Towards baseline proposals for 200 Gb/s per lane optical PMDs supporting 500 m and 2 km reaches

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IEEE P802.3df 200 Gb/s, 400 Gb/s, 800 Gb/s, and 1.6 Tb/s Ethernet Task Force

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Adopted physical layer specification objectives with adopted nomenclature

- 200GBASE-DR1
  - Define a physical layer specification that supports 200 Gb/s operation over 1 pair of SMF with lengths up to at least 500 m
- 200GBASE-FR1
  - Define a physical layer specification that supports 200 Gb/s operation over 1 pair of SMF with lengths up to at least 2000 m
- 400GBASE-DR2
  - Define a physical layer specification that supports 400 Gb/s operation over 2 pairs of SMF with lengths up to at least 500 m
- 800GBASE-DR4
  - Define a physical layer specification that supports 800 Gb/s operation over 4 pairs of SMF with lengths up to at least 500 m
- 800GBASE-DR4-2
  - Define a physical layer specification that supports 800 Gb/s operation over 4 pairs of SMF with lengths up to at least 2000 m
- 800GBASE-FR4
  - Define a physical layer specification that supports 800 Gb/s operation over 4 wavelengths over a single SMF with lengths up to at least 2000 m
- 1.6TBASE-DR8
  - Define a physical layer specification that supports 1.6 Tb/s operation over 8 pairs of SMF with lengths up to at least 500 m
- 1.6TBASE-DR8-2
  - Define a physical layer specification that supports 1.6 Tb/s operation over 8 pairs of SMF with lengths up to at least 2000 m

TDECQ study

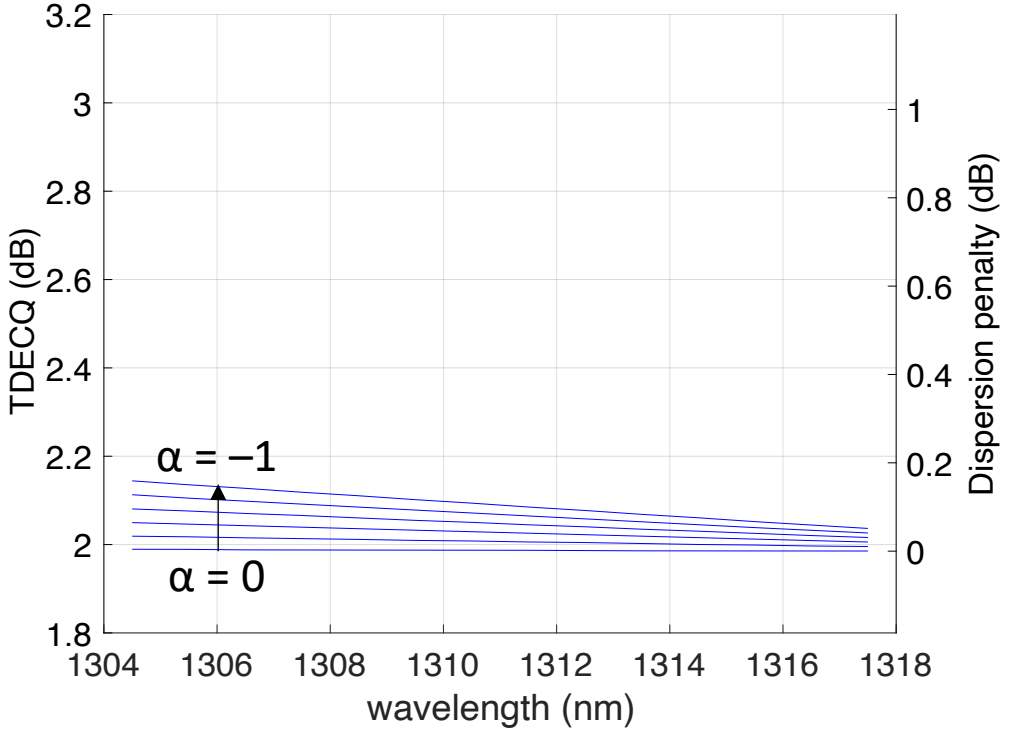
Introduction to TDECQ study

- The following slides illustrate studies of TDECQ vs wavelength for:
  - Single-wavelength PMDs (i.e. all objectives except 800GBASE-FR4)
    - Showing results for 2 km and for the wavelength range of 1304.5 nm to 1317.5 nm
  - CWDM PMD (i.e. 800GBASE-FR4 objective)
    - Showing results for 2 km and for the wavelength range of 1264.5 nm to 1337.5 nm
- SMF zero-dispersion wavelength (ZDW) extremes of 1300 nm and 1324 nm are considered. Worst-case SMF dispersion slope of 0.093 ps/nm^2 km is assumed
- Chirp factor (α) range from –1 to +1 is considered, in steps of 0.2
- As a baseline for these studies, we assume that a Tx can be achieved with TECQ (i.e. Tx measured without chromatic dispersion) of ≈2 dB at 106.25 GBd, measured with a target SER of 4.8 x 10^{-4}
  - For example, Intel demonstrate TDECQ of 1.7 dB with Si MRM (OFC 2022)
- Signaling rates of 106.25 GBd and 112.5 GBd are considered, where 106.25 GBd is representative of RS(544, 514) FEC and 112.5 GBd is representative of RS(576, 514) FEC, i.e. a stronger alternative
- A comparison with the 53.125 GBd case is first provided in order to highlight the implication of doubling the signaling rate in this Task Force, relative to earlier standards such as 802.3cu

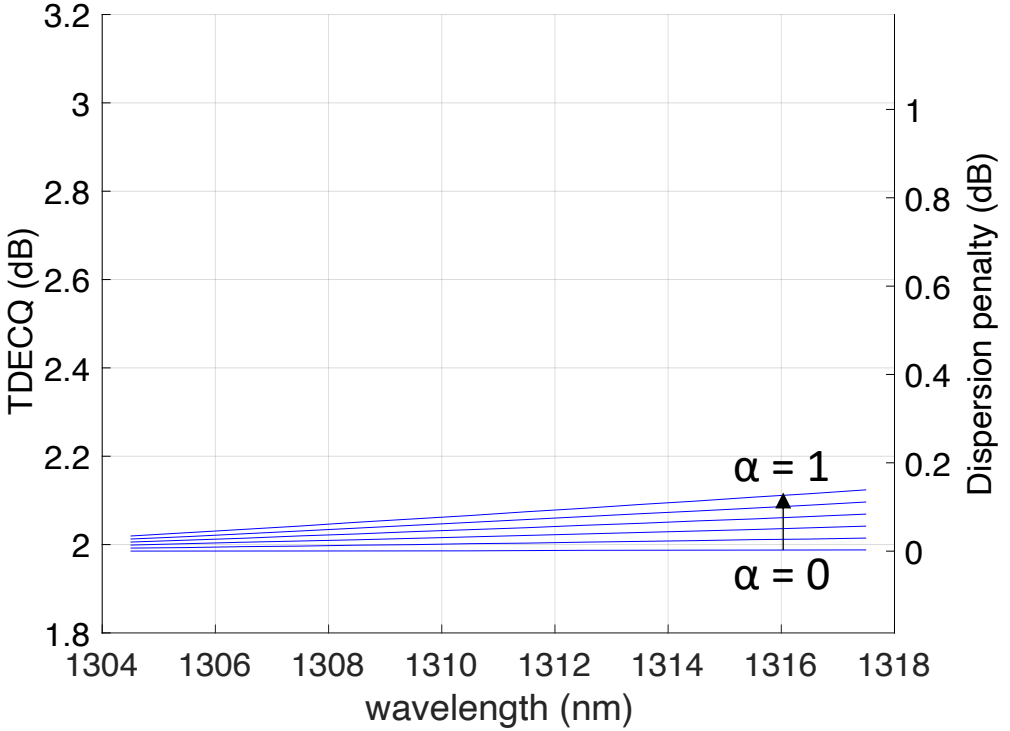
TDECQ study: single wavelength @ 53.125 GBd and 106.25 GBd

TDECQ study: single wavelength @ 53.125 GBd

ZDW: 1324 nm
Worst case is negative chirp



ZDW: 1300 nm
Worst case is positive chirp

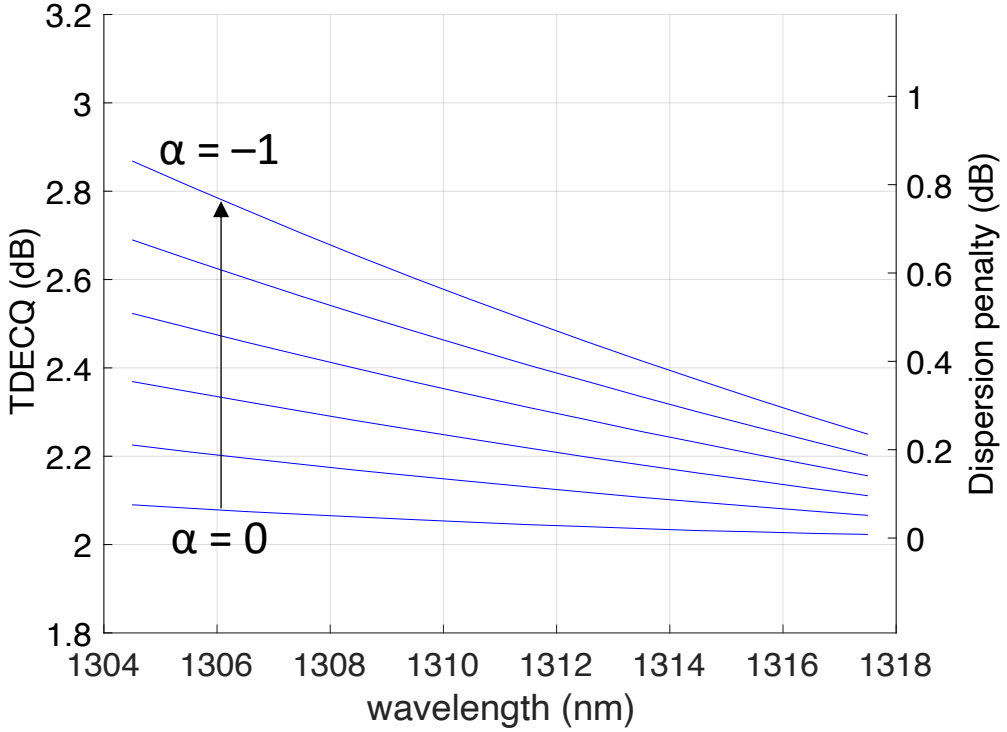


53.125 GBd with TDECQ SER target of 4.8×10^{-4}
2 km SMF
5-tap FFE reference equalizer

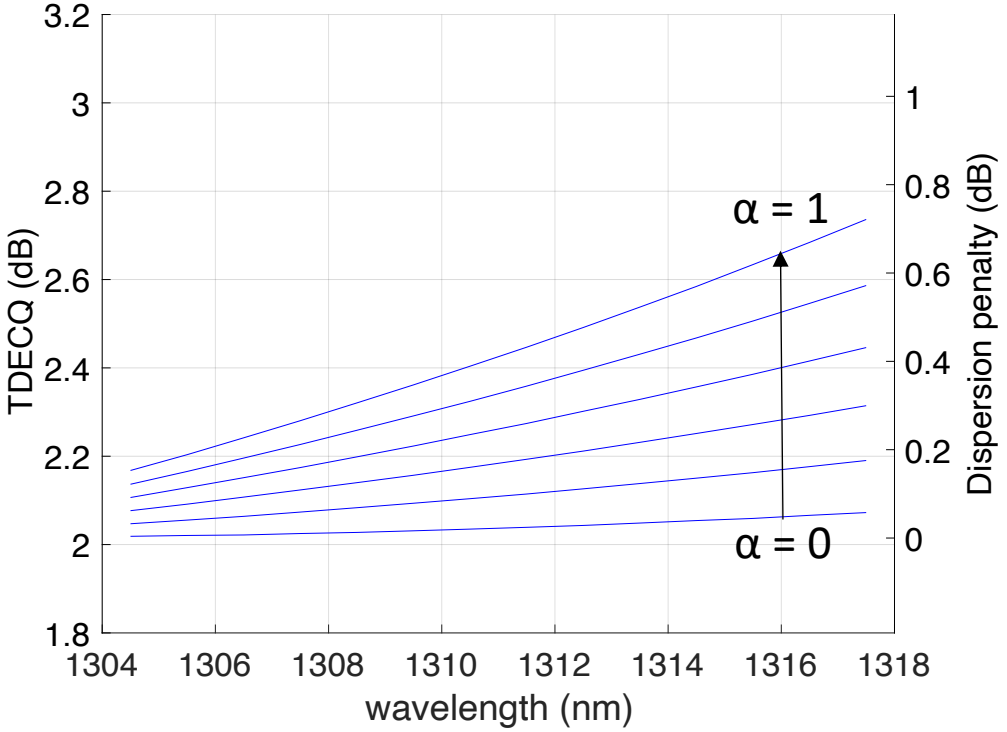
Results provided as a baseline, being representative of an 802.3cu 100 Gb/s per lane PMD: 100GBASE-FR1

TDECQ study: single wavelength @ 106.25 GBd

ZDW: 1324 nm
Worst case is negative chirp



ZDW: 1300 nm
Worst case is positive chirp



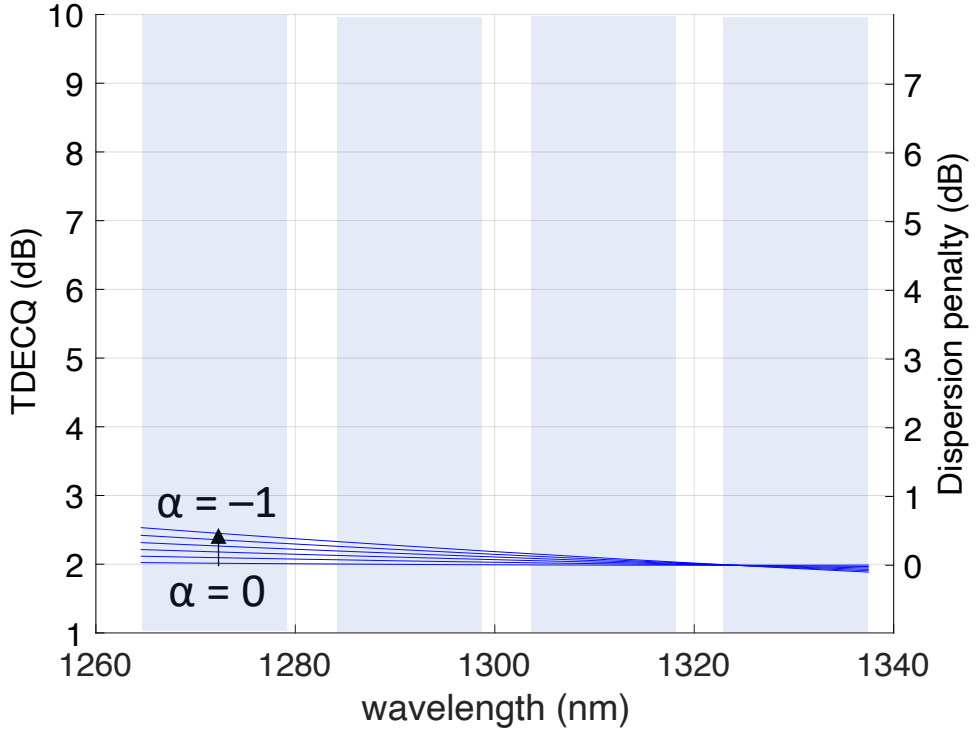
106.25 GBd with TDECQ SER target of 4.8×10^{-4}
2 km SMF
5-tap FFE reference equalizer

Worst-case dispersion penalty significantly larger than for 53.125 GBd case, but tolerable

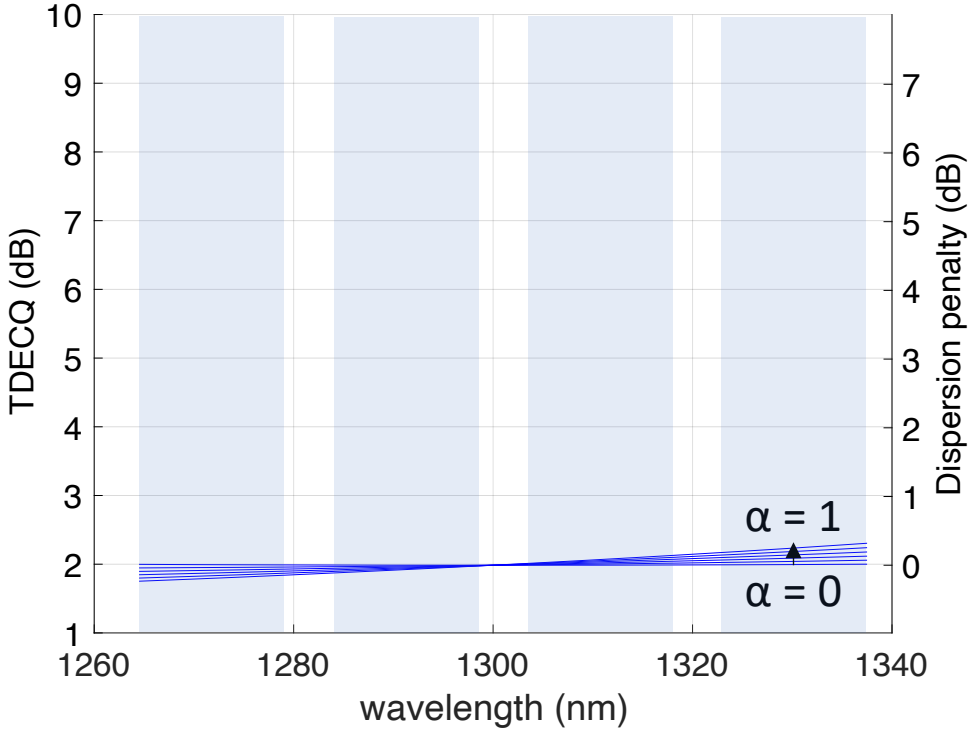
TDECQ study: CWDM @ 53.125 GBd and 106.25 GBd

TDECQ study: CWDM @ 53.125 GBd

ZDW: 1324 nm
Worst case is negative chirp



ZDW: 1300 nm
Worst case is positive chirp

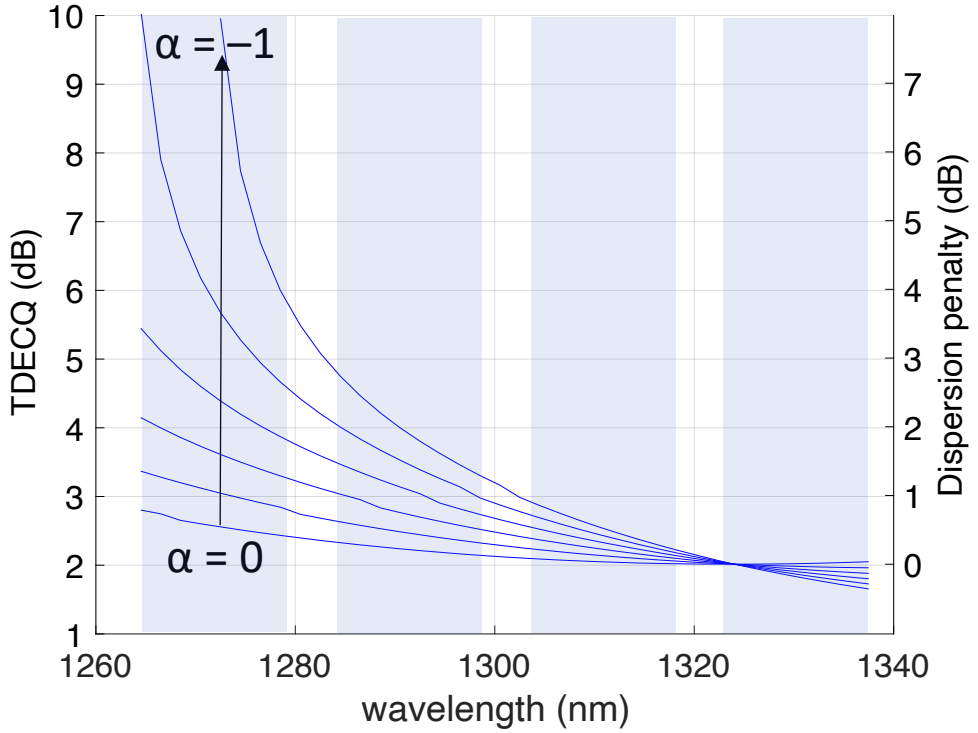


53.125 GBd with TDECQ SER target of 4.8×10^{-4}
2 km SMF
5-tap FFE reference equalizer

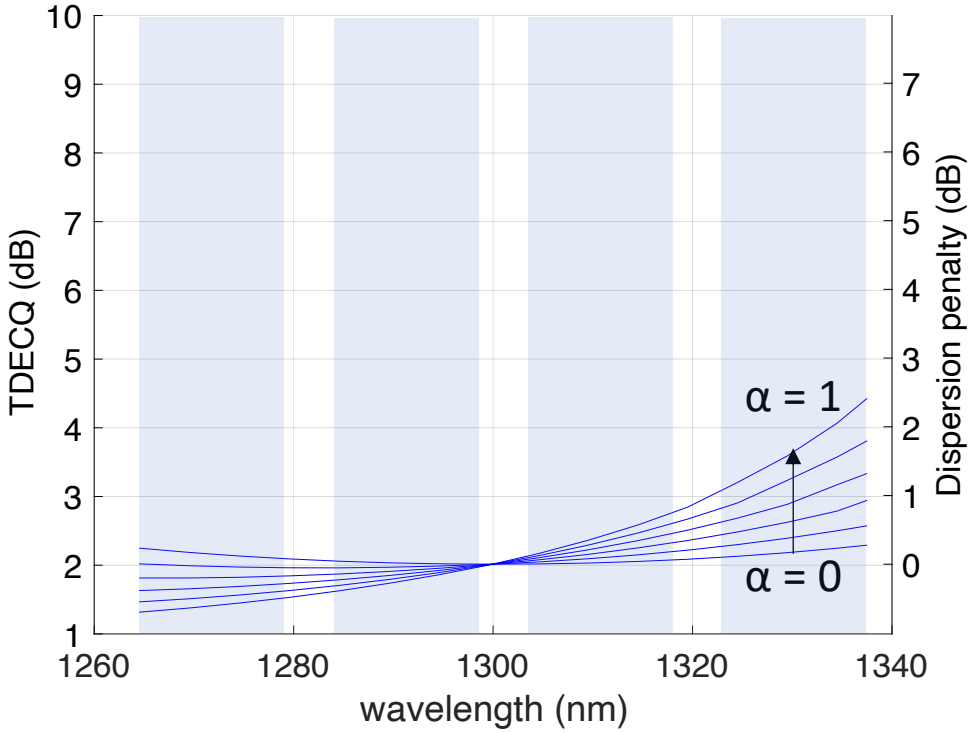
Results provided as a baseline, being representative of an 802.3cu 100 Gb/s per lane PMD: 400GBASE-FR4

TDECQ study: CWDM @ 106.25 GBd

ZDW: 1324 nm
Worst case is negative chirp



ZDW: 1300 nm
Worst case is positive chirp



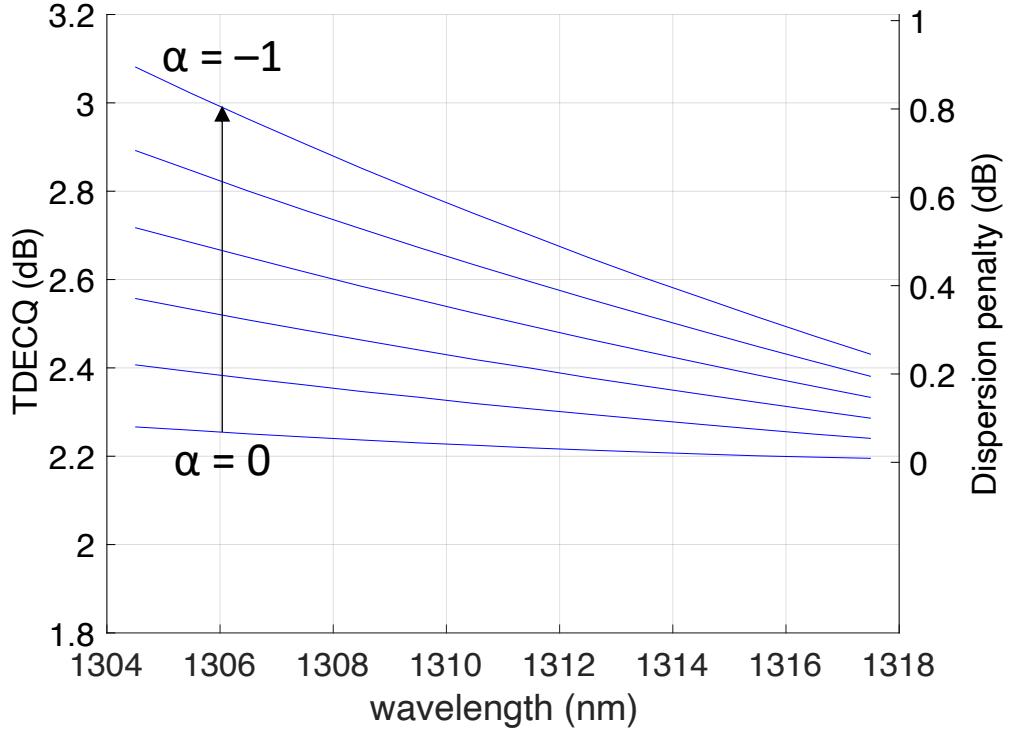
106.25 GBd with TDECQ SER target of 4.8×10^{-4}
2 km SMF
5-tap FFE reference equalizer

Acceptable TDECQ for outer CWDM lanes requires chirp factor to be tightly controlled

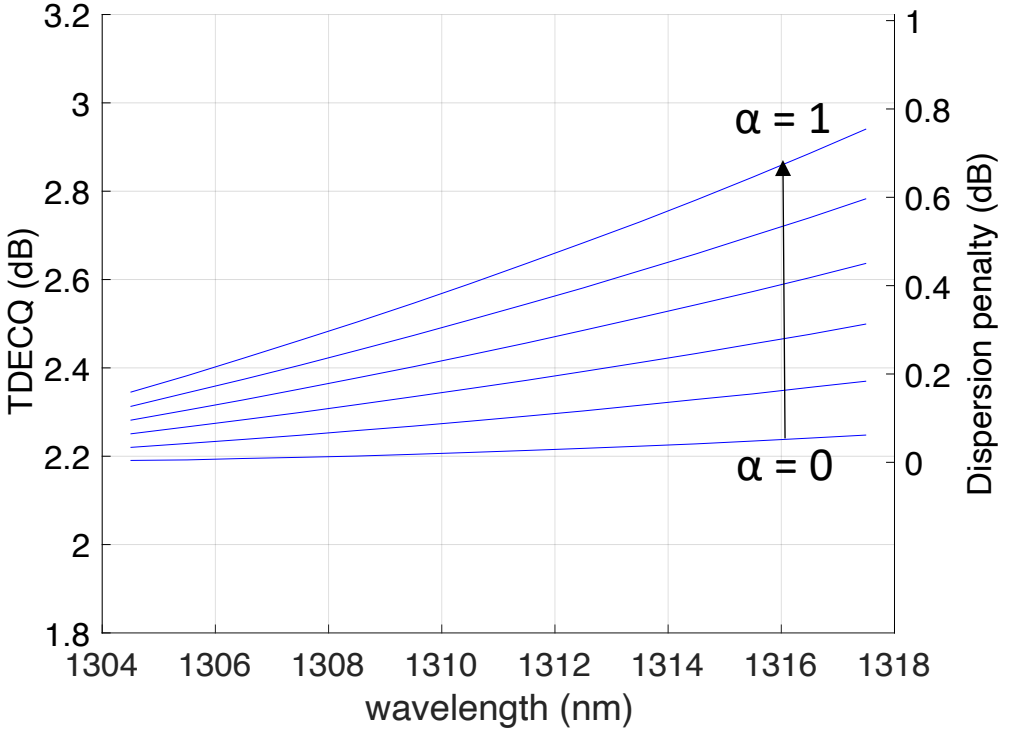
TDECQ study: increasing signaling rate from 106.25 GBd to 112.5 GBd

TDECQ study: single wavelength @ 112.5 GBd

ZDW: 1324 nm
Worst case is negative chirp



ZDW: 1300 nm
Worst case is positive chirp

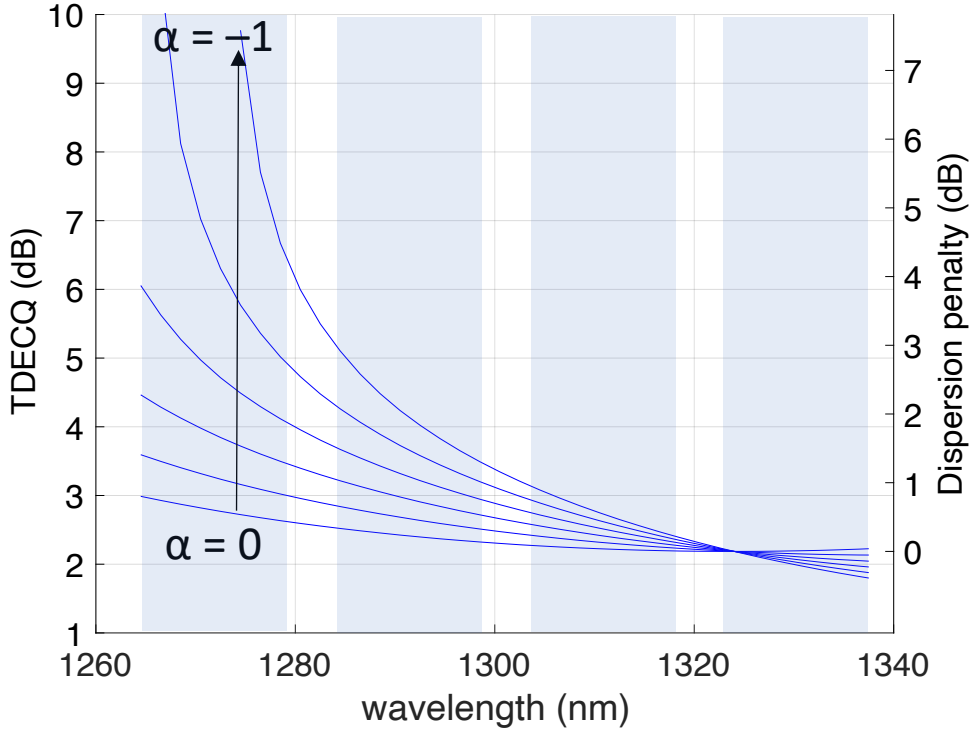


112.5 GBd with TDECQ SER target of 2.2 x 10^{-3}
2 km SMF
5-tap FFE reference equalizer

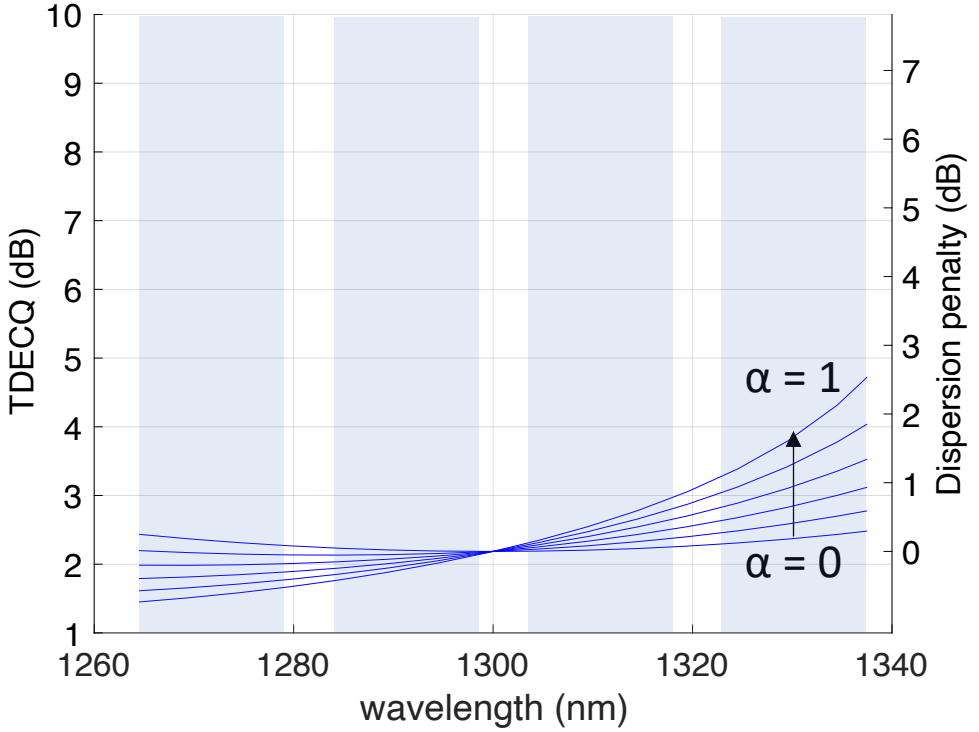
Higher signaling rate and SER target results in 0.2 dB increase in TDECQ and similar dispersion penalty range to 106.25 GBd case

TDECQ study: CWDM @ 112.5 GBd

ZDW: 1324 nm
Worst case is negative chirp



ZDW: 1300 nm
Worst case is positive chirp



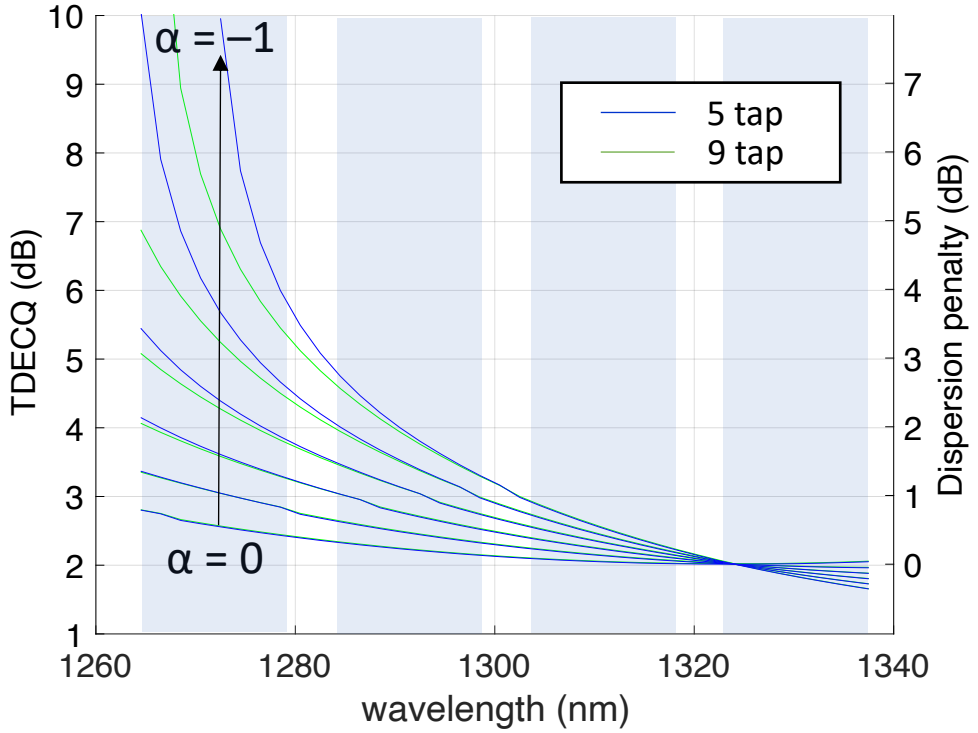
112.5 GBd with TDECQ SER target of 2.2×10^{-3}
2 km SMF
5-tap FFE reference equalizer

As before, acceptable TDECQ for outer CWDM lanes requires chirp factor to be tightly controlled

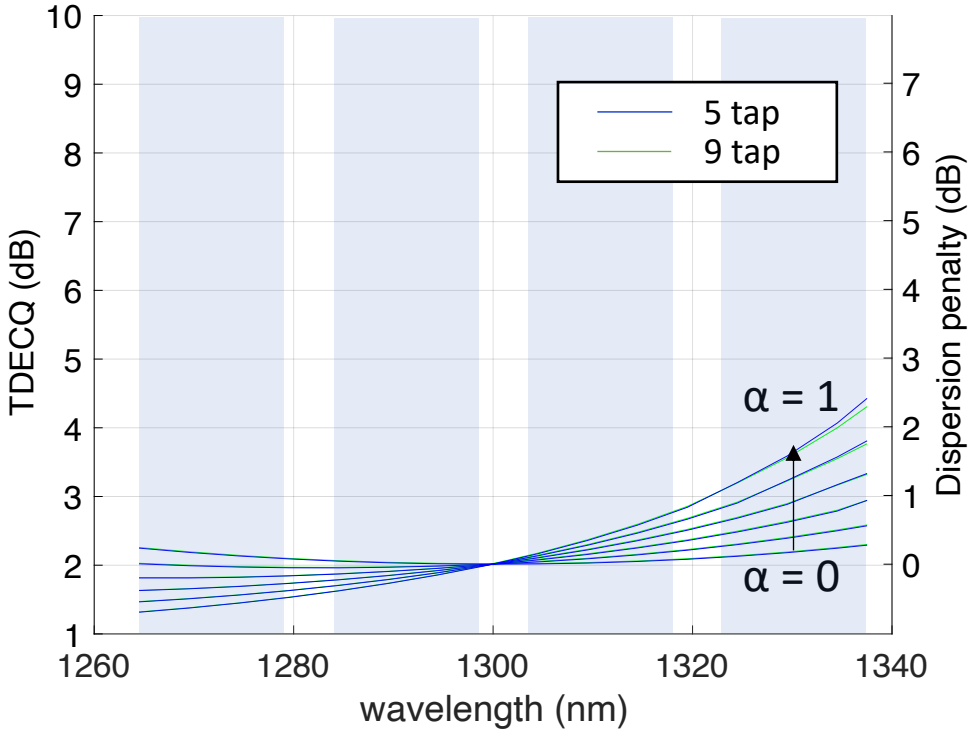
TDECQ study: increasing FFE length from 5 taps to 9 taps

TDECQ study: CWDM @ 106.25 GBd

ZDW: 1324 nm
Worst case is negative chirp



ZDW: 1300 nm
Worst case is positive chirp



106.25 GBd with TDECQ SER target of 4.8×10^{-4}
2 km SMF
5-tap and 9-tap FFE reference equalizers

Longer FFE has effect only at high chirp factors in the 1264.5 nm to 1277.5 nm lane

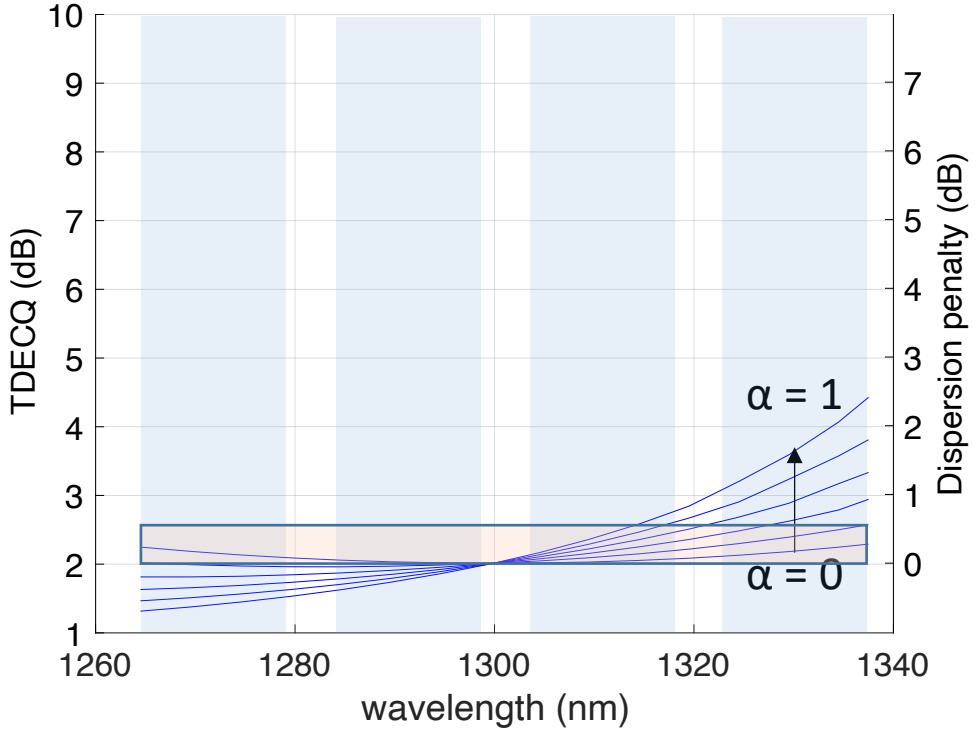
TDECQ study: chirp factor ranges

Chirp factor ranges for 200 Gb/s transmitters

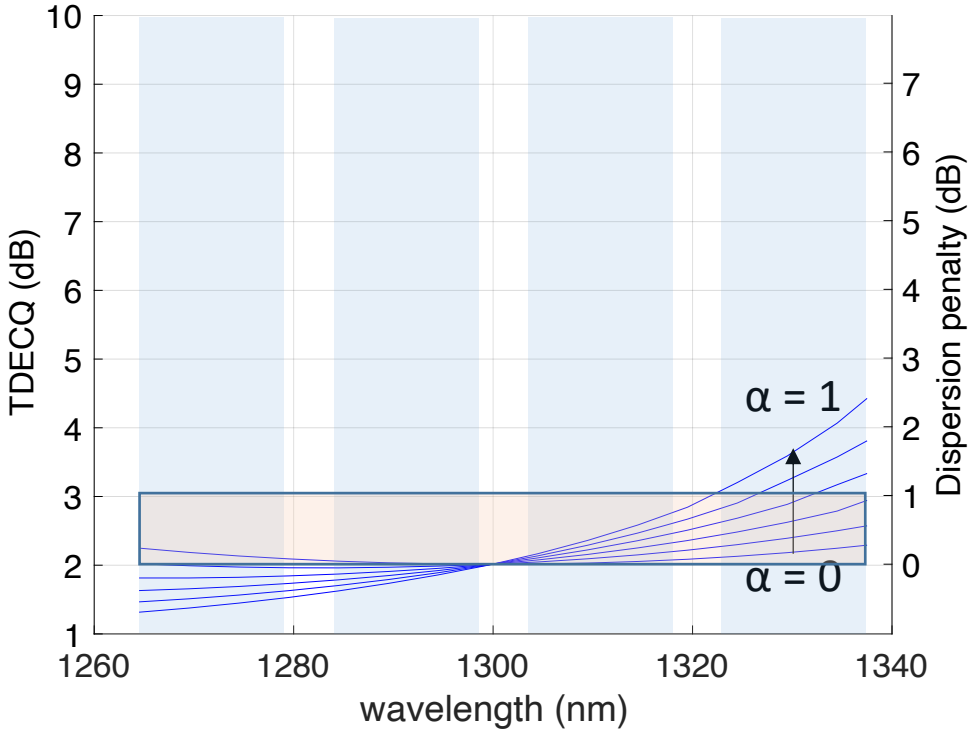
- Tentative chirp factor ranges
  - Thin-film $LiNbO_3$ MZM
    - 0 to 0.1
  - Si MZM
    - 0 to 0.2
  - EAM
    - 0 to 0.5
      - See J. Johnson, “Dispersion considerations for greater than 50G bidirectional optics,” IEEE 802.3 New Ethernet Applications Ad Hoc, January 2022
  - Si MRM
    - 0 to 1
- From above, expect positive chirp to be the limiting case

CWDM TDECQ with chirp factor ranges

Si/$LiNbO_3$ MZM
Horizontal box represents $0 < \alpha < 0.2$



EAM
Horizontal box represents $0 < \alpha < 0.5$



106.25 GBd with TDECQ SER target of 4.8×10^{-4}
2 km SMF
5-tap FFE reference equalizer

Preliminary baseline specification

Changes relative to Clauses 140 and 151

- Receiver
  - Rx sensitivity (OMA_{outer}) (max) increased by 1.5 dB
  - Stressed Rx sensitivity (OMA_{outer}) (max) increased by 1.5 dB
- Transmitter
  - Outer Optical Modulation Amplitude (OMA_{outer}) (min) increased by 1.5 dB
  - Average launch power (min) increased by 1.5 dB
  - Transmitter transition time (max) decreased from 17 ps to 9 ps
  - RIN_xOMA (max) decreased by 3 dB
    - See J. Ingham, P. Dumais and E. Bernier, "Optical modeling of 100 GBd PAM4 with relevance to single-wavelength 200 Gb/s PMDs", IEEE P802.3df Task Force, July 2022 Session, for justification
- Transmitter and Receiver
  - Signaling rate changed to 106.25 GBd ± 50 ppm

- Changes are highlighted in **bold** in the following preliminary transmit and receive parameter tables

Preliminary transmit characteristics

Description	200GBASE-DR1 400GBASE-DR2 800GBASE-DR4 1.6TBASE-DR8	200GBASE-FR1 800GBASE-DR4-2 1.6TBASE-DR8-2	800GBASE-FR4	Unit
Signaling rate (range)	~~53.125~~ **106.25** ± ~~100~~ **50** ppm	~~53.125~~ **106.25** ± ~~100~~ **50** ppm	~~53.125~~ **106.25** ± ~~100~~ **50** ppm	GBd
Modulation format	PAM4	PAM4	PAM4	
Lane wavelengths (range)	1304.5 to 1317.5	1304.5 to 1317.5	1264.5 to 1277.5 1284.5 to 1297.5 1304.5 to 1317.5 1324.5 to 1337.5	nm
Side-mode suppression ratio (SMSR) (min)	30	30	30	dB
Total average launch power (max)	—	—	10.4	dBm
Average launch power (max)	4	4	4.4	dBm
Average launch power (min)	~~−2.9~~ **−1.4**	~~−3.1~~ **−1.6**	~~−3.2~~ **−1.7**	dBm
Outer Optical Modulation Amplitude (OMA_{outer}) (max)	4.2	4.2	3.7	dBm
Outer Optical Modulation Amplitude (OMA_{outer}) (min) for TDECQ < 1.4 dB for 1.4 dB ≤ TDECQ ≤ 3.4 dB	 **0.7** **−0.7 + TDECQ**	 ~~−0.1~~ **1.4** ~~−1.5 + TDECQ~~ **0 + TDECQ**	 ~~−0.2~~ **1.3** ~~−1.6 + TDECQ~~ **−0.1 + TDECQ**	 dBm dBm
Difference in launch power between any two lanes (OMA_{outer}) (max)	—	—	3.9	dB
Transmitter and dispersion eye closure for PAM4 (TDECQ) (max)	3.4	3.4	3.4	dB
Transmitter eye closure for PAM4 (TECQ) (max)	3.4	3.4	3.4	dB
|TDECQ – TECQ| (max)	2.5	2.5	2.5	dB
Over/under-shoot (max)	22	22	22	%
Transmitter power excursion (max)	2	2	1.8	dBm
Extinction ratio (min)	3.5	3.5	3.5	dB
Transmitter transition time (max)	~~17~~ **9**	~~17~~ **9**	~~17~~ **9**	ps
Average launch power of OFF transmitter (max)	−15	−15	−16	dBm
RIN_xOMA (max), where *x* is the optical return loss tolerance (max)	~~−136~~ **−139**	~~−136~~ **−139**	~~−136~~ **−139**	dB/Hz
Optical return loss tolerance (max)	15.5	17.1	17.1	dB
Transmitter reflectance (max)	−26	−26	−26	dB

Preliminary receive characteristics

Description	200GBASE-DR1 400GBASE-DR2 800GBASE-DR4 1.6TBASE-DR8	200GBASE-FR1 800GBASE-DR4-2 1.6TBASE-DR8-2	800GBASE-FR4	Unit
Signaling rate (range)	~~53.125~~ **106.25** ± ~~100~~ **50** ppm	~~53.125~~ **106.25** ± ~~100~~ **50** ppm	~~53.125~~ **106.25** ± ~~100~~ **50** ppm	GBd
Modulation format	PAM4	PAM4	PAM4	
Lane wavelengths (range)	1304.5 to 1317.5	1304.5 to 1317.5	1264.5 to 1277.5 1284.5 to 1297.5 1304.5 to 1317.5 1324.5 to 1337.5	nm
Damage threshold	5	5	5.4	dBm
Average receive power (max)	4	4	4.4	dBm
Average receive power (min)	–4.9	–4.9	–7.2	dBm
Receive power (OMA_{outer}) (max)	4.2	4.2	3.7	dBm
Difference in receive power between any two lanes (OMA_{outer}) (max)	—	—	4.1	dB
Receiver reflectance (max)	–26	–26	–26	dB
Receiver sensitivity (OMA_{outer}) (max) for TECQ < 1.4 dB for 1.4 dB ≤ TECQ ≤ 3.4 dB	 **–2.4** **–3.8 + TECQ**	 ~~–4.5~~ **–3** ~~–5.9 + TECQ~~ **–4.4 + TECQ**	 ~~–4.6~~ **–3.1** ~~–6 + TECQ~~ **–4.5 + TECQ**	 dBm dBm
Stressed receiver sensitivity (OMA_{outer}) (max)	~~–1.9~~ **–0.4**	~~–2.5~~ **–1**	~~–2.6~~ **–1.1**	dBm
Conditions of stressed receiver sensitivity test:				
Stressed eye closure for PAM4 (SECQ)	3.4	3.4	3.4	dB
OMA_{outer} of each aggressor lane	1.4	1.4	1.4	dBm

Preliminary illustrative link power budgets

Parameter	200GBASE-DR1 400GBASE-DR2 800GBASE-DR4 1.6TBASE-DR8	200GBASE-FR1 800GBASE-DR4-2 1.6TBASE-DR8-2	800GBASE-FR4	Unit
Power budget (for max TDECQ)	6.5	7.8	7.8	dB
Operating distance	500	2000	2000	m
Channel insertion loss	3	4	4	dB
Maximum discrete reflectance	–35	–35	–35	dB
Allocation for penalties (for max TDECQ)	3.5	3.8	3.8	dB
Additional insertion loss allowed	0	0	0	dB

Comments on test methodology

- For 200GBASE-DR1, 400GBASE-DR2, 800GBASE-DR4, 1.6TBASE-DR8, 200GBASE-FR1, 800GBASE-DR4-2 and 1.6TBASE-DR8-2
  - Test methodology can be based on Clause 140, with the following exceptions:
    - Half-symbol-rate filter bandwidth: 53.125 GHz
    - Reference equalizer: TBD

- For 800GBASE-FR4
  - Test methodology can be based on Clause 151, with the following exceptions:
    - Half-symbol-rate filter bandwidth: 53.125 GHz
    - Reference equalizer: TBD

Comments on test methodology (cont.)

- Reference equalizer
  - >5 FFE taps does not provide significant improvement in mitigation of chromatic dispersion, except for high chirp factors in the lowest-wavelength CWDM lane
  - Longer FFE may be beneficial in compensating for electrical channels and non-ideal O-E components
  - Excessively strong reference equalizers should be avoided, as they may lead to interoperability issues. Substantial margin relative to implementations is desirable
  - Further modeling studies and experimental input required

Summary

- Performed TDECQ study and considered key specifications for 200 Gb/s per lane optical PMDs
- Changes relative to Clauses 140 and 151 proposed
- Preliminary tables of transmit and receive characteristics provided

Next steps

- Further reference equalizer study
- MPI study
- Appropriate updates depending on FEC choice