computing and Storage, Server networks, Internet Exchange and Interconnection points
- 10-1500km: VOD, IPTV, HDTV, Computing and Storage, Server networks, Internet Exchange and Interconnection points, Broadband Access Service Provider, Wifi, WiMax, 3G
- 100G: Research and Education, Content Provider

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100G Applications

- **Backbone Aggregation to replace N*10G LAG**
  Traffic requirement in the carrier backbone are doubling every 12-18 months driven by broadband service (video applications). Client connections are migrating to 10GE interface. To resolve BW bottleneck, N*10G LAG is used. 100G is to replace LAG to resolve operating complexity and improve efficiency of data flow management and distribution.

- **Data Center Network Aggregation and Enterprise Computing**
  Driven by computing storage application, 10GE is starting to deploy in Servers. As 10G increases, there is a need for higher speed switch uplink. 100GE will also be used in data center for network aggregation in data center. 100GE will be used inter-switch links and Metropolitan/Wide Area Network (MAN/WAN) connectivity.
100G Applications-continue

- Convergence of Transport and Ethernet at 100 G-Ethernet transport
  - Carrier network is now undergoing migration to packet based transport network. Ethernet peer to peer transport is becoming a trend.
  - Expected OTN client signal: E-Line, E-Tree, E-LAN.
  - Service: peer to peer video sharing, internet gaming, internet video, mobile back haul etc.
Progress of 100G standard

100G standard area

OIF
Project towards to Implementation Agreement

IEEE 802.3 standardization

40GbE Transcoding

ITUT SG15 standardization

40GbE Transcoding

IEEE 802.3 standardization

LAN
Ethernet: 10GE, 40GE, 100GE

OTN Framing + Mapping

OTN (G.709)

OTN Framing + Mapping

LAN
Ethernet: 10GE, 40GE, 100GE

Efficient mapping required (Ethernet over OTN)

MMF Parallel

SMF

DWDM

SMF

MMF Parallel
IEEE 802.3ba 100GE Interface architecture decisions (see draft 1.0):

<table>
<thead>
<tr>
<th>100GE MAC rate</th>
<th>100.0Gbit/s</th>
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<tbody>
<tr>
<td>100GE line rate</td>
<td>103.125 Gbit/s with 64B/66B block encoding</td>
</tr>
<tr>
<td>(100GBASE-R MAC/PCS)</td>
<td></td>
</tr>
<tr>
<td>100GBASE-CR10</td>
<td>10m copper</td>
</tr>
<tr>
<td></td>
<td>10x10G based on 10G Base-KR</td>
</tr>
<tr>
<td>100GBASE-SR10</td>
<td>100m MMF</td>
</tr>
<tr>
<td></td>
<td>10x10G, 10 fibers per direction</td>
</tr>
<tr>
<td>100GBASE-LR4</td>
<td>10km SMF</td>
</tr>
<tr>
<td></td>
<td>4x25G, 1.3µm LAN WDM (800 GHz)</td>
</tr>
<tr>
<td></td>
<td>L0:1295.56nm, L1:1300.05nm, L2:1304.58nm, L3:1309.14nm</td>
</tr>
<tr>
<td>100GBASE-ER4</td>
<td>40km SMF</td>
</tr>
<tr>
<td></td>
<td>4x25G, 1.3µm LAN WDM (800 GHz)</td>
</tr>
<tr>
<td></td>
<td>L0:1295.56nm, L1:1300.05nm, L2:1304.58nm, L3:1309.14nm</td>
</tr>
</tbody>
</table>

Currently no serial interface is defined
Possible 100GE LAN optical module implementations and form factor

100GE LR4/ER4 optical module

MAC/PCS

10
CAUI

10*10.3125G

10:4
CAUI

10*10.3125G

10:4

WDM optics
(4*25G)

PMA

4×λ, 10km/40km SMF

Example: LX4, X40, retimed

100GE SR10 optical module

MAC/PCS

10
CAUI

10*10.3125G

10:10

parallel optics
(10*10G)

PMA

10*10G 100m MMF

Examples: SNAP12

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ITU-T OTN Agreements reached (ITU-T Q11 interim meeting on 9/22/08)

- Mapping 40 GbE into OPU3
  - Agreement reached to standardize transcoding of 1024B/1027B code method in G.709

- ODU4/OTU4 bit rates
  - For 100GbE, OTN transport (ODU4/OTU4 bit rate) of 111.809973 Gb/s (= 255/227x 2.488320 Gb/s X 40) agreed by ITU-T SG15, Q11
  - Decision on rate to be made end of 2008.
- OIF Physical Link Layer (PLL) has proposed CEI-28G-SR, a SR short reach high speed electrical interface between nominal baud rates of 19.90 Gsym/s to 28.00 Gsym/s using NRZ coding

- New projects
  - 100G Long Distance DWDM Transmission Framework - target 1500km using DP-QPSK
  - Forward Error Correction for 100G DP-QPSK Long Distance Communication IA - Defining a common basis for an FEC encoder, interleaving and overhead rate for 100G OTN.
  - 100G Long Distance DWDM Integrated Photonics Components -
    --Develop implementation agreements for transmit and receive photonic components
    --Create a foundation for MSAs for transmit and receive photonic components

Ref: John McDonough, OIF workshop 2008
100G transport requirement

- 100G has to be transported on the existing 10G network, and meet 10G link design rules (not touch the line structure, not touch the existing service):
  - 100G signal need to be compatible with exhibiting 10G and 40G signal.
    - 100G should not be impacted by coexisting 10G and 40G signal.
  - Dispersion tolerance: ±800ps/nm
  - PMD tolerance: 10ps (mean)
  - Transmission distance >1500km
  - 100G Need to support 50GHz channel spacing, 80+channels
  - Support 20+ ROADM node cascading.
    - Resistant to filter passband narrowing.

This pose great challenges for 100G Long-haul transport!
OSNR: ASE noise limitations

OSNR sensitivity is inverse proportional to data rate/bandwidth.

Span loss

Required OSNR @ BER 1e-9

100G: 28dB
40G: 24dB
10G: 18dB

100G NRZ OOK has very limited reach capability.
CD tolerance is inverse proportional to the square of the data rates (BW)
-40G(100G) CD tolerance is 16(100) times worse than 10G

PMD tolerance is inverse proportional to the data rate.
-40G(100G) PMD tolerance is 4 (10) times worse than 10G

Intra-channel nonlinear becomes dominant which distinguish from 10G, 10G dispersion map maybe a problem-due to interplay of dispersion with nonlinearity.

High Filtering penalty in 50GHz DWDM network, and even worse with ROADM cascading.

100G spectrum BW is about 2 times of bit rate. To pack the 100G signal inside the 50GHz Channel grid, a high spectral efficient (greater than 2 bit/s/Hz) signal is required!
Content

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  - Coherent detection
  - Modulation format
- Summary
Key technologies

- **FEC**: a key device enabling 100G transmission.
  Line coding, a pre-calculated parity is attached to the transmitted data sequence.

- Efficient to correct Gaussian ASE noise induced random bit errors—>a reduction of OSNR requirement.
- G709 OTN define RS(255,239) as standard FEC.
- In 40G, Vendor specific Enhanced FEC/Ultra FEC (defined in G.975) are used normally to provide about 8dB coding gain.
- More powerful FEC (algorithm) needed for 100G transport.

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*Image: Graph showing BER vs. power (dB) for different coding schemes and years.*

<table>
<thead>
<tr>
<th>Year</th>
<th>Coding Scheme</th>
<th>Net Coding Gain (@ $10^{-13}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1993</td>
<td>RS(255,239)</td>
<td>5.8dB</td>
</tr>
<tr>
<td>2000</td>
<td>Concatenated RS, BCH</td>
<td>7~9dB</td>
</tr>
<tr>
<td>2003</td>
<td>Block Turbo Code, LDPC</td>
<td>~10dB</td>
</tr>
</tbody>
</table>

Key Technologies

- **Adaptive dispersion compensation** - key device: OTDC
  - tackle temperature induced dispersion variance which could exceed the dispersion tolerance.
  - enhance dispersion tolerance with accurate residual CD compensation.

- **OTDC technologies**
  - FBG based OTDC: thermal turning, mature, and largely deployed in 40G. Demonstrated in 100G RZ DQPSK system [OFC08, NMC2]. Offer both symmetric and asymmetric turning.
  - Etalon based OTDC: thermal turning, hard to achieve large BW, not yet deployed. Only offer symmetrical turning.
  - PLC based OTDC: not mature yet!

(RZ)-DQPSK

OTDC for 100G is ready!
Key technologies

- Adaptive optical PMD compensation.

  PMD becomes a limiting effect for 100G even if the newest fiber is used. Adaptive PMD compensation is essential as PMD in installed fiber is random due to perturbation by temperature, shaking, tremor, vibration. Normally PMD changes slow (from ms to minutes), sometimes it changes fast (faster than 3 krad/s observed in field). Optical PMD compensation is most difficult.

  Currently there is no cost-effective and convincing solution in the market.

- PMD compensation solutions:
  - Narrowband OPMDC
  - Distributed fast polarization scrambling
Optical PMD compensation

- **Narrow band OPMDC**

  both first order and second order can only take effect in a narrower spectral width, only per-channel compensation can provide nine 9 network availability. very expensive!

  The effectiveness depends on:
  - Feedback signal: should reflect the real PMD! (eg. Nonlinear and ASE also impact DOP)
  - Optimizing algorithm: not to trap in suboptimal position.

  in reality, it is easy to trap in suboptimal.
**Optical PMD compensation**

- **Distributed fast polarization scrambling-broadband solution**

Fast polarization scramblers deliberately accelerate the PMD changes to reduce PMD induced burst error period and redistribute them to all over the FEC frames, to make the errors in each FEC frame less than BECL such that FEC can correct it like random errors.

This method works for all channels in the fiber, and it is a cheap solution. The effectiveness should be further tested in the system [C. Xie, IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 20, NO. 6, MARCH 15, 2008]. This solution can be used in 40G system. Since for 100G, coherent and DSP may be used, fast polarization scrambling may not be applied.
**Key technologies**

- **Coherent detection**
  - Improves the OSNR
  - Digital coherent detection moves the carrier and phase recovery to the digital domain without using the optical PLL.
  - Need narrow linewidth laser
  - Coherent detection normally needs polarization diversity detection, and intellectual property oriented implementation of DSP for phase and carrier recovery and equalization. It becomes complex and costly. It needs new development in optics and electronics. Photonics Integration maybe a way to shrink the footprint and more importantly the cost.

- **Balanced detection has better OSNR than single end detection**
Key technologies

- **Electrical equalization**
  To use the power of electronic to mitigate the distortion induced by linear or nonlinear effect either based on eye opening (Q) or BER minimizing.

- **Methods**
  - Adaptive analog filter-based methods
    - FFE: feed forward, Finite impulse response (FIR)
    - DFE: recursive, using decided bits
  - DSP equalization
    - MLSE (Viterbi equalizer): Statistical method based on conditional probability.
    - More complex DSP equalization: OFDM, DSP aided coherent detection.
Electrical equalization

- Adaptive analog filter

**FFE**

- Linear
- Delays are usually equal, and tap numbers usually are odd
- Tap weights magnitudes set gain, give ‘impulse response’
- deal with both leading and trailing ISI

**DFE**

- Nonlinear
- Recursive filter using decided bits, often need only 1 tap,
- only deals with trailing ISI
- Baud-rate sampled data feedback

**FFE+DFE**

- 5 taps FFE+1 tap DFE is often used to improve performance

Reduce noise
Remove leading ISI
Improve efficiency

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Electrical equalization

- DSP equalization
- MLSE

Using surrounding bits to decide what is most likely of current bit. It uses conditional probability. Sort through the received states and select the sequence with the highest probability of having generated the received noisy/distorted data.

$\text{state count} = 2^{(ISI-1)}$

MLSE is powerful than FFE and DFE, efficient to equalize CD, PMD, and narrow filtering induced and intra-channel deterministic non-linearity induced distortion. Efficient in dispersion managed system.

Commercial 10G MLSE is based on 2sample/bit. It can be extend to 40G PM QPSK or 100G with 10G baud rate (eg. PM 16QAM).
### Electrical equalization

- **Coherent DSP equalization**

  DSP is used to overcome the linear distortion induced by CD, PMD and other effects. An example is multiple input multiple output (MIMO) FIR filters. Coherent improves the DSP efficiency since it recovers the full optical field in the electrical domain.

- The resolution >5bit DAC/ADC is preferred. Currently, lack of high-speed 25G ADC becomes the major hurdle of 100G. Further development of the high-speed DAC with high-bit depth and DSP engine is required.
Key technologies

- **Modulation formats**

  - The trend for high-spectral efficient and long haul DWDM transmission has spawned many modulation schemes for 100G.
    - DQPSK (DD): 56Gbaud
    - Coherent PM-QPSK: 28Gbaud
    - Coherent OFDM:
    - Coherent 16QAM: 28G baud/PM 16QAM: 14Gbaud
Modulation formats

- **DQPSK**

  ![Diagram of DQPSK](image)

  **BER after 700 km**

  ![Graph showing BER vs. OSNR](image)

  **2 symbol/bit**

  - \( \Delta \phi = 0 \)
  - \( \Delta \phi = \pi/2 \)
  - \( \Delta \phi = \pi \)

  **Repeater placement**

  - \( \lambda_1 \)
  - \( \lambda_2 \)
  - CW channels dropped

  107 Gb/s TX

  500 km

  200 km

  107 Gb/s RX

  **OFC08,OMQ4**
- **111G PM RZ QPSK**

  - QPSK Coder, Drivers, LPFs
  - CW LD
  - 27.75GHz driver

- **117G PM QPSK +10*10.7G OOK**

  - Results for 1140 km, with different CPE averaging intervals

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ECOC08,Mo4E2

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- **OFDM-digital multicarrier technique**

  OFDM uses frequency division multiplexing to transmit data. Data is transmitted over many (say, $N$) parallel frequencies (subcarriers), each with a baud rate of $\frac{1}{(N \log_2 m)}$ of the total data rate, where $m$ is the order of the $m$-QAM modulation of each subcarrier.

  $$f_k - f_j = \frac{m}{T_c}$$

- **High spectral efficiency**
- **High CD, PMD tolerance**
- **Dispersion can be handled by Guard bands or Cyclic Prefixes.**
- **Susceptible to nonlinear effect, FWM between sub carriers. Good performance in CD uncompensated fiber link. Bad in period CD compensated links.**
- (PM) 16QAM
- $2^N$ QAM signal processes $N$ bits in a single channel, so it has $N$ times spectral efficiency compared with OOK. 16QAM SE improves 4 times.
- Baud rate: 14Gbaud (Nortel: 12.5Gbaud, can utilize its 40G DSP ASICs)

Figure 1: Experimental setup and block diagram of the intradyne detection scheme.
### Summary on the performance of different modulation formats

<table>
<thead>
<tr>
<th></th>
<th>OOK</th>
<th>PSBT</th>
<th>DPSK</th>
<th>DQPSK</th>
<th>QPSK</th>
<th>PM-DQPSK</th>
<th>PM-QPSK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral Efficiency</td>
<td>0.4 bits/s/Hz</td>
<td>1 bits/s/Hz</td>
<td>0.8 bits/s/Hz</td>
<td>1.6 bits/s/Hz</td>
<td>1.6 bits/s/Hz</td>
<td>3 bits/s/Hz</td>
<td>3 bits/s/Hz</td>
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<tr>
<td>OSNR sensitivity</td>
<td>20dB/0.1nm</td>
<td>20dB/0.1nm</td>
<td>17dB/0.1nm</td>
<td>18dB/0.1nm</td>
<td>15.5dB/0.1nm</td>
<td>18dB/0.1nm</td>
<td>15.5dB/0.1nm</td>
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<tr>
<td>PMD tolerance</td>
<td>1ps</td>
<td>1ps</td>
<td>1ps</td>
<td>2ps</td>
<td>2ps</td>
<td>2.5ps</td>
<td>2.5ps</td>
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<tr>
<td>CD tolerance</td>
<td>15ps/nm</td>
<td>50ps/nm</td>
<td>12ps/nm</td>
<td>35ps/nm</td>
<td>35ps/nm</td>
<td>140ps/nm</td>
<td>140ps/nm</td>
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<tr>
<td>Analogue electronics complexity</td>
<td>HIGH</td>
<td>HIGH</td>
<td>HIGH</td>
<td>MEDIUM</td>
<td>MEDIUM</td>
<td>LOW</td>
<td>LOW</td>
</tr>
<tr>
<td>Digital electronics complexity</td>
<td>LOW</td>
<td>LOW</td>
<td>LOW</td>
<td>LOW</td>
<td>HIGH</td>
<td>MEDIUM</td>
<td>HIGH</td>
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<tr>
<td>Optical complexity</td>
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<td>MEDIUM</td>
<td>MEDIUM</td>
<td>MEDIUM</td>
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<td>Reach estimate</td>
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<td>400km</td>
<td>800km</td>
<td>700km</td>
<td>1,000km</td>
<td>700km</td>
<td>1,000km</td>
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<tr>
<td>Cost estimate</td>
<td>0%</td>
<td>+10%</td>
<td>+20%</td>
<td>+50%</td>
<td>+70%</td>
<td>+90%</td>
<td>+110%</td>
</tr>
</tbody>
</table>
# 100G demonstrations

<table>
<thead>
<tr>
<th>Ref</th>
<th>Affiliation</th>
<th>modulation</th>
<th>Capacity</th>
<th>Distance</th>
<th>Note:</th>
</tr>
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<tbody>
<tr>
<td>OFC8,PDP1</td>
<td>AT&amp;T</td>
<td>PM-RZ-8PSK</td>
<td>8*114G</td>
<td>640km SSMF</td>
<td>no inline DCF</td>
</tr>
<tr>
<td>OFC8,PDP3</td>
<td>AL</td>
<td>PM-QPSK</td>
<td>164*100G</td>
<td>2550km +D/-D/ +D UW</td>
<td>Raman</td>
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<tr>
<td>OFC8,PDP7</td>
<td>ARC</td>
<td>PDM CO-OFTDM</td>
<td>107G</td>
<td>1000km</td>
<td>No inline DCF</td>
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<tr>
<td>OFC8,NTUB3</td>
<td>Simense</td>
<td>CP-RZ-DQPSK</td>
<td>111G</td>
<td>2375Km SSMF+DCF</td>
<td>Raman</td>
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<td>OFC8,OMQ3</td>
<td>AT&amp;T</td>
<td>RZ-DQPSK</td>
<td>20 107 G</td>
<td>1005km</td>
<td>200GHz</td>
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<tr>
<td>OFC8,NMC2</td>
<td>Verizon</td>
<td>DQPSK</td>
<td>107G+10G</td>
<td>504km NZDSF (field)</td>
<td>Raman</td>
</tr>
<tr>
<td>OFC8,OMQ4</td>
<td>AL</td>
<td>NRZ(RZ) DQPSK</td>
<td>107G +10G</td>
<td>700km LEAF, TW(field)</td>
<td>Raman</td>
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<tr>
<td>ECOC8,TH3E1</td>
<td>NTT</td>
<td>COOFDM</td>
<td>134 x 111G</td>
<td>3600 SMF</td>
<td>No DCF, Raman</td>
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<td>ECOC8,TH3E2</td>
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<td>PM-RZ-8PSK</td>
<td>161*114G</td>
<td>662km ULL</td>
<td>NO DCF</td>
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<td>ECOC8,TH3E5</td>
<td>AL</td>
<td>PM 16QAM</td>
<td>10*112G</td>
<td>315km SMF</td>
<td>No DCF, 25GHz</td>
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<tr>
<td>ECOC8,TH2e2</td>
<td>Verizon</td>
<td>PM RZ QPSK</td>
<td>111G+2x43G+8x10.7G</td>
<td>1040km deployed fiber</td>
<td>NA</td>
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<td>ECOC8,Mo4E2</td>
<td>TUE</td>
<td>PM RZ QPSK</td>
<td>111G+10*10.7G</td>
<td>1140km SMF</td>
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<td>ECOC8,TH2A2</td>
<td>NEC</td>
<td>PM RZ QPSK</td>
<td>20*112G</td>
<td>1540km/ 1120km SSMF</td>
<td>No DCF</td>
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<td>ECOC07, PD1.7</td>
<td>NTT</td>
<td>OFDM (DD)</td>
<td>30*100G</td>
<td>1300 SMF</td>
<td>Raman</td>
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<tr>
<td>ECOC07, PD1.9</td>
<td>AL</td>
<td>PM DQPSK(DD)</td>
<td>8<em>107G+8</em>42.7G RZ-DQPSK</td>
<td>1280km SSMF</td>
<td></td>
</tr>
</tbody>
</table>

Note: indicate the compliance with the typical existing network structure (50GHz channel spacing, use EDFA, SSMF+DCF period compensation)

All the existing demos indicates existing 100G transport technical feasible, but has difficulties to get the same reach as 10G system in the existing 10G networks.
Summary

- There are many challenges for 100G transport. 100G LH commercial transport market will not established before 2010.
  - Demonstrated technologies still can not match reach requirement with 10G links. Need more innovation to tackle the transport issues.
  - OTU4 standard is in discussion, but not sure when it will be finalized.
  - Commercial FEC/OTN framer for 100G can not be seen be available with 3 years. 100G may need strong FEC.
  - For 100G, currently coherent PM-QPSK appears a promising solution, thanks to OIF), However it requires 56GS/s ADC/DAC, commercial devices will not be available soon.
- 100G brings opportunities for
  - Research institutions: a new area for research funding and innovations.
  - Components and module providers: A new high revenue market, but with high investment!
  - System vendors: A new chance to turn the table and take the lead in the market!
We are ready to know your needs for 100G

We are happy to offer you cost-efficient solutions
Thank you!

Q&A

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Luster lightTech Corp.

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