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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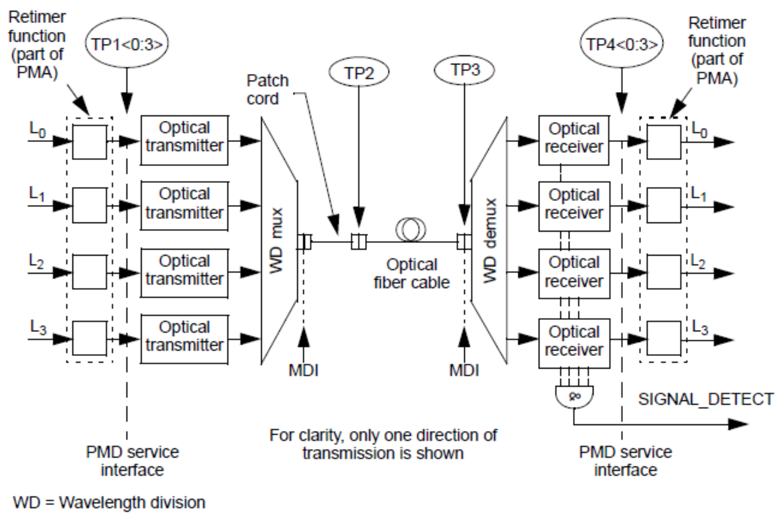
General

- 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

	Optical Fiber	Wavelengths
400GBASE-FR4	2m to 2km SMF	CWDM
400GBASE-LR4	2m to 10km SMF	LANWDM



Block Diagram

Center Wavelengths

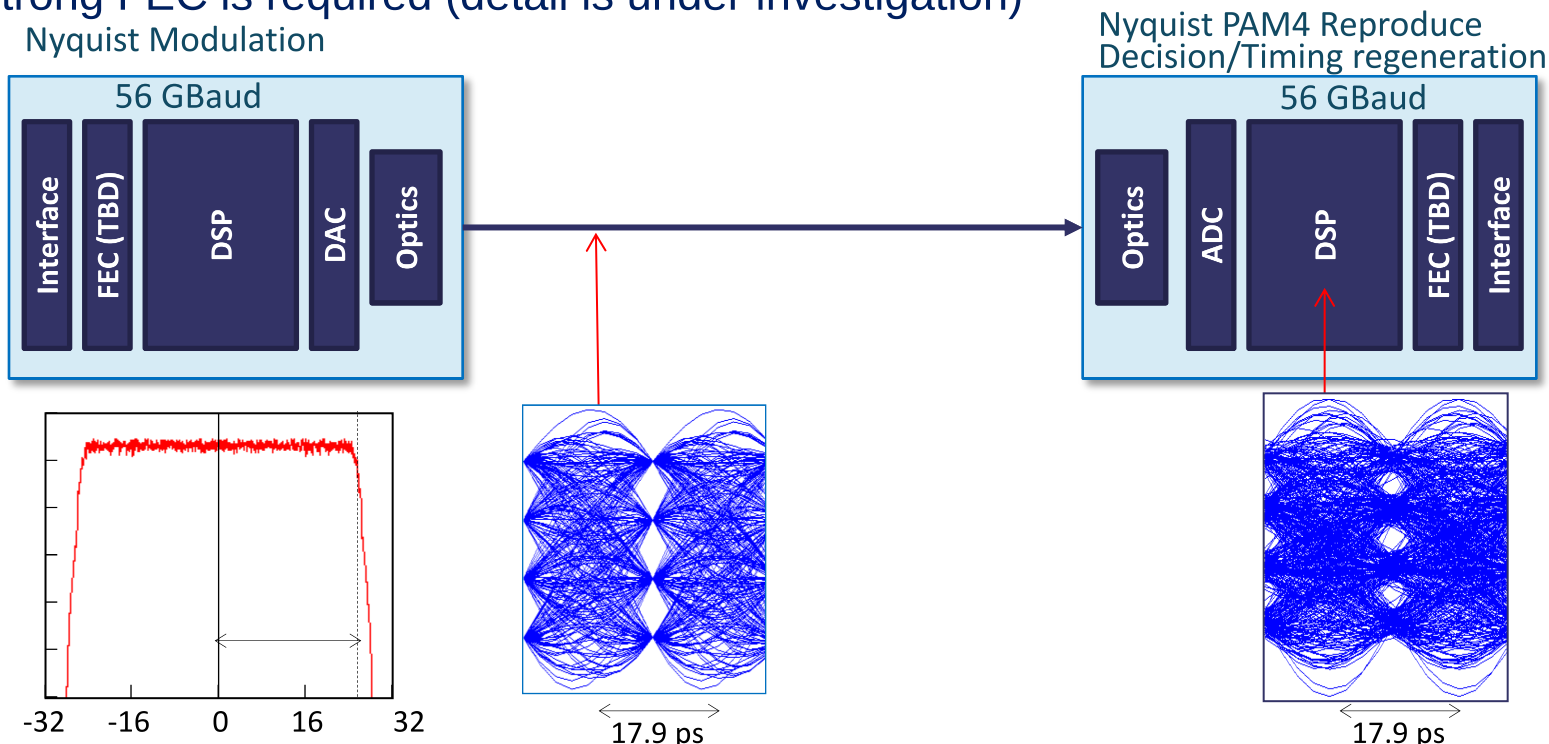
	-FR4	-LR4
	CWDM	LANWDM
L0	1271 nm	1295.56 nm
L1	1291 nm	1300.05 nm
L2	1311 nm	1304.58 nm
L3	1331 nm	1309.14 nm

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

Correct value is 62G

  - Strong FEC is required (detail is under investigation)



Frequency spectrum

Transmitter waveform

Reproduced waveform

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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

Roll-off Filter

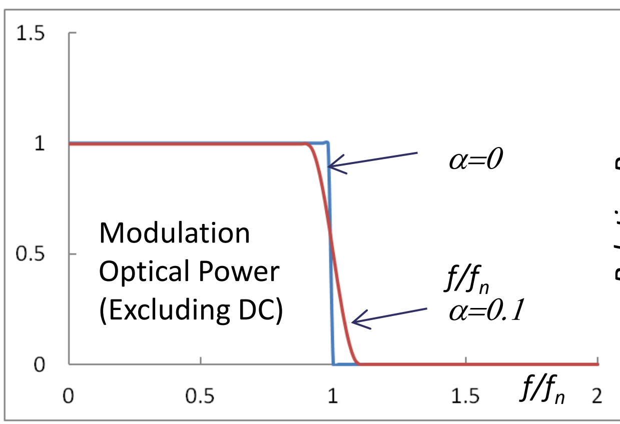
$$|H(f)| = \begin{cases} 1 & 0 \le f \le (1-\alpha) f_n \\ \frac{1}{2}\left\{1 - \sin\left(\frac{\pi}{2\alpha}\left[\frac{f}{f_n} - (1-\alpha)\right]\right)\right\} & (1-\alpha) f_n \le f \le (1+\alpha) f_n \\ 0 & (1+\alpha) f_n \le f \end{cases}$$

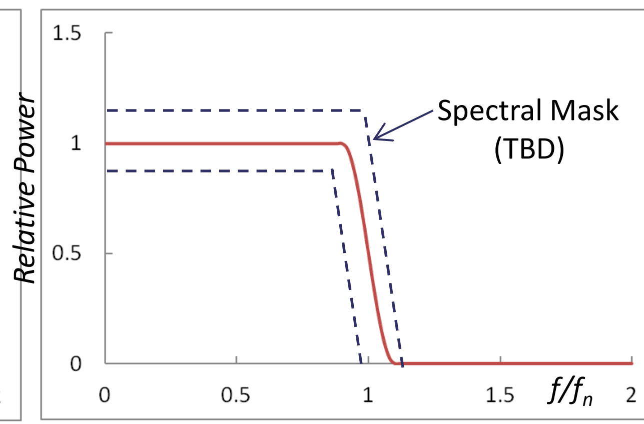
where f_n=28GHz

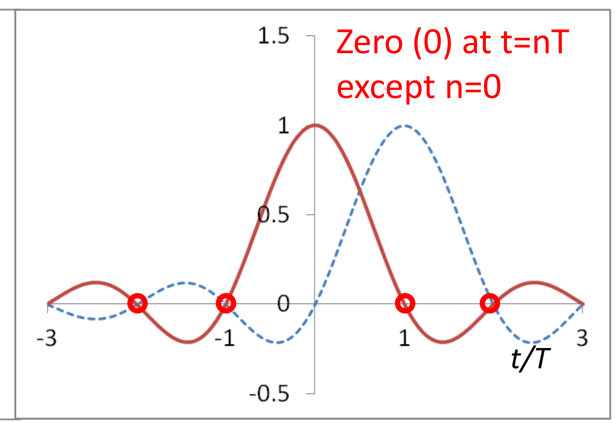
Impulse Response of *H(f)*

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

where T=17.9ps

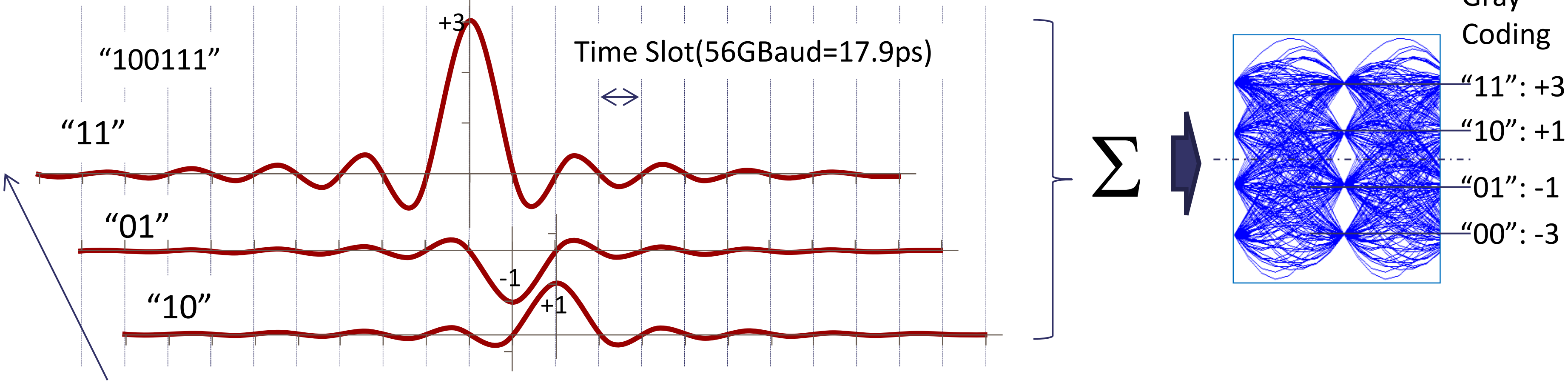




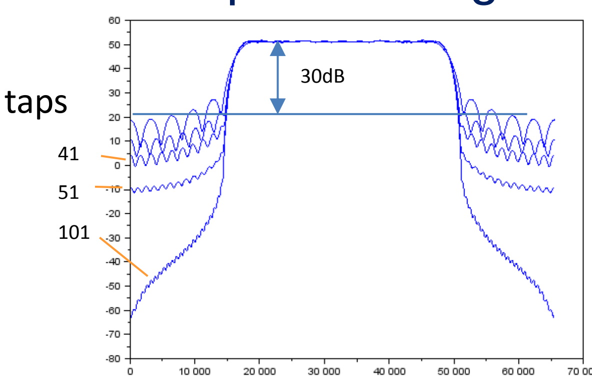


Implementation of Nyquist PAM4

- Implementation Example: Use Fixed Look-up table

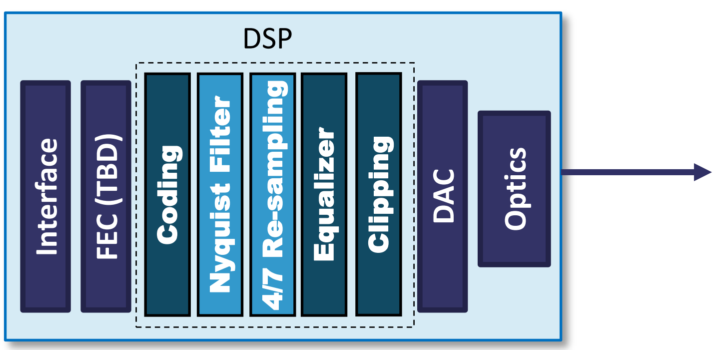


- Estimated gate count: <0.6M Gate
  - ✓ 41 taps is enough for Nyquist PAM4



Spectrum dependence on number of taps for Nyquist pulse shaping

Tx Block Diagram



	Clock	Length	Gate count
Nyquist Filter	112G	41 tap	<0.3 MGate
Re-sampling	64G	19 tap	0.3 MGate

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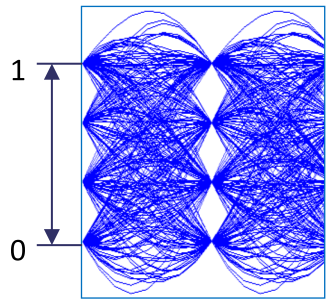
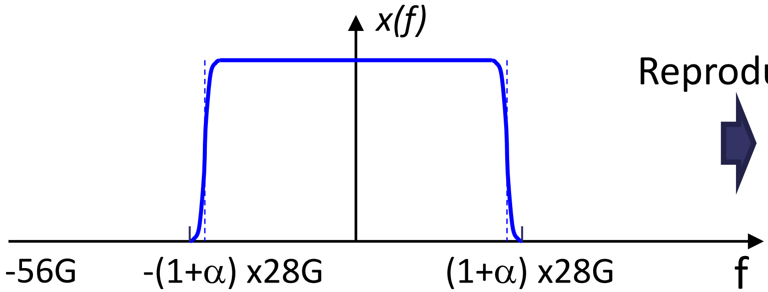
Receiver Sampling Rate

- Receive Sampling Rate at (1+α)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

<u>112Gbit/s (56GBaud) Nyquist-PAM4</u>



Waveform



Spectrum

Reproduce

Sampling Rate > (1+α)x56G Sa/s

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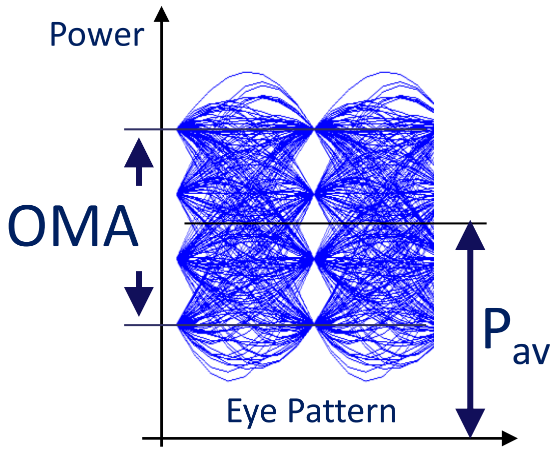
Experimental results

- 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.



Experimental values (Hirai_3bs_01_0914)

	Pav	OMA
Tx power (w/o MUX)	+3.4 dBm	+3.8 dBm
Rx sensitivity @BER=2E-3 (*) (w/o demux)	-8.5 dBm	-8.1 dBm
Tx power minus Rx sensitivity	11.9dB	

(*) Super FEC is required (detail is under investigation)

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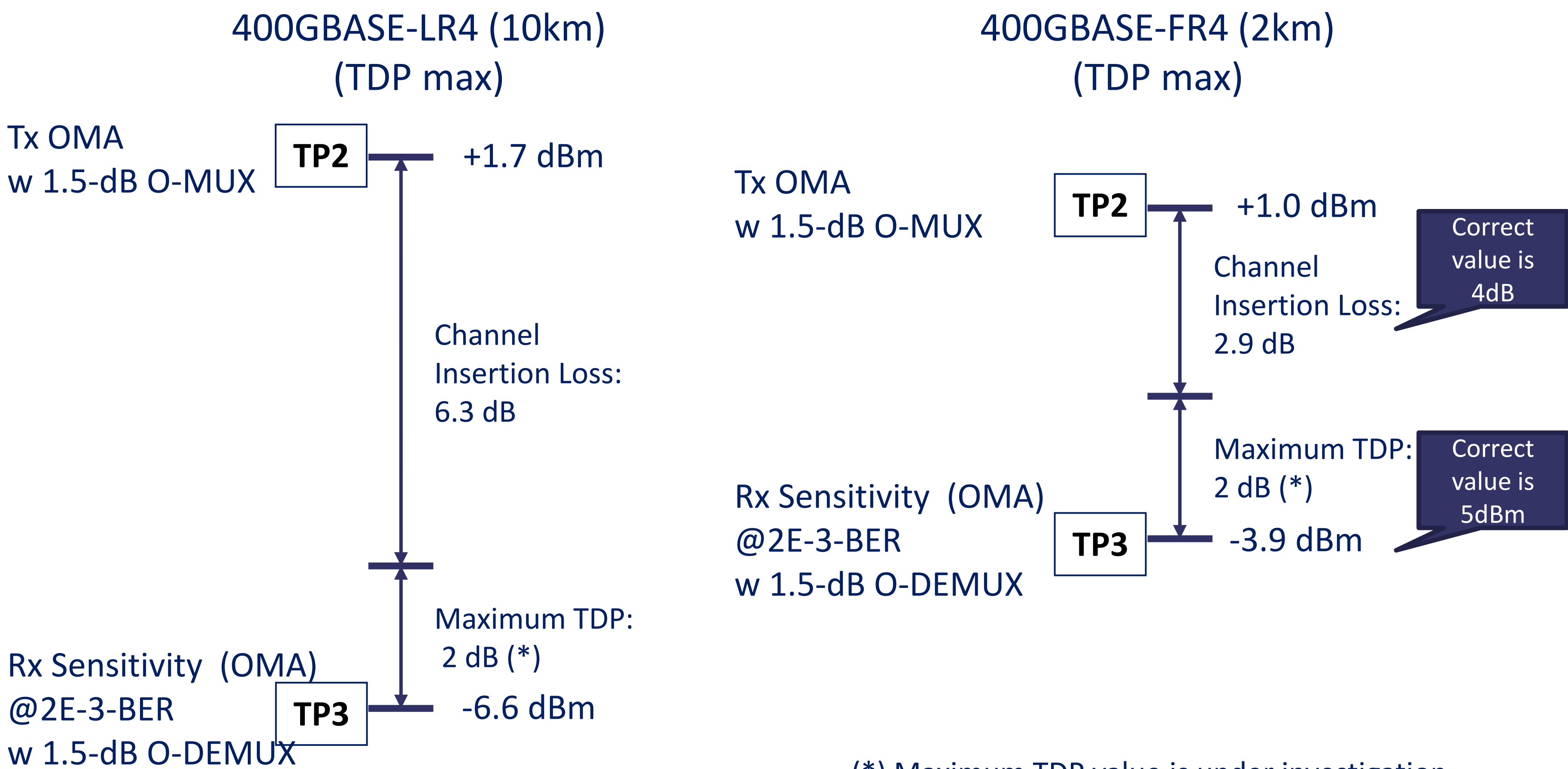
Optical Budget Proposal

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



(*) 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.

Correct value is 62G

THANK YOU.