400GbE using Nyquist PAM4 for 2km and 10km PMD

P802.3bs 400 Gb/s Ethernet Task Force, 08-13 Sep 2014

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General

- We propose 400GbE using a single Lambda per 100G and Nyquist PAM4 for 2km and 10km
  - Each lambda transmits a single 100Gbit/s serial channel

- Why Nyquist PAM4?
  - Reduces transmitted signal spectral width which allows lower sampling rate at the receiver
  - Reduces BW requirement which allows technology reuse of 100GbE LR4 components
  - Receiver-side signal processing at lower sampling rate
  - Sensitivity can be improved using DSP EQ technologies

- Our study confirms 400GbE using Nyquist-PAM4 is possible with existing components
Proposal

- We propose 400GBASE-FR4 and –LR4 with single mode fiber (SMF)
  - In both cases we use 4-lane wavelength Division multiplexing (WDM)
  - Each lane transmits and receives 100Gbit/s data using Nyquist PAM4

<table>
<thead>
<tr>
<th></th>
<th>Optical Fiber</th>
<th>Wavelengths</th>
</tr>
</thead>
<tbody>
<tr>
<td>400GBASE-FR4</td>
<td>2m to 2km SMF</td>
<td>CWDM</td>
</tr>
<tr>
<td>400GBASE-LR4</td>
<td>2m to 10km SMF</td>
<td>LANWDM</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Center Wavelengths</th>
</tr>
</thead>
<tbody>
<tr>
<td>-FR4</td>
<td>-LR4</td>
</tr>
<tr>
<td>L0</td>
<td>1271 nm</td>
</tr>
<tr>
<td>L1</td>
<td>1291 nm</td>
</tr>
<tr>
<td>L2</td>
<td>1311 nm</td>
</tr>
<tr>
<td>L3</td>
<td>1331 nm</td>
</tr>
</tbody>
</table>

Block Diagram
Nyquist PAM4 for Single Channel

- Proposal and features
  - Filter PAM4 at the TX side
    ✓ Transmitter output spectrum width is reduced by half with Nyquist pulse shaping
      • Optical devices will require about 28GHz bandwidth.
    ✓ ISI is not degraded due to reduced spectrum (Zero ISI criteria compliance)
  - Regenerate signal at RX side at 56G Sa/s as required by Nyquist-Shannon theorem
  - Strong FEC is required (detail is under investigation)

Nyquist Modulation

- Correct value is 62G

Nyquist PAM4 Reproduce Decision/Timing regeneration

- 56 Gbaud

Transmitter waveform

Reproduced waveform

- 17.9 ps

Frequency spectrum

Optics

DAC

FEC (TBD)

Interface

FEC (TBD)

Interface

Optics

ADC

DSP

Optics

FEC (TBD)

Interface

Optics

DAC

FEC (TBD)

Interface

Optics

ADC

DSP

Optics

FEC (TBD)

Interface
Nyquist Filter Proposal

- We propose Roll-off (or Raised-cosine) Filter with Roll-off factor $\alpha = 0.1$
  - The base band spectrum is 31GHz (1.1*28G)
  - It complies with Nyquist’s first criterion for zero inter-symbol interference (ISI) Each pulse is zero at the sampling time of other pulses

$$|H(f)| = \begin{cases} 
1 & \text{for } 0 \leq f \leq (1 - \alpha)f_n \\
\frac{1}{2} \left\{ 1 - \sin \left( \frac{\pi}{2\alpha} \left[ \frac{f}{f_n} - (1 - \alpha) \right] \right) \right\} & \text{for } (1 - \alpha)f_n \leq f \leq (1 + \alpha)f_n \\
0 & \text{for } (1 + \alpha)f_n \leq f 
\end{cases}$$

where $f_n = 28$GHz

Impulse Response of $H(f)$

$$h(t) = \frac{\sin \frac{\pi t}{T}}{\frac{\pi t}{T}} \cdot \frac{\cos \frac{\pi \alpha t}{T}}{1 - \left( \frac{2t\alpha}{T} \right)^2}$$

where $T = 17.9$ps

![Diagram](https://via.placeholder.com/150)

**Relative Power**
- Modulation Optical Power (Excluding DC)
- $f/f_n = 0$
- $f/f_n = 0.1$

**Spectral Mask (TBD)**
- Spectral Mask
- Zero (0) at $t = nT$ except $n = 0$
Implementation of Nyquist PAM4

- **Implementation Example: Use Fixed Look-up table**

- **Estimated gate count: <0.6M Gate**
  - 41 taps is enough for Nyquist PAM4

- Spectrum dependence on number of taps for Nyquist pulse shaping

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**Tx Block Diagram**

- **Clock**
- **Length**
- **Gate count**

<table>
<thead>
<tr>
<th></th>
<th>Clock</th>
<th>Length</th>
<th>Gate count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nyquist Filter</td>
<td>112G</td>
<td>41 tap</td>
<td>&lt;0.3 MGate</td>
</tr>
<tr>
<td>Re-sampling</td>
<td>64G</td>
<td>19 tap</td>
<td>0.3 MGate</td>
</tr>
</tbody>
</table>

**Gray Coding**

- “11”: +3
- “10”: +1
- “01”: -1
- “00”: -3

**After Gray Coding**
Receiver Sampling Rate

- Receive Sampling Rate at \((1+\alpha)x56G\) Sa/s
  - Can apply currently available ADC & DSP technologies
  - Easier receiver-side signal processing with lower sampling rate
- Sensitivity can be improved with equalization technology such as
  - FFE
  - DFE
  - MLSE

112Gbit/s (56GBaud) Nyquist-PAM4

![Waveform and Spectrum Diagram](image-url)
Experimental results

- Experiment using 1310nm commercial available 25-G EML at 102.4 Gbit/s
- Demonstrated capability of 8.9dB Link budget with estimated O-Mux/DeMux insertion loss of total 3dB.

<table>
<thead>
<tr>
<th></th>
<th>Pav</th>
<th>OMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tx power (w/o MUX)</td>
<td>+3.4 dBm</td>
<td>+3.8 dBm</td>
</tr>
<tr>
<td>Rx sensitivity @BER=2E-3 (*) (w/o demux)</td>
<td>-8.5 dBm</td>
<td>-8.1 dBm</td>
</tr>
<tr>
<td>Tx power minus Rx sensitivity</td>
<td></td>
<td>11.9dB</td>
</tr>
</tbody>
</table>

(*) Super FEC is required (detail is under investigation)
Optical Budget Proposal

- Link budgets for 2km and 10km are proposed below.
- The use of APD or SOA increases margin for LR4.

400GBASE-LR4 (10km) (TDP max)

- Tx OMA w 1.5-dB O-MUX
- Channel Insertion Loss: 6.3 dB
- Rx Sensitivity (OMA) @2E-3-BER w 1.5-dB O-DEMUX
  - Maximum TDP: 2 dB (*)
  - -6.6 dBm

400GBASE-FR4 (2km) (TDP max)

- Tx OMA w 1.5-dB O-MUX
- Channel Insertion Loss: 2.9 dB
- Rx Sensitivity (OMA) @2E-3-BER w 1.5-dB O-DEMUX
  - Maximum TDP: 2 dB (*)
  - -3.9 dBm

(*) Maximum TDP value is under investigation.
Summary

- We propose 400GbE using single lambda 100G using Nyquist-PAM4 for 2km and 10km

- For each 100G/lambda channel
  - PAM4 with Nyquist filtering at the TX side to reduce the spectrum which lowers the component BW to 28GHz
  - Regenerate signal at RX side at 56G Sa/s
  - Can apply currently available ADC, DAC & DSP technologies

- Sensitivity can be further improved with equalization technologies such as DFE, FFE and MLSE.

- Additional DSP power consumption with Nyquist filtering is reasonably low.
THANK YOU.