Super-PON Link Budget Analysis
Effect of Raman

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Google Fiber

Raman effect

- The Raman fiber nonlinearities were observed in the Google Fiber tests
- Raman is a fiber nonlinearity whereby power in shorter wavelength signals are transferred to longer wavelength signals
- Mathematically, the process is governed by:

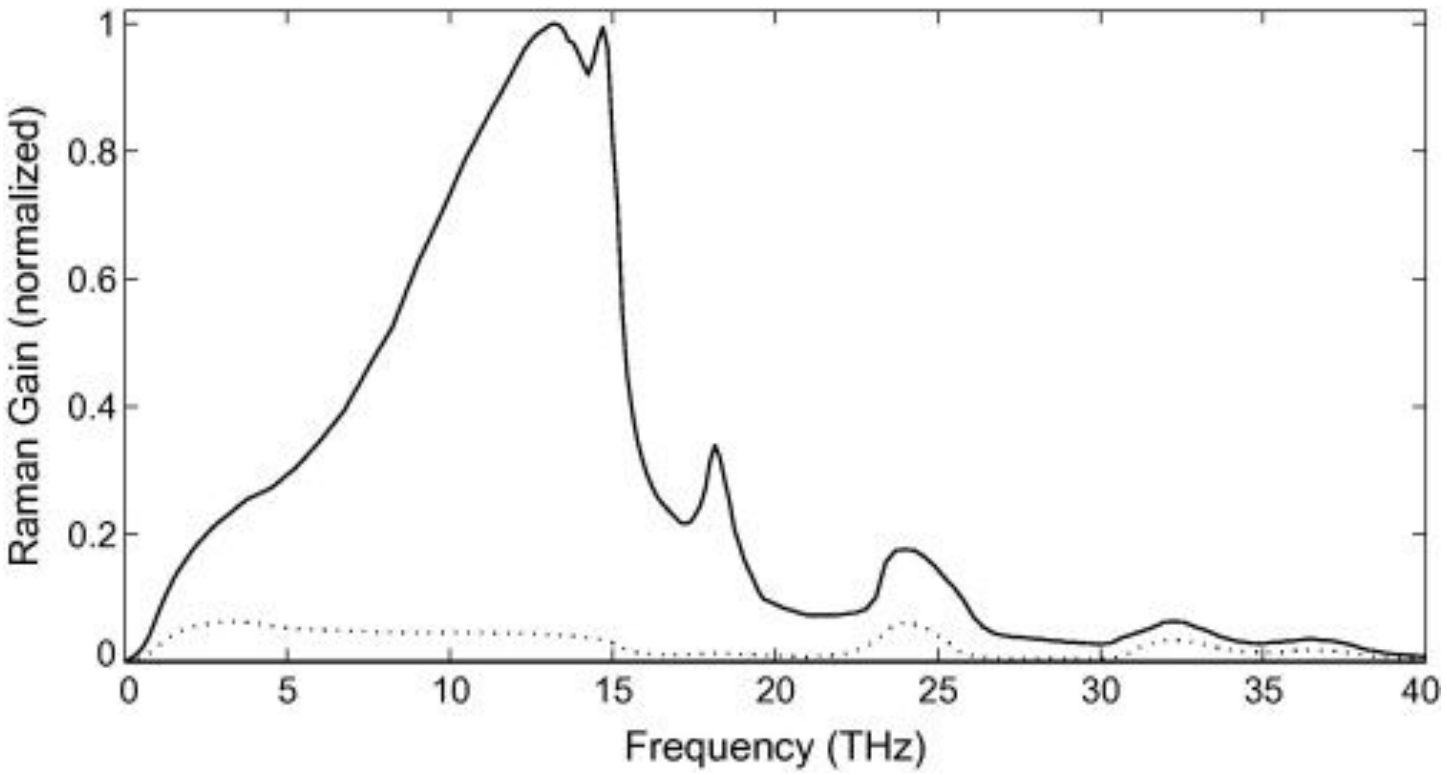
$$\frac{dI_S}{dz} = g_R I_p I_S - \alpha I_S,$$

$$\frac{dI_p}{dz} = -\frac{\omega_p}{\omega_S} g_R I_p I_S - \alpha I_p,$$

where p is the pump (power doner),
and s is the Stokes (power receiver).

Raman effect

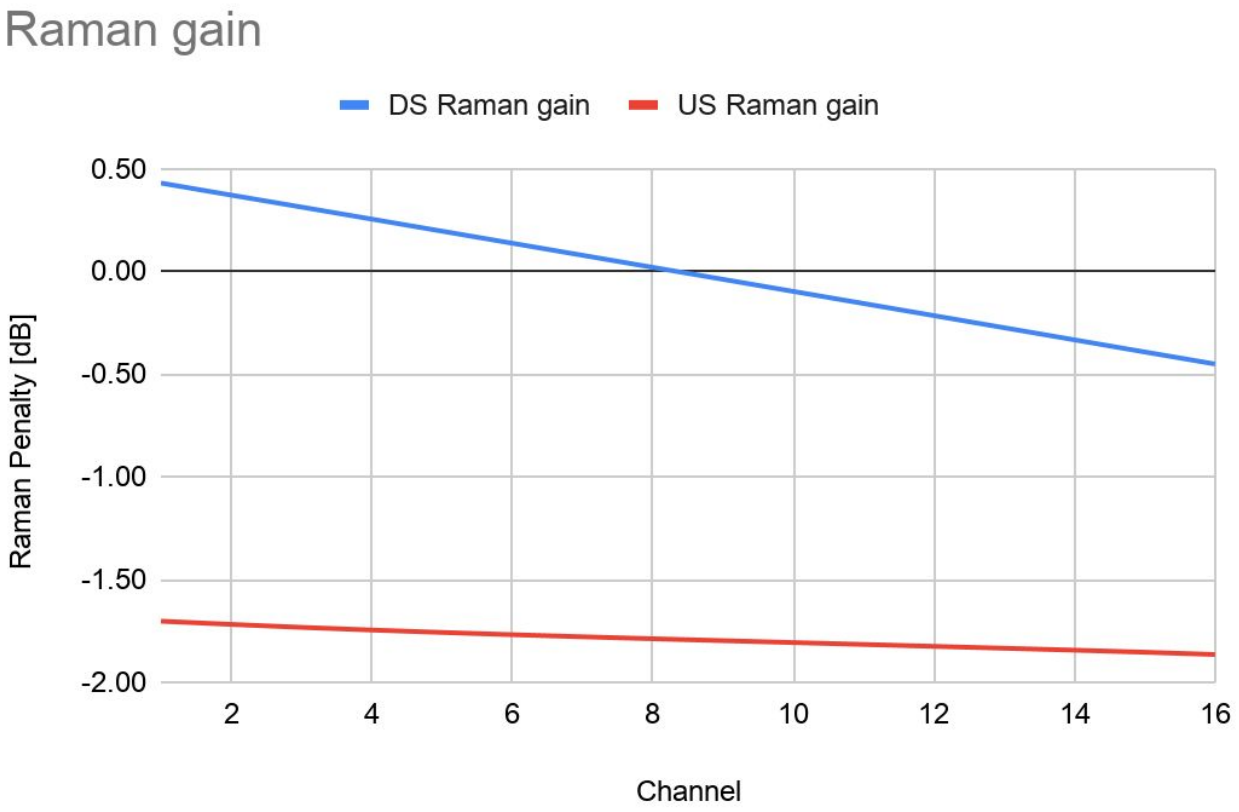
- Raman gain is dependent on frequency separation of the spectral components
- Increases with separation to ~100 nm (12 THz around C-band)
- We use almost 6 THz, Raman coefficient is significant



Raman effect

- Using 11.3 dBm per DS channel launch into the fiber, and 50 km of fiber

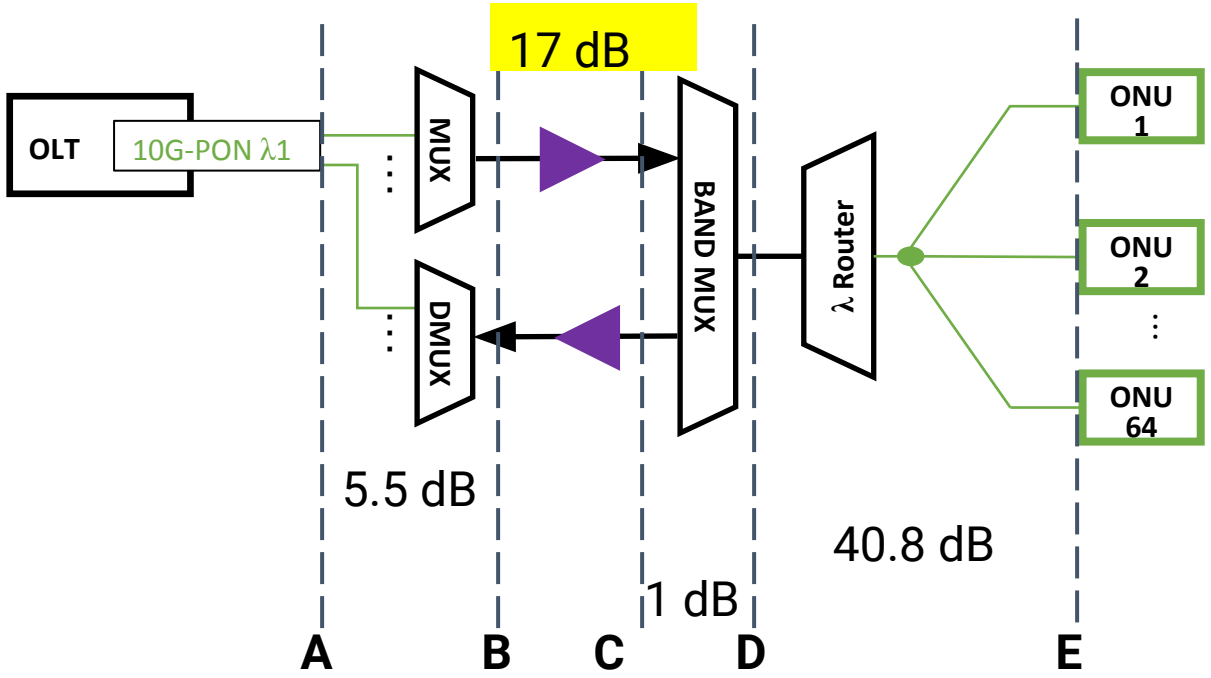
	Gen X			
	Downstream		Upstream	
Channel	Frequency	Raman gain	Frequency	Raman gain
1	189.807	0.43	194.193	-1.70
2	189.906	0.37	194.294	-1.72
3	190.004	0.31	194.396	-1.73
4	190.103	0.25	194.497	-1.75
5	190.202	0.20	194.598	-1.76
6	190.301	0.14	194.699	-1.77
7	190.400	0.08	194.800	-1.78
8	190.499	0.02	194.901	-1.79
9	190.597	-0.04	195.003	-1.80
10	190.696	-0.10	195.104	-1.81
11	190.795	-0.16	195.205	-1.82
12	190.894	-0.21	195.306	-1.82
13	190.993	-0.27	195.407	-1.83
14	191.092	-0.33	195.508	-1.84
15	191.191	-0.39	195.609	-1.85
16	191.289	-0.45	195.711	-1.86



802.3ca PCS increases the link budget

- Benefit of LDPC in laubach_3ca_1b_0118.pdf
  - US: 2.0 dB benefit in receiver limited Rx -> ~4.0 dB benefit in ASE limited Rx
  - DS: 2.6 dB benefit in AWGN model (both are receiver limited Rx)

Downstream power levels without Raman



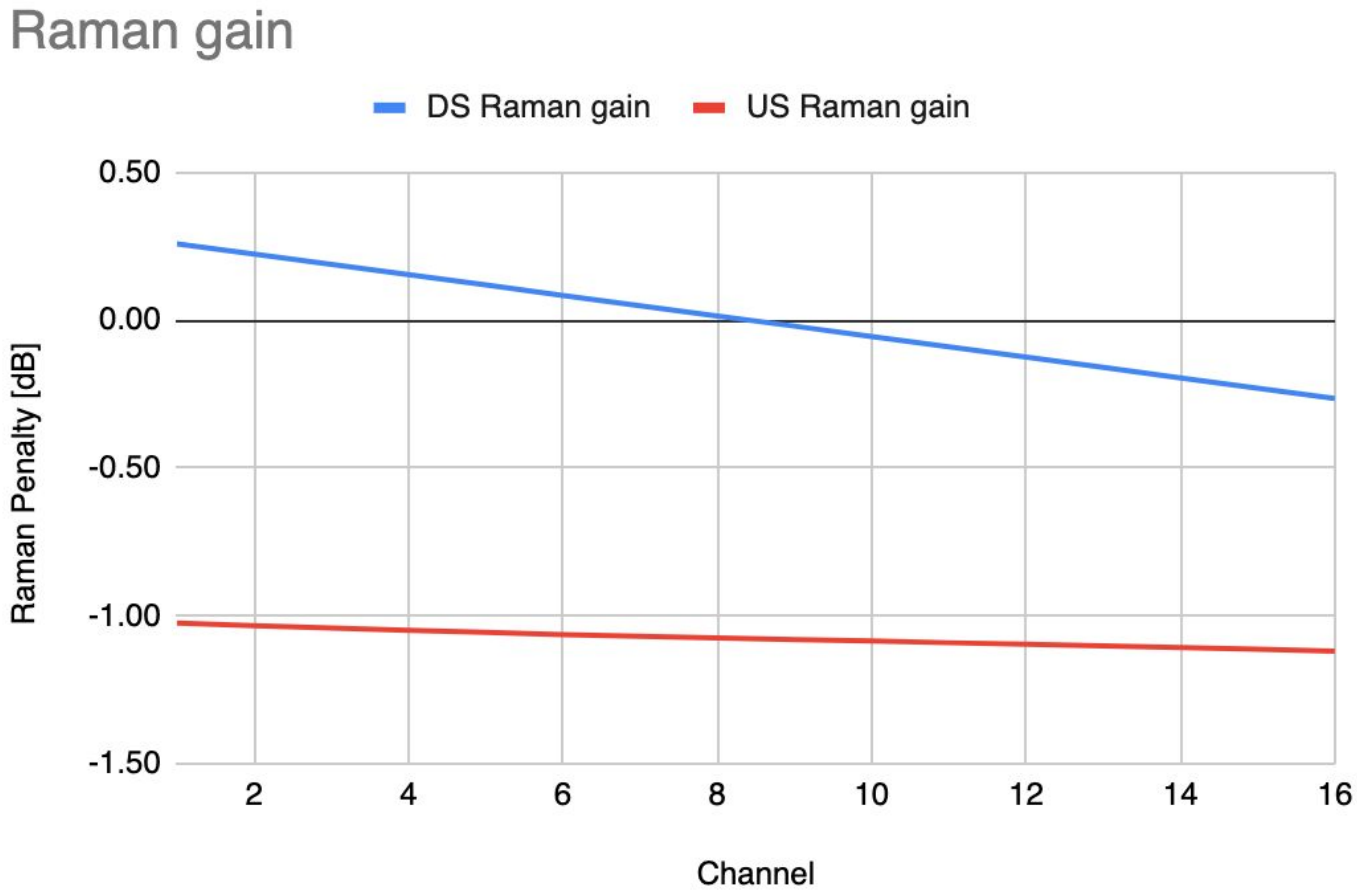
Location	DS/WL [dBm]	DS total [dBm]
A	-2.3	
B	-7.8	4.8
C	9.8	21.8
D	8.8	20.8
E	-32 (PR40 -2.5)	

- Lower DS output power will reduce the effect of Raman
- Assume an average per wavelength power 1.0 dB above the minimum to allow for power imbalance between wavelengths
- Generate Raman penalties for 9.1 dBm DS launch power

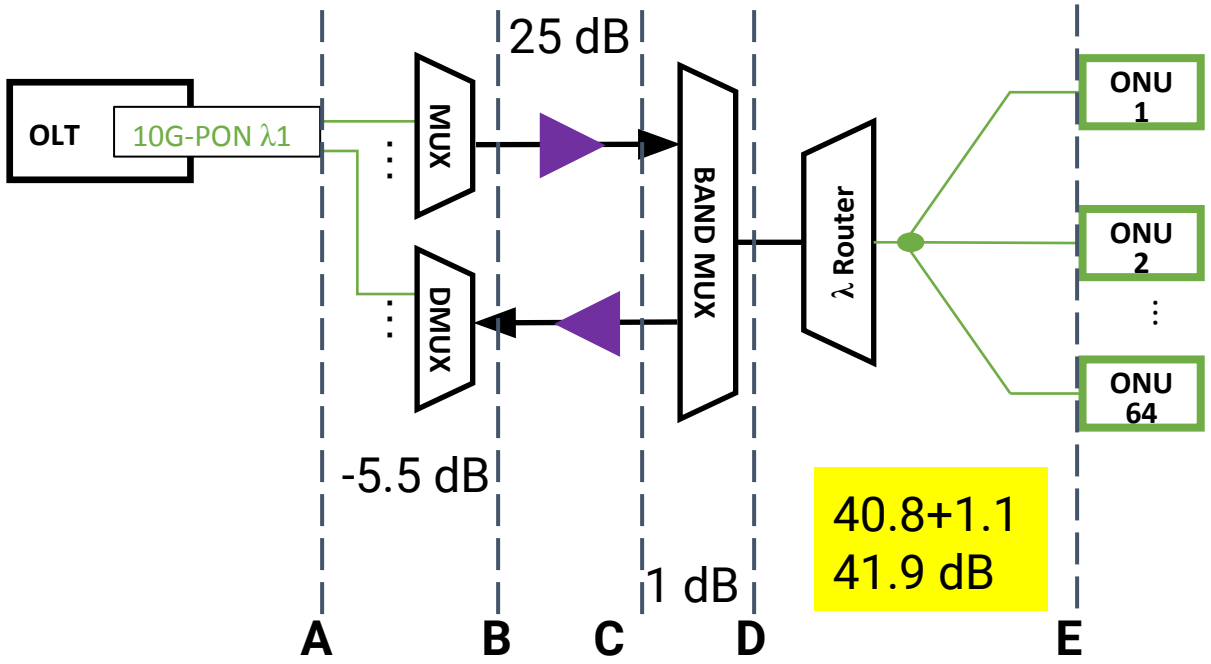
Raman effect: 9.1 dBm DS launch power

- 50 km of fiber used
- Raman penalty: US 1.1 dB; DS 0.3 dB

	Gen X			
	Downstream		Upstream	
Channel	Frequency	Raman gain	Frequency	Raman gain
1	187.613	0.26	192.000	-1.02
2	187.711	0.22	192.100	-1.03
3	187.809	0.19	192.200	-1.04
4	187.906	0.15	192.300	-1.05
5	188.004	0.12	192.400	-1.06
6	188.102	0.08	192.500	-1.06
7	188.200	0.05	192.600	-1.07
8	188.297	0.01	192.700	-1.08
9	188.395	-0.02	192.800	-1.08
10	188.493	-0.06	192.900	-1.09
11	188.590	-0.09	193.000	-1.09
12	188.688	-0.13	193.100	-1.10
13	188.786	-0.16	193.200	-1.10
14	188.883	-0.20	193.300	-1.11
15	188.981	-0.23	193.400	-1.11
16	189.079	-0.27	193.500	-1.12



Upstream power levels

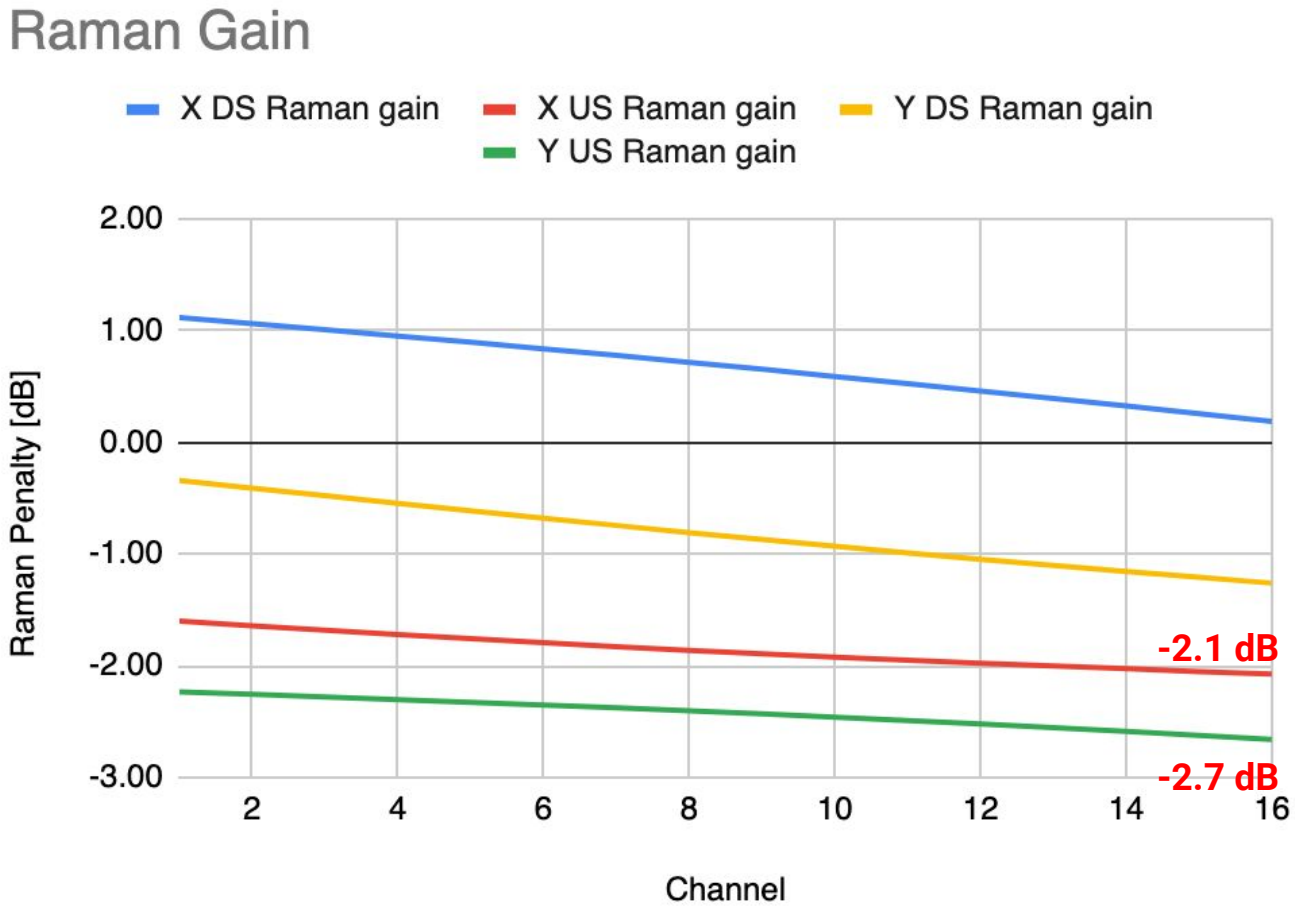


Location	US/WL [dBm]	US total [dBm]
A	-19.5	
B	-14	0
C	-37	-25
D	-42	-26
E	-0.1	

- 1.7 dBm ONT launch power is required at 8.5-dB ER
- DS launch power required is 9.1 dBm per wavelength channel to account of Raman gain of the DS channels

Raman effect: 2 generations

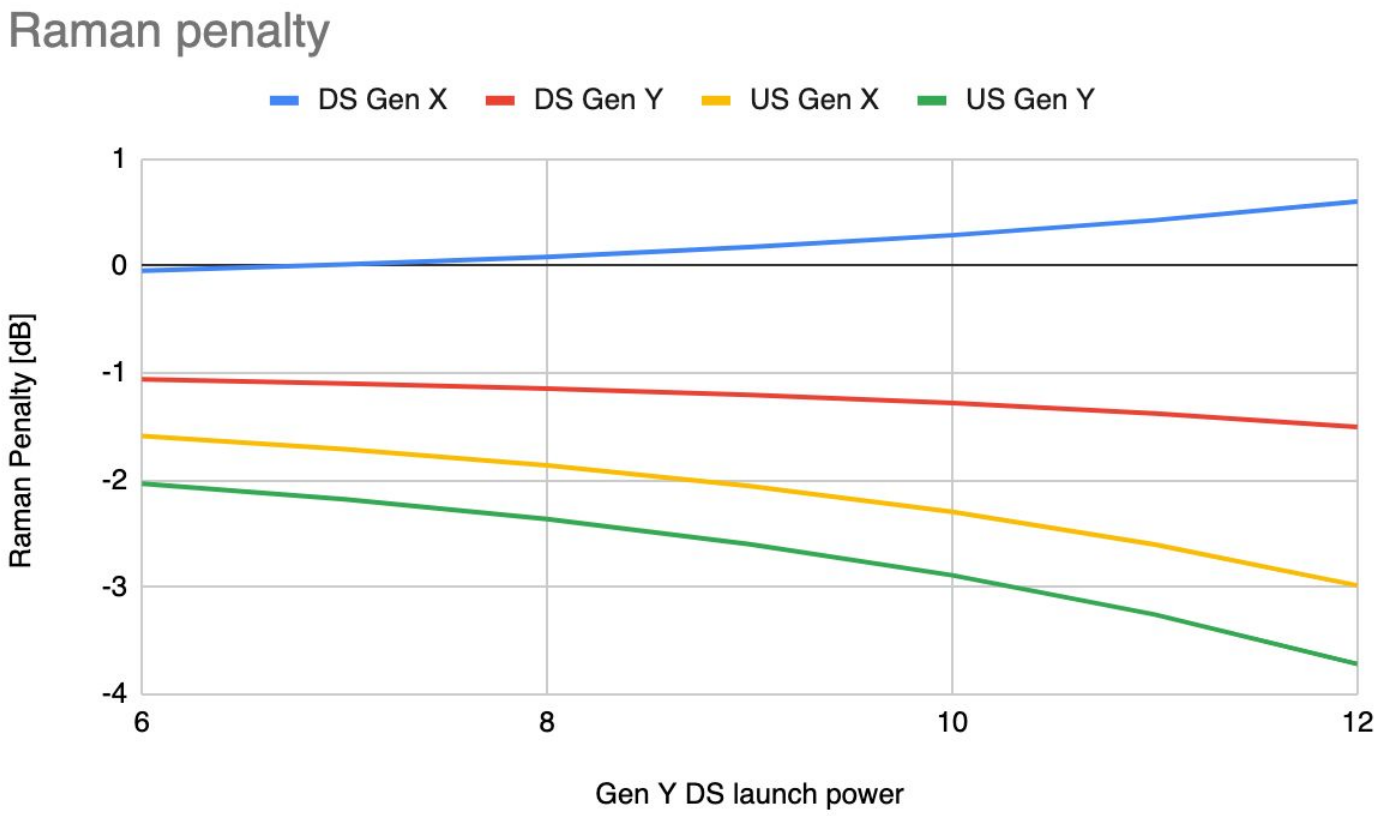
- Using 9.1 dBm per DS channel launch into the fiber, and 50 km of fiber
- Penalty in Gen X US increases to 2.1 dB.
  - This assumes no increase in DS power for the next generation
  - Penalty for new generation US is 2.7 dB
- This requires budgeting an extra 1.0 dB for the Gen X US, increasing the reference 8.5 dB ER power to 2.7 dBm
- 1.5 dB penalty in Gen Y DS will likely need to be compensated for with higher power
- Gen X == FSR Set 1
- Gen Y == FSR Set 2



Raman effect: 2 generations

- Gen X DS power = 9.1 dBm
- Gen Y DS power swept
- Gen Y DS around 1 dB higher than Gen X DS (without gen Y)
  - assume 10 dBm DS power for gen Y
- Penalties at 10 dBm Gen Y DS power:
  - Gen X US (total from Raman): 2.3 dB
  - Gen X US (from to Gen X only): 1.2 dB
  - Gen Y US: 2.8 dB

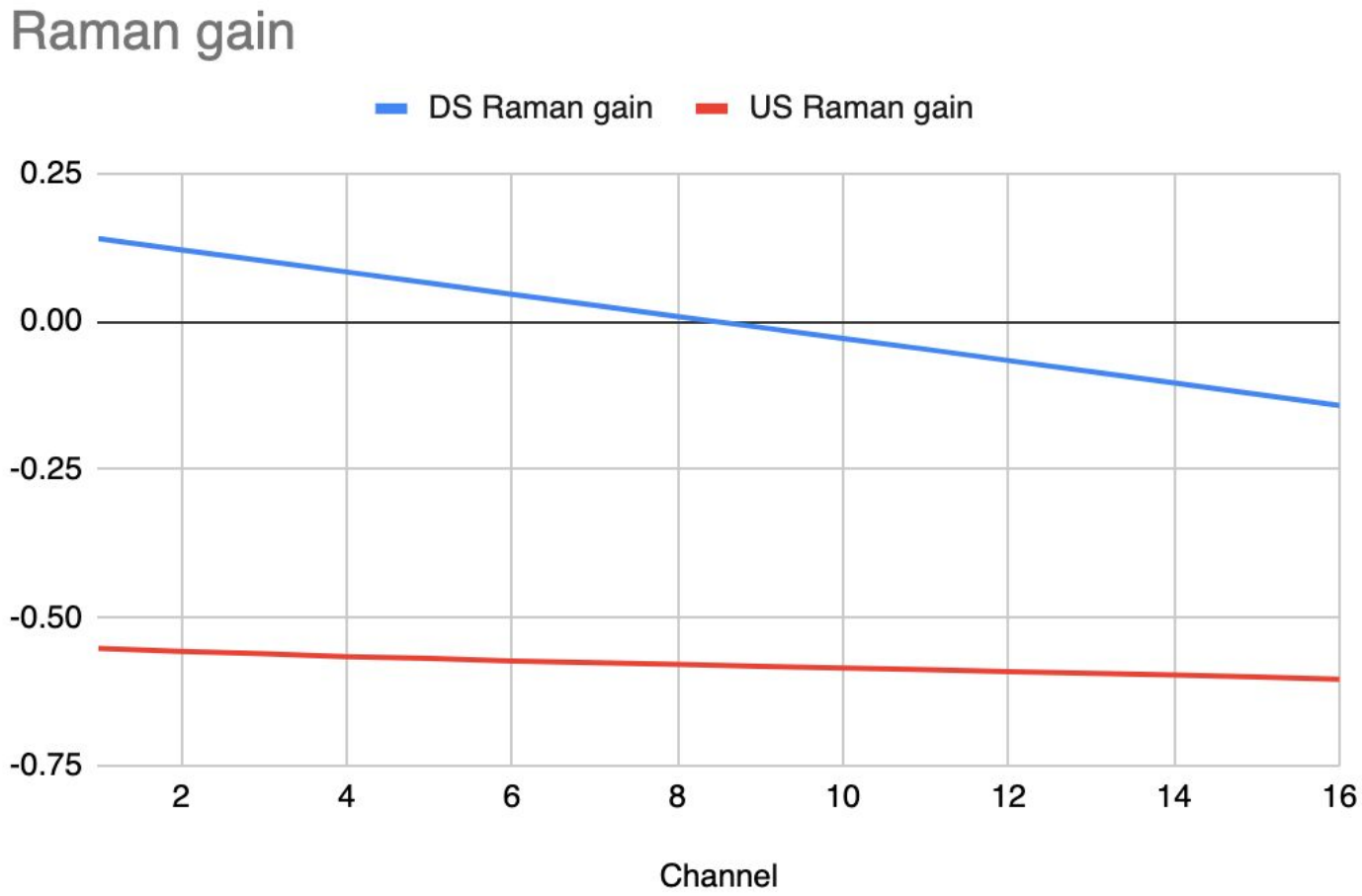
- Gen X US power required 1.1 dBm



Raman effect: 6.7 dBm DS launch power

- 40 km of fiber used
- Raman penalty: US 0.6 dB; DS 0.14 dB

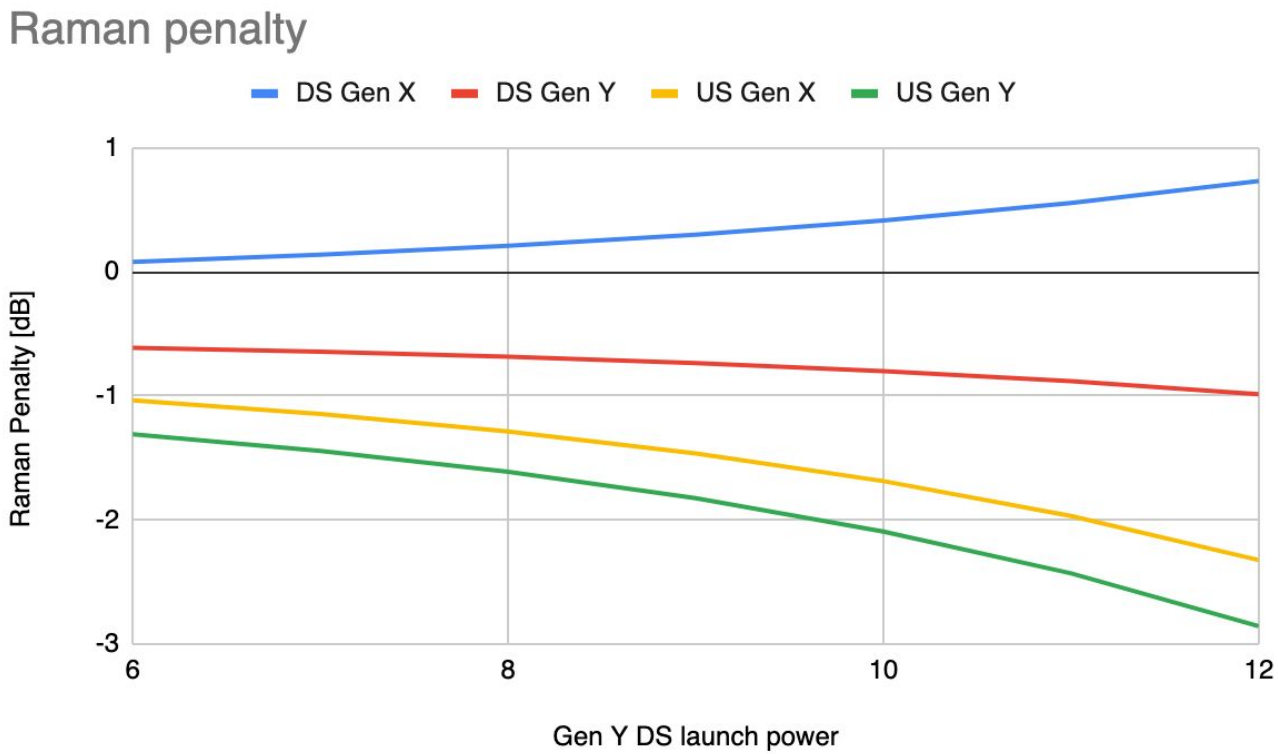
	Gen X			
	Downstream		Upstream	
Channel	Frequency	Raman gain	Frequency	Raman gain
1	187.613	0.14	192.000	-0.55
2	187.711	0.12	192.100	-0.56
3	187.809	0.10	192.200	-0.56
4	187.906	0.08	192.300	-0.57
5	188.004	0.06	192.400	-0.57
6	188.102	0.05	192.500	-0.57
7	188.200	0.03	192.600	-0.58
8	188.297	0.01	192.700	-0.58
9	188.395	-0.01	192.800	-0.58
10	188.493	-0.03	192.900	-0.59
11	188.590	-0.05	193.000	-0.59
12	188.688	-0.07	193.100	-0.59
13	188.786	-0.09	193.200	-0.59
14	188.883	-0.10	193.300	-0.60
15	188.981	-0.12	193.400	-0.60
16	189.079	-0.14	193.500	-0.60



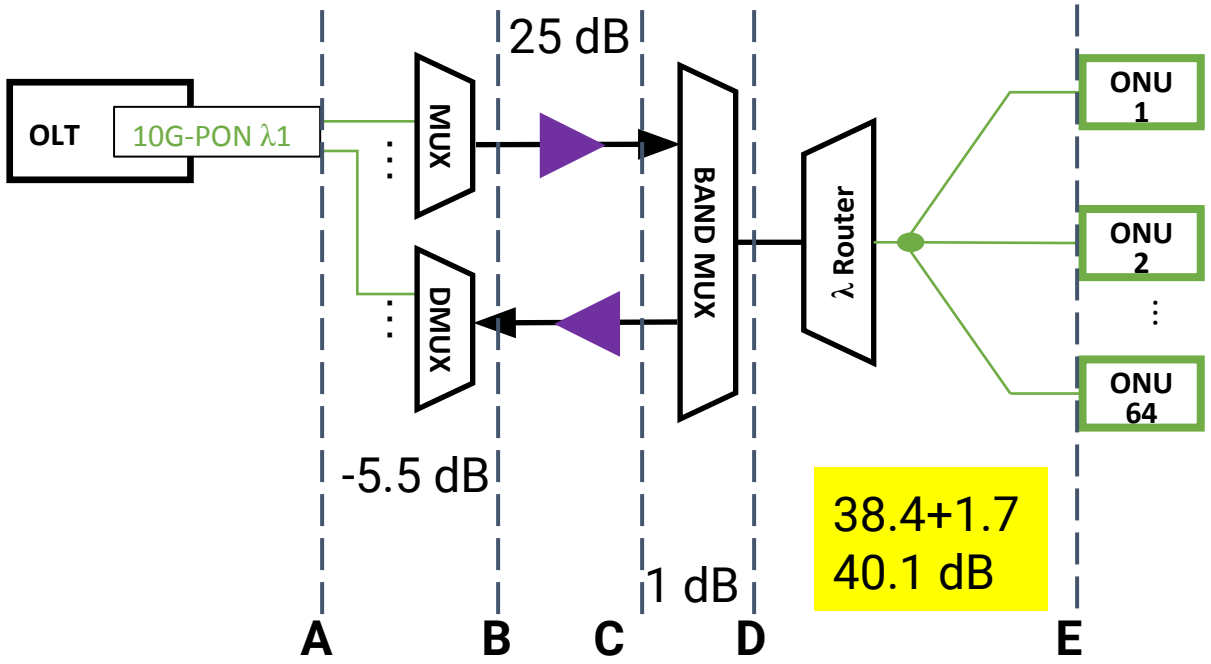
Raman effect: 2 generations

- Gen X DS power = 6.7 dBm
- Gen Y DS power swept
- 40 km of fiber simulated

- Penalty on DS Gen Y is reduced to 1 dB, allowing for lower Gen Y DS power
- US Raman penalties at 9 dBm Gen Y DS power
  - Gen X US (total from Raman): 1.7 dB
  - Gen Y US: 2.1 dB
- 2.4 dB power reduction is ~10-km reach reduction



Upstream power levels

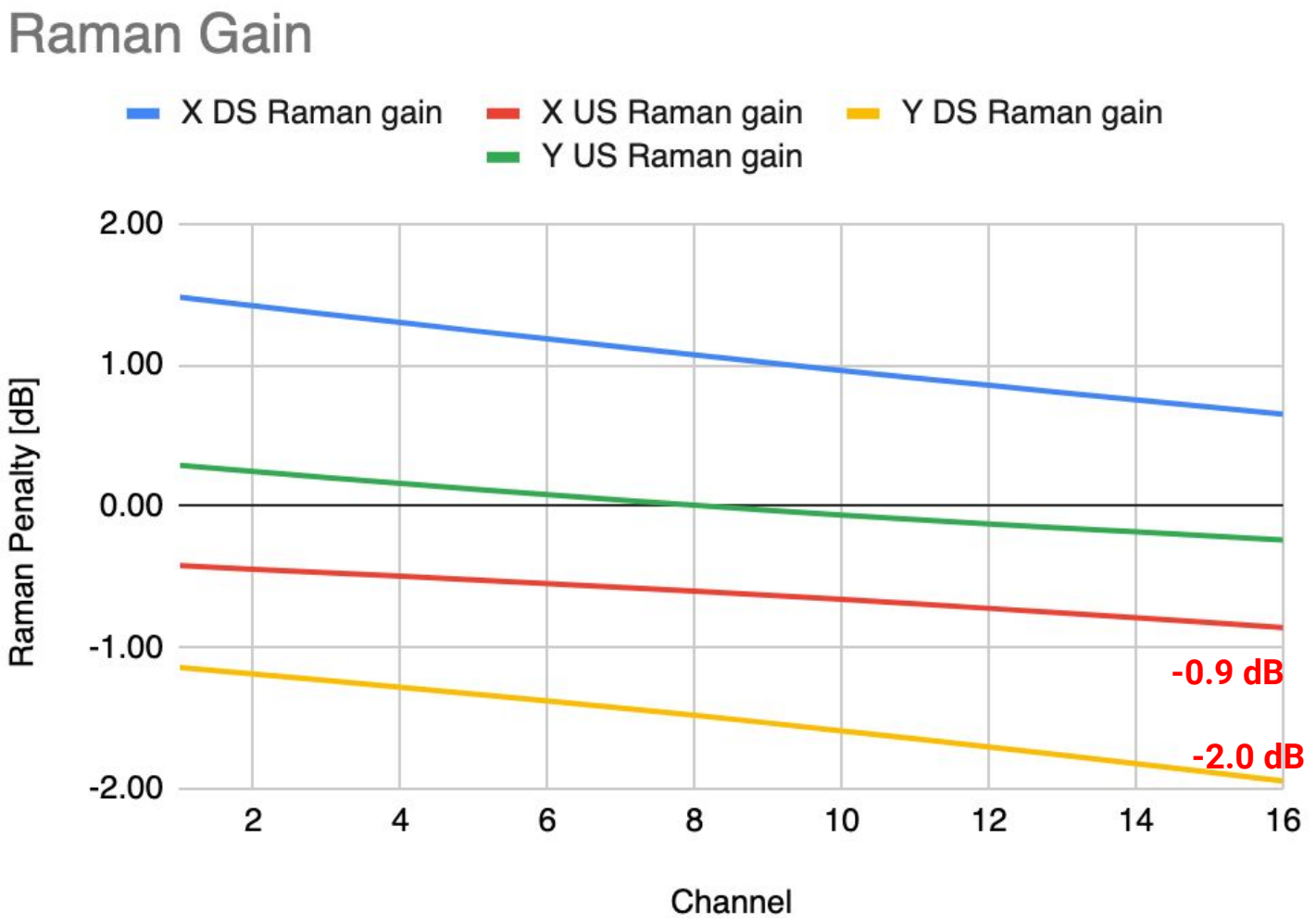


Location	US/WL [dBm]	US total [dBm]
A	-19.5	
B	-14	0
C	-37	-25
D	-42	-26
E	-1.9	

- -1.9 dBm ONT launch power is required at 8.5-dB ER
- DS launch power required is 6.6 dBm per wavelength channel to account of Raman gain of the DS channels
  - (Raman penalty is 0.1-0.2 dB lower than the 9.1 dBm launch power case)

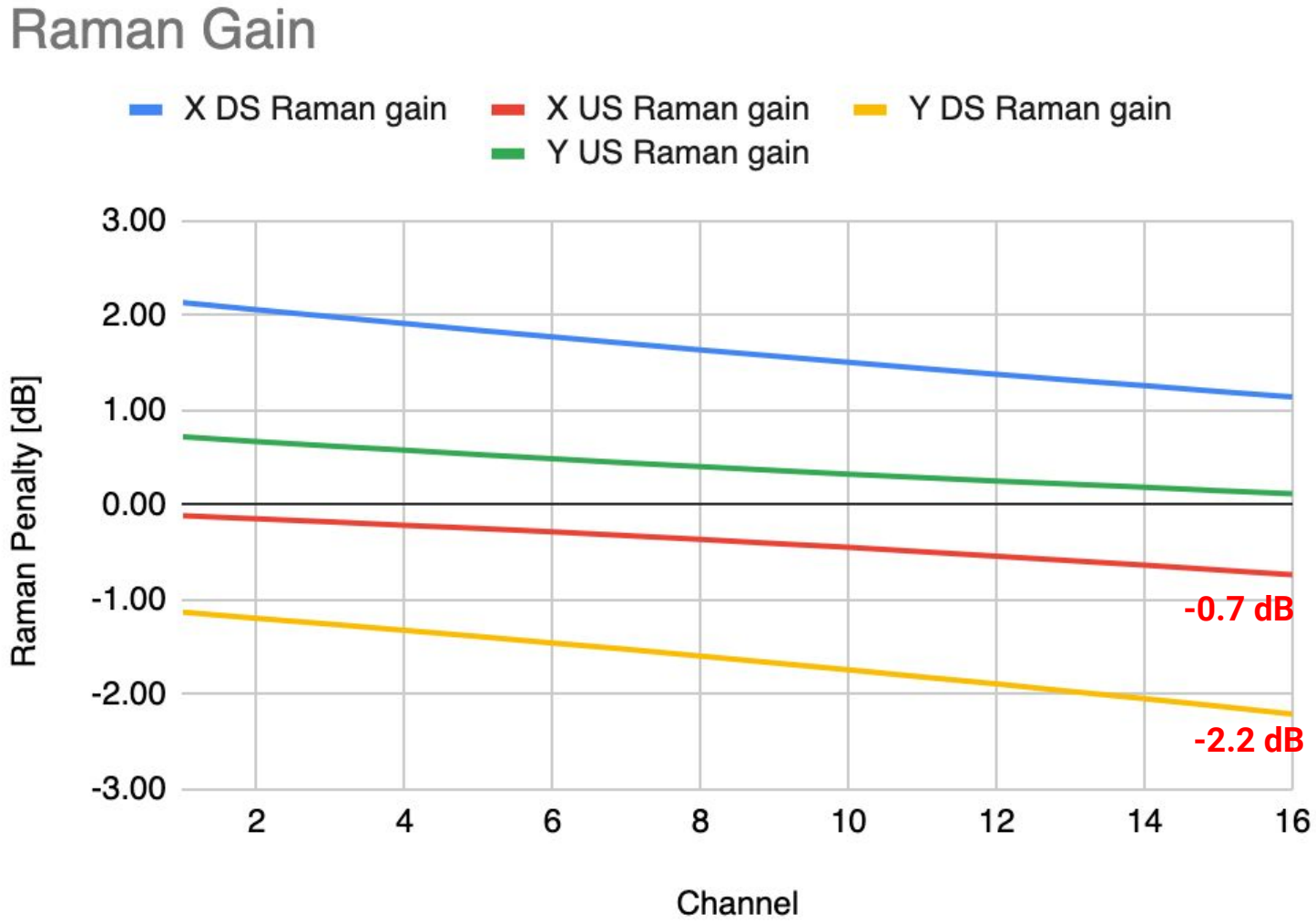
Raman effect: 2 generations (Gen Y flipped)

- Flipping the US/DS allocation for Gen Y. DS power at 9.1 dBm for both gens
- 2.0 dB Raman penalty on Gen Y DS
  - This will likely result in a higher required DS launch power
- 0.9 dB Raman penalty on Gen X US.
  - This is **lower** than **without** Gen Y signals
  - The shorter wavelength Gen Y DS signals are providing gain to the Gen X US signals, as well as the Gen X DS signals



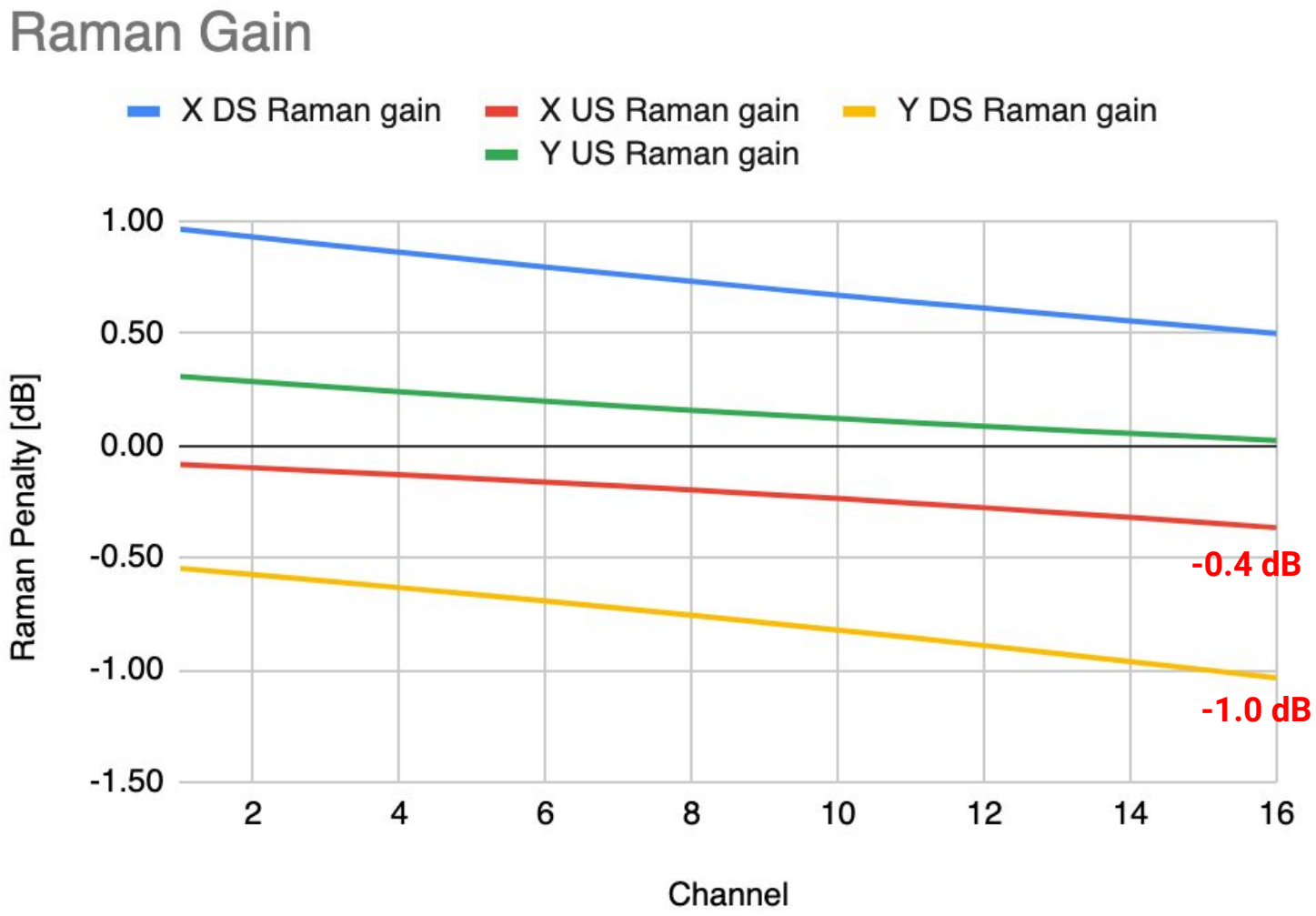
Raman effect: 2 generations (Gen Y flipped)

- Gen X DS at 9.1 dBm/wave
- Gen Y DS at 11.0 dBm/wave
  - This is the shortest wavelength.
  - More power -> more penalty on itself, gain for other bands.
- 2.2 dB Raman penalty on Gen Y DS.
  - 11.0 dBm needed assuming same ONT sensitivity as gen X
- 0.7 dB Raman penalty on Gen X US.
  - This is **lower** than **without** Gen Y signals
  - Same US launch power would be required for single generation: -0.1 dBm



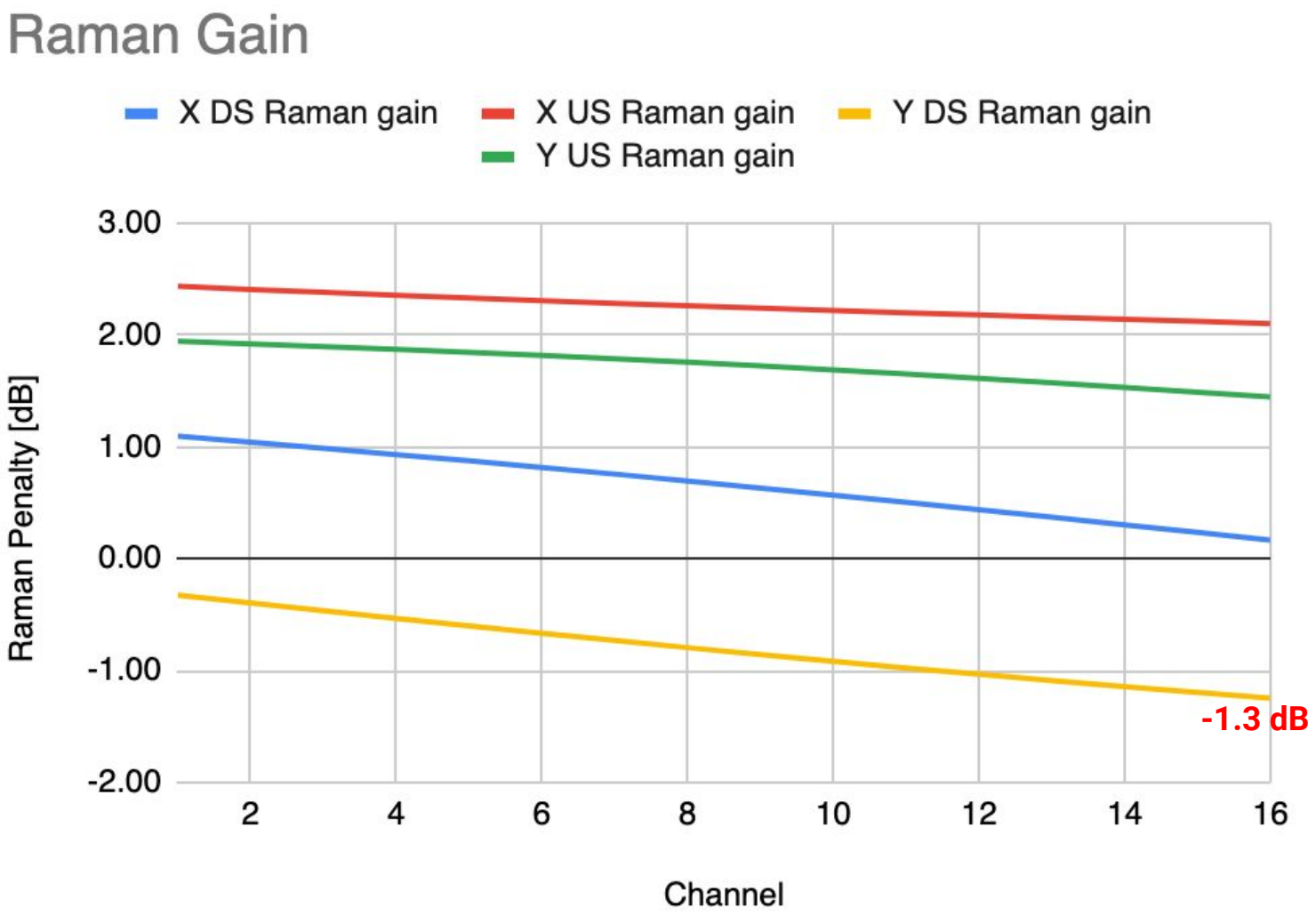
Raman effect: 2 generations (Gen Y flipped)

- Gen X DS at 6.7 dBm/wave
- Gen Y DS at 7.4 dBm/wave
  - 1 dB penalty at 7.4 dBm. 0.7 dB higher than Gen X DS so adjusted up by 0.7 dB
- 0.4 dB Raman penalty on Gen X US.
  - This is **lower** than **without** Gen Y signals
  - Reducing Raman penalty to 0.6 dB produces 39.0 dB link budget and -3 dBm US launch power



Raman effect: 2 generations (Gen X/Y flipped)

- Run both gens with:
  - DS: C-band
  - US: L-band
  - DS @ 9.1 dBm for both
- Only band that experiences a power penalty is the DS GenY band
  - Compensation with higher launch powers does results in gain in other bands
- No Raman gain US power is 0.6 dBm
- Need L-band lasers for ONUs of next generation systems
  - L-band is becoming more common but supply is still much lower than C-band



Summary (1)

- Summarize powers
- US powers referenced as the 8.5 dB ER

Gen X DS/US	Gen Y DS/US	Reach [km]	DS power [dBm]	10G US power [dBm]	2.5G US power [dBm]
L/C	L/C	50	9.1	1.1	-3.4
L/C	C/L	50	9.1	-0.1	-4.6
C/L	C/L	50	9.1	-1.2	-5.7
L/C	L/C	40	6.6	-1.9	-6.4
L/C	C/L	40	6.6	-3	-7.5

Summary (2)

- US powers scaled assuming the more realistic 6.0 dB ER
- 3.4 dBm US power is still challenging
  - There is still no allowance for system margin right now
- Possible ways forward are
  - flip the C/L bands for Gen Y (FSR Set 2)
  - reduce the target link budget
  - or both

Gen X DS/US	Gen Y DS/US	Reach [km]	DS power [dBm]	10G US power [dBm]	2.5G US power [dBm]
L/C	L/C	50	9.1	3.4	-1.1
L/C	C/L	50	9.1	2.2	-2.3
C/L	C/L	50	9.1	1.1	-3.4
L/C	L/C	40	6.6	0.4	-4.1
L/C	C/L	40	6.6	-0.7	-5.2

Summary (3)

- Raman penalty for operation of only Gen X can be absorbed by using the 802.3ca FEC, especially in the signal-ASE limited US
- Keeping the US in C-band and DS in L-band for Gen Y further increases Raman penalties.
  - To ensure upgradability, we will have to guess a likely Gen Y DS power and allocate a margin for future Raman penalties accordingly
  - Will need to guess the likely power of the future DS system as the DS power will adversely affect the US band
- Raman penalties can be mostly avoided if we place the high launch power DS signals in the C-band and the lower power US signals in the L-band
  - This has negative impacts on component supply as there are fewer L-band laser suppliers for the high volume ONUs
- A potential way forward is flipping the US/DS band allocation for the future Gen Y systems (i.e., FSR Set 2)

Thank you