The Requirement Analysis of 400GE FEC for Gen1 PMDs

400GE Study Group
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Outline

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- The Limitation of FEC Coding Gain
- The Calculation of 400GE FEC Coding Gain
- Summary
- The Effect of 400GE Architecture w/ FEC
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The Promising Options of 400GE Gen1

- To enable quick time to the market and moderate development cost, we propose the SG to consider the first generation 400GE optics approaches that reuse mainstream 25GBaud technology.
- According to the contributions from previous meetings, the possible solutions could be:
  - 16*25GB NRZ
  - 4* (4*25GB) NRZ
  - 8*25GB PAM4
  - ……
- In order to achieve lowest cost and not too tight specifications for 400GE it is probably unavoidable to use FEC. In this contribution, based on these options, the results of link simulations and the requirements of FEC will be analyzed.

The Limitation of FEC Coding Gain

- Generally, FEC algorithms could be classified as three levels:
  - Level 1, e.g. RS(255,239), overhead: ~7%, NCG: 6~7dB
  - Level 2, e.g. RS*RS, RS*BCH, overhead: ~7%, NCG: 8~10dB
  - Level 3, soft decision algorithm, e.g. Turbo, LDPC, TPC, overhead: 20%, NCG: 10.5~11.5dB.
- Generally, we have to introduce the soft decision algorithm for the requirement like NCG>10dB.
- With the increasing of overhead is more than 20%, the coding gain is improved slowly.

The Calculation of 400GE FEC Coding Gain

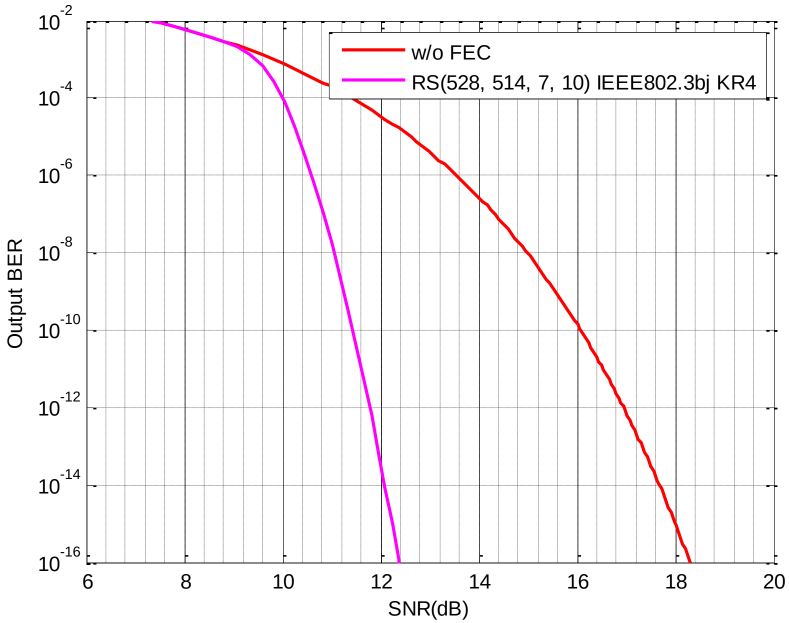
W/ or W/O SOA PMD type	Reach(km)	Input BER (Note 1)	Requirement of CG (dB)	
			BER target 1e-12	BER target 1e-15
Without SOA 16*25GB NRZ	2	1e-24	/	/
	10	1e-8	1.9623	3.0155
	40	0.38	27.245 (Note 2)	28.2982
With SOA 16*25GB NRZ	2	1e-70	/	/
	10	1e-50	/	/
	40	2e-6	3.6680	4.7213
Without SOA 4*4*25G NRZ	2	1e-87	/	/
	10	1e-56	/	/
	40	9e-2	14.3977	15.4509
With SOA 4*4*25G NRZ	2	5e-94	/	/
	10	1e-86	/	/
	40	4e-20	/	/

Note: 1. The methodology of simulation and detailed parameters are included in appendix slides.
2. The red color data indicate that the requirement of CG is very high, even the SD-FEC can't meet the requirement because the limitation of overhead and the implementation cost.
3. Here CG(Not NCG) is calculated, NCG evaluation need some specific FEC algorithm defined.

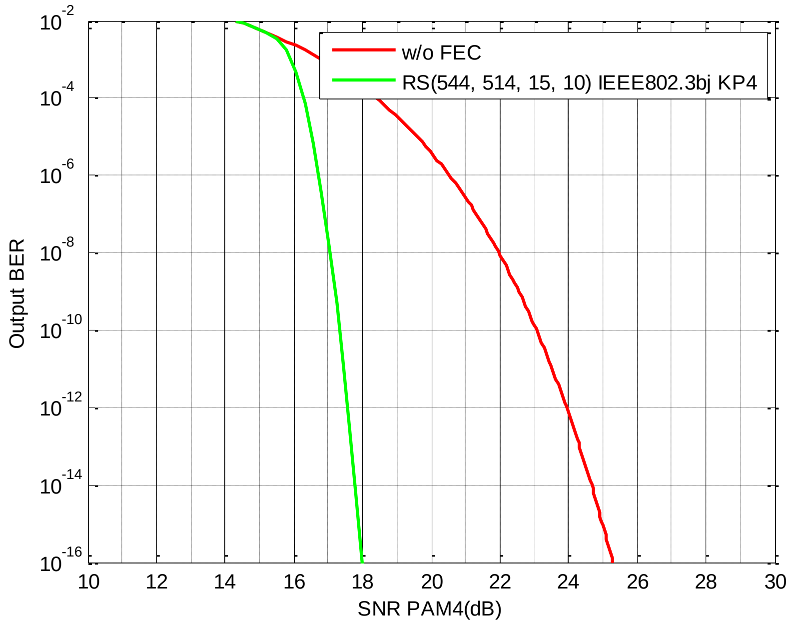
The Calculation of 400GE FEC Coding Gain (cont.)

W/ or W/O SOA PMD type	Reach(km)	Input BER	Requirement of CG (dB)	
			BER target 1e-12	BER target 1e-15
Without SOA 8*25GB PAM4	0.5	1e-4	5.5361	6.5893
	2	3e-4	6.2347	7.2879
	10	3e-2	11.4578	12.5111
With SOA 8*25GB PAM4	0.5	5e-6	4.0418	5.0950
	2	6e-6	4.1199	5.1732
	10	4e-5	5.0250	6.0783

The Theoretical Net Coding Gain of FEC

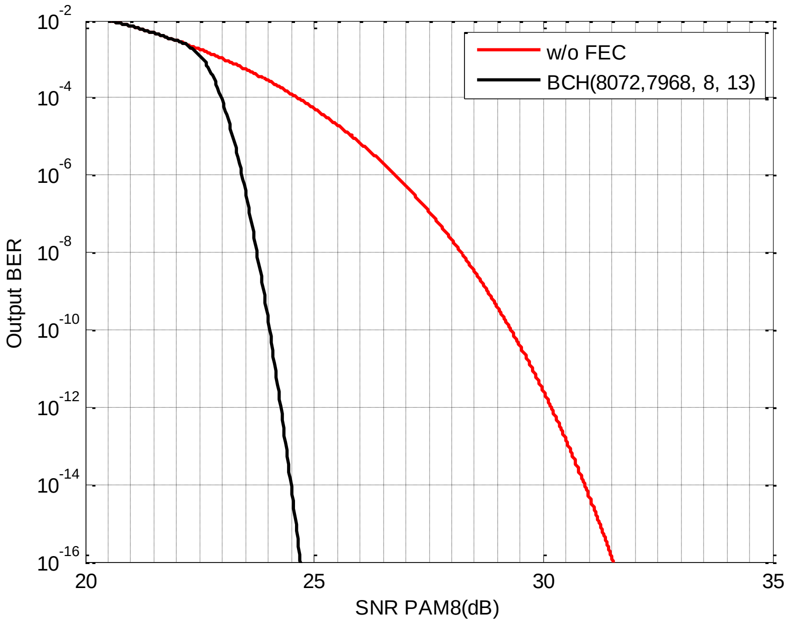


RS(528,514) for NRZ

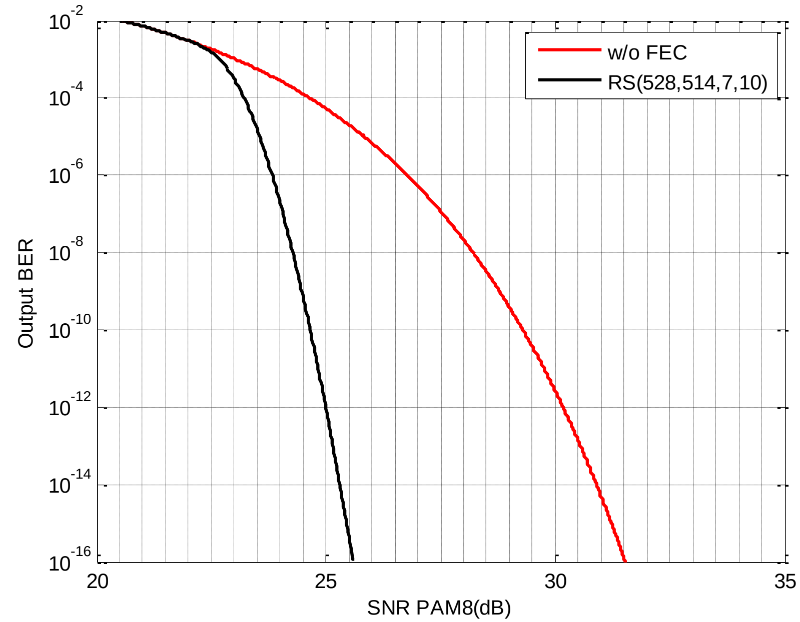


RS(544,514) for PAM4

The Theoretical Net Coding Gain of FEC (cont.)



BCH(8072, 7968, 9, 13) for PAM8



RS(528, 514) for PAM8

The Theoretical Net Coding Gain of FEC (cont.)

Schemes	Output BER / SNR (dB)	Input BER / SNR (dB)	Net Coding Gain(dB)
RS(528,514) for NRZ	1 e-12 / 16.9446	5.2669e-5 /11.7721	5.1725
	1e-15 / 17.9979	2.1802e-5 / 12.2292	5.7687
RS(544,514) for PAM4	1 e-12 / 23.9343	3.6384e-4 / 17.5653	6.3690
	1 e-15 / 24.9876	2.2614e-4 / 17.8897	7.0979
RS(528, 514) for PAM8	1.1687e-12 / 30.4	5.3729e-5 / 25.0	4.6
	1.2212e-15 / 31.3	2.2334e-5 / 25.4	5.9
BCH(8072, 7968, 8, 13) for PAM8	1.0421e-12 / 30.2	1.8116e-4 / 24.75	5.45
	1.4835e-15 / 31.25	1.0917e-4 / 24.1	7.15

Note: 1. Here is the NCG value calculated. Because the value is calculated by the SNR difference between using FEC and not using FEC.

Summary of the calculation

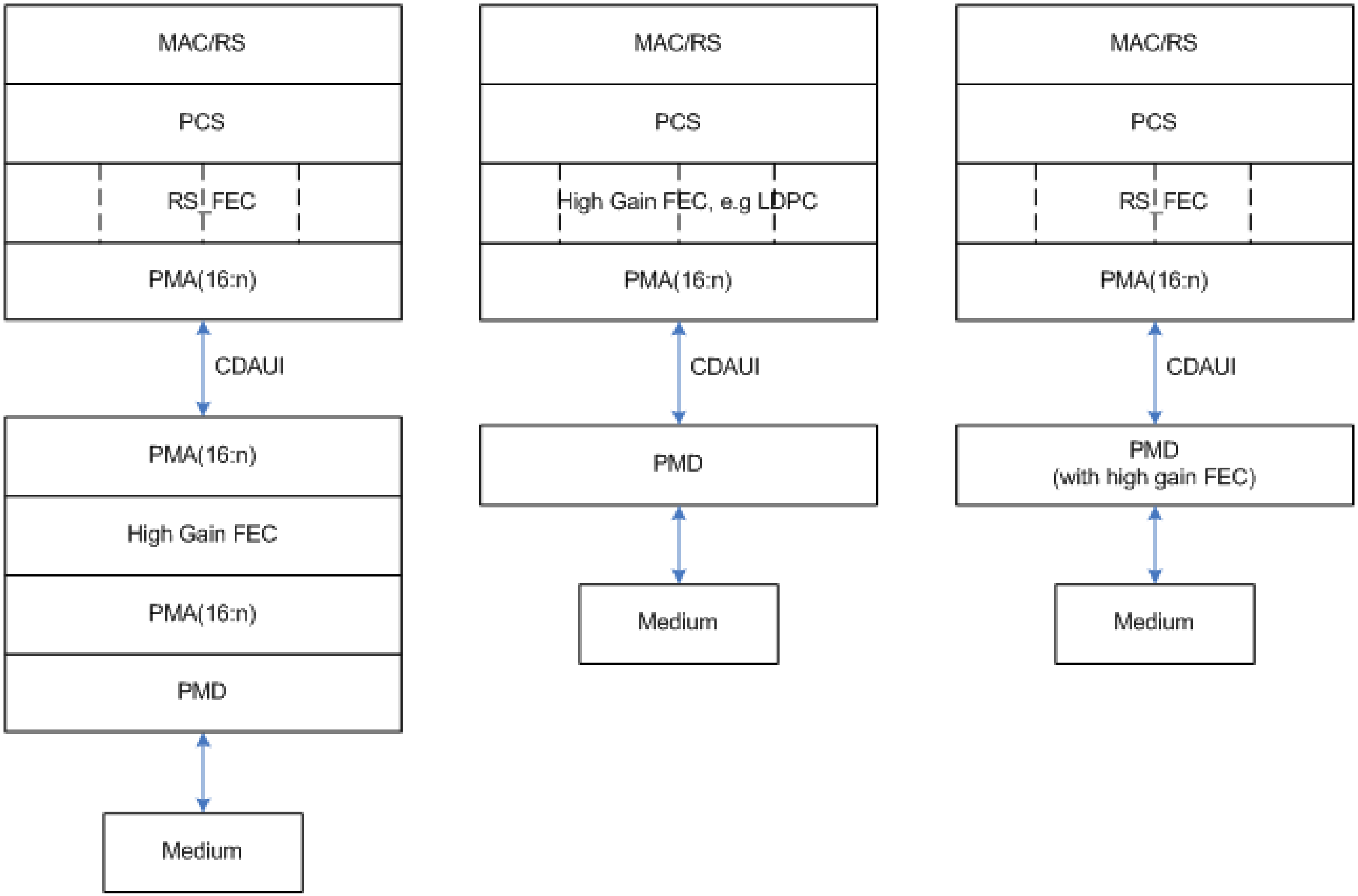
From what have been discussed above, we come to the following conclusions:

- For the 4* (4*25GB) NRZ:
  - For the 2km/10km application, there is no need to add FEC to satisfy 1e-15 BER target.
- For the 16*25GB NRZ:
  - For the 2km application, there is no need to add FEC.
  - For the 10km application, RS(528,514) will meet the CG requirement.
  - For the 40km application
    - The scheme W/ SOA + RS(528,514) will meet the BER requirement.
    - W/O SOA / APD, we have to introduce FEC, but the coding gain will be: 27.245dB@1e-12, 28.2982@dB1e-15, which will gone beyond the capability of RS and BCH FEC.
- For 8*25GB PAM4:
  - For the 500m/2km application, RS(544,514) will meet the CG requirement.
  - For the10km application
    - The scheme W/ SOA + RS(544,514) will probably meet the BER requirement.
    - W/O SOA / APD, we have to introduce FEC and the coding gain will be: 11.4578dB@1e-12, 12.5111dB@1e-15, SD-FEC e.g. LDPC, TPC etc. will meet the requirement of 11.4578dB@1e-12 but with ~20% overhead. For 12.5111dB@1e-15, it is a challenge.

The Effect of 400GE Architecture w/ FEC

- According to the summary, the existing RS(528,514) / RS(544, 514) FEC will be a promising way to satisfy some of the application.
- To be addressed, will the higher coding gain requirement affect the architecture of 400GE?
  - Opt 1: to introduce an additional electrical chip (DSP?) to deal with the high gain FEC.
  - Opt 2: to implement the higher gain FEC in the PMD.
  - Opt 3: change the FEC algorithm reside in the 400GE.
- Which option is more appropriate?
  - For option 1 & 2, considering the overhead and the actual electrical Serdes rate, for the 25G Serdes, 7% overhead is a limit.
  - For option 3, due to the optical module could be 32GB for 25GB device, 15%~20% overhead is a moderate choice.
- In the following figures, FEC could be one instance for 400GE or four instances for 4*100GE.

The Effect of 400GE Architecture w/ FEC (cont.)



Option 1 Option 2 Option 3

The future work

- Refine the analysis results if necessary.
- Further work on the future possible FEC algorithm corresponding to the future possible high modulation PMD.

Thank you

Appendix 1 --- The Methodology for Calculation of Coding Gain

The Methodology for Calculation of Coding Gain

- CG: BER reduction by the FEC expressed in dB.
- NCG: This takes into account the fact that the increased bandwidth needed for the FEC results in the increased noise in the receiver.

$$CG = 20 * \log_{10}(erfcinv(2 * BER_{ref})) - 20 * \log_{10}(erfcinv(2 * BER_{in}))$$

$$NCG = 20 * \log_{10}(erfcinv(2 * BER_{ref})) - 20 * \log_{10}(erfcinv(2 * BER_{in})) + 10 * \log_{10}(R)$$

Among above formula, R is the FEC code rate.

The Calculation of Theoretical RS BER

- RS(n,k,t,m) theoretical BER calculation formula is as following:

$$P_{out} = \sum_{i=t+1}^{n} \frac{i}{n} \bullet \frac{n!}{i!(n-i)!} \bullet P_{in}^{\ i} \bullet (1 - P_{in})^{(n-i)}$$

$$BER_{in} = 1 - (1 - P_{in})^{1/m}$$

$$BER_{out} = 1 - (1 - P_{out})^{1/m}$$

m is the bits/symbol. Pin is the symbol error probability. Pout is the symbol error probability after the error correction.

The Relationship between the BER and SNR

- The SNR and Q formula is as following. M is the modulation factor. For NRZ, m=2, for PAM4, m=4, for PAM8, m=8….

$$SNR = \frac{(m^2 - 1)}{3} * Q^2$$

$$Q = \sqrt{2} * erfcinv(2 * BER)$$

- From the above formula, the relationship between SNR and BER can be got as following:

$$SNR = \frac{2 * (m^2 - 1)}{3} * (erfcinv(2 * BER))^2$$

Appendix 2 --- The Simulation of Link Level

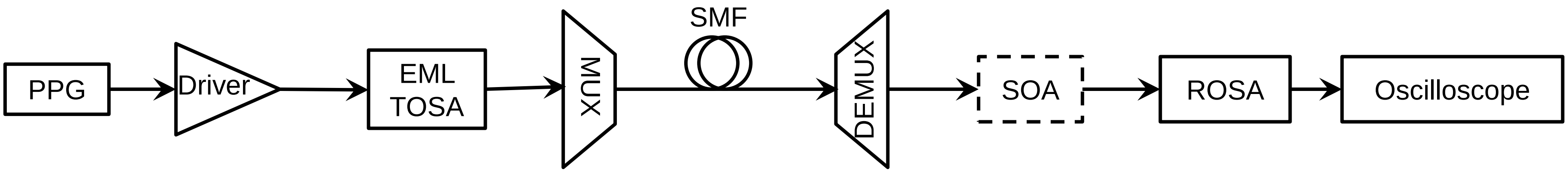
Link Simulation 1: 16*25G NRZ

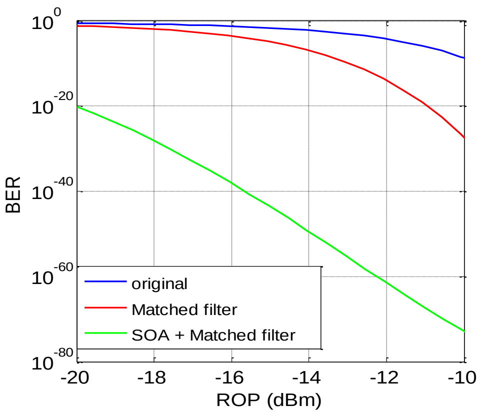
[T1] SNR @ Driver=27dB (NRZ)
[T2] Vpp @ Driver=2V

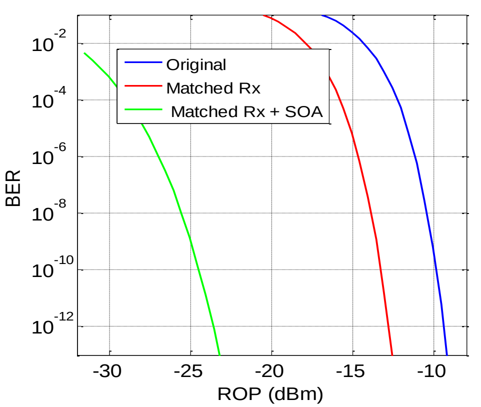
[T4] ER=8dB
[T5] Vpp=2V, Vb=-1V
[T6] RIN=-144dB/Hz
[T7] BW of EML=19GHz

[R5] Gain=20dB
[R6] NF=7dB

[R1] Responsivity=0.65A/W
[R2] BW of RCV=22/32 GHz
[R3] Dark current =10nA
[R4] TIA noise=20/40 pA/√Hz







PMDs	NRZ 16*25Gbps			NRZ 16*25Gbps (W/ SOA)		
Error floor	-			-		
LD+Modulator output power / dBm	5.5			5.5		
Mux&coupling / dB	7			7		
Demux&coupling / dB	6			6		
Connector / dB	2			2		
Link insertion loss / dB	0.86	4.3	17.2	0.86	4.3	17.2
Receive power / dBm	-10.36	-13.8	-19.7	-10.36	-13.8	-19.7
BER	1e-24	1e-8	0.38	1e-70	1e-50	2e-6
Reach / km	2	10	40	2	10	40

The considerations of power budget simulation :

- Tx output power: -1.5dBm per channel (considering the eye security limitation).
- Total connector loss is 2dB.
- Insertion loss of PLC Mux/Demux and coupling, Tx: 7dB, Rx: 6dB.

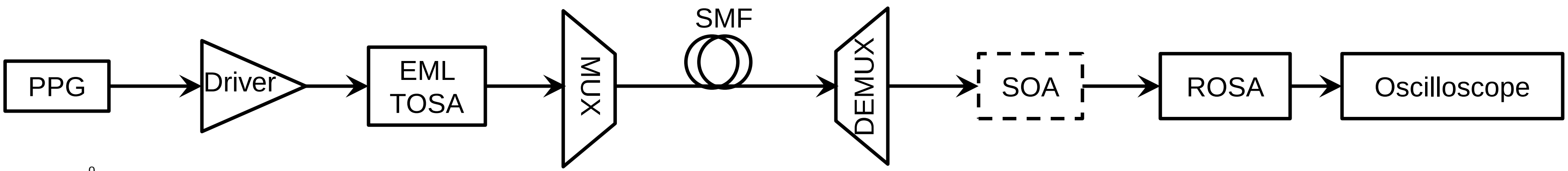
Link Simulation 2: 4* (4*25GB) NRZ

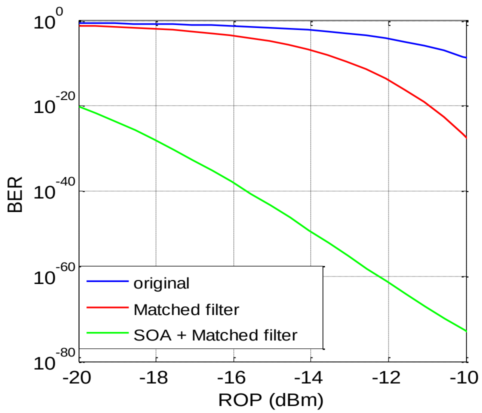
[T1] SNR @ Driver = 27dB (NRZ)
[T2] Vpp @ Driver = 2V

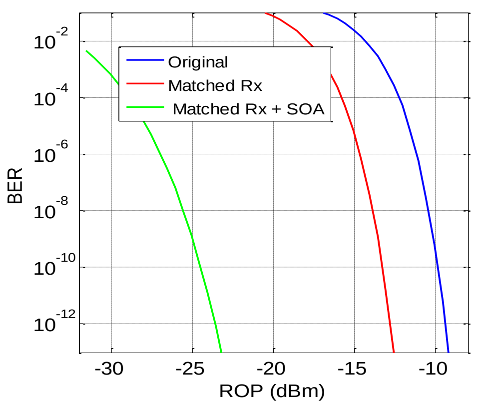
[T4] ER = 8dB
[T5] Vpp=2V, Vb=-1V
[T6] RIN =-144dB/Hz
[T7] BW of EML = 19GHz

[R5] Gain = 20dB
[R6] NF = 7dB

[R1] Responsivity = 0.65A/W
[R2] BW of RCV= 22/32 GHz
[R3] Dark current = 10nA
[R4] TIA noise = 20/40pA/√Hz







PMDs	NRZ 4*4*25Gbps			NRZ 4*4*25Gbps (W/ SOA)		
Error floor	-			-		
LD+Modulator output power / dBm	6			6		
Mux&coupling / dB	4			4		
Demux&coupling / dB	3			3		
Connector loss / dB	2			2		
Link insertion loss / dB	0.86	4.3	17.2	0.86	4.3	17.2
Receive power / dBm	-3.86	-7.3	-20.2	-3.86	-7.3	-20.2
BER	1e-87	1e-56	9e-2	5e-94	1e-86	4e-20
Reach / km	2	10	40	2	10	40

The considerations of power budget simulation :

- Total connector loss is 2dB.
- Insertion loss of TFF Mux/Demux and coupling, Tx: 4dB, Rx: 3dB.

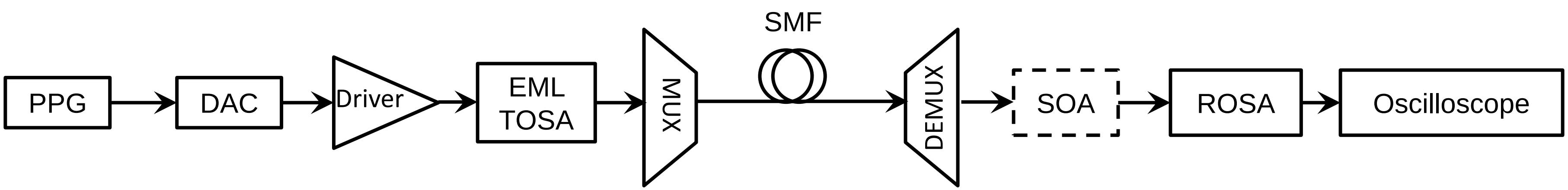
Link simulation 3: 8*25GBaud PAM4

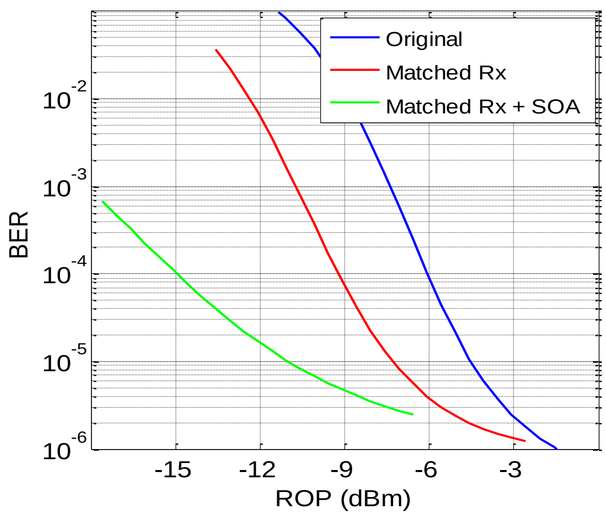
[T1] SNR after driver = 21dB
[T2] Input DJ=1.5 ps
[T3] Input RJ=400 fs

[T5] ER = 8dB
[T6] Vpp=2V, Vb=-1V
[T7] RIN =-144dB/Hz
[T8] BW of EML = 19GHz

[R5] Gain = 20dB
[R6] NF = 7dB

[R1] Responsivity = 0.9A/W
[R2] BW of RCV= 22/32G
[R3] Dark current = 10nA
[R4] TIA noise = 20/40pA/√Hz





PMDs	PAM4 8*50Gbps			PAM4 8*50Gbps (W/ SOA)		
Error floor	<1e-5			<1e-5		
LD+Modulator output power / dBm	6			6		
Mux&coupling / dB	7			4		
Demux&coupling / dB	6			6		
Connector loss / dB	2			2		
Link insertion loss / dB	0.22	0.86	4.3	0.22	0.86	4.3
Receive power / dBm	-9.22	-9.86	-13.3	-9.22	-9.86	-13.3
BER	1e-4	3e-4	3e-2	5e-6	6e-6	4e-5

The considerations of power budget simulation :

- Tx output power: -1.5dBm per channel (considering the eye security limitation).
- Insertion loss of PLC Mux/Demux and coupling, Tx: 7dB, Rx: 6dB.