Wavelength "Plan D"
O-band upstream, C-band downstream

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Wavelength plan inventory

Wavelength Plan Inventory as of 7/27/16

	A	B	C	D	E	F	G
ds0	O	O	O	S/C/L	O	O	
ds1	O	O	S/C/L	S/C/L	S/C/L	L	
ds2	O	O	S/C/L	S/C/L	S/C/L	L	
ds3	O	O	S/C/L	S/C/L	S/C/L	L	
ds4	none	O or none	S/C/L or none	none	none	L	
us0	O	O	O	O	O	O	
us1	O	O	S/C/L	O	O	C	
us2	O	O	S/C/L	O	O	C	
us3	O	O	S/C/L	O	O	C	
us4	none	O or none	S/C/L or none	none	none	C	
author	JJ+FE+YG #1	EH #1	EH#2	JJ	DL	ED	

This contribution

kramer_3ca_5_0716.pdf

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Pros and Cons of fiber transmission bands

	O-Band	S-Band	C-Band	L-Band
PRO	• Lowest fiber dispersion - no DCM for 20km PMDs* • Existing cooled 100G-LR4 lasers and EMLs • Existing high power uncooled 25G lasers	• Low fiber insertion loss • Moderate fiber dispersion - no DCM for 10km PMDs • Open fiber spectrum - no coexistence objectives	• Low fiber insertion loss • Moderate fiber dispersion - no DCM for 10km PMDs • High power booster EDFAs • Low-NF preamp EDFAs	• Low fiber insertion loss • High power booster EDFAs • Low-NF preamp EDFAs
CON	• High fiber insertion loss • Limited fiber spectrum – 10G WDM coexistence and zero dispersion zone • SOA preamp has high NF • SOA booster has limited Psat	• DCM required for 20km PMDs • No existing 25G sources • SOA preamp has high NF • SOA booster has limited Psat	• DCM required for 20km PMDs • 10G WDM coexistence prevents use of 1560-1600nm	• High fiber dispersion - DCM required for all PMDs • Limited fiber spectrum – 10G WDM coexistence and OTDR band • Lower laser efficiency

* Assuming NRZ modulation format.

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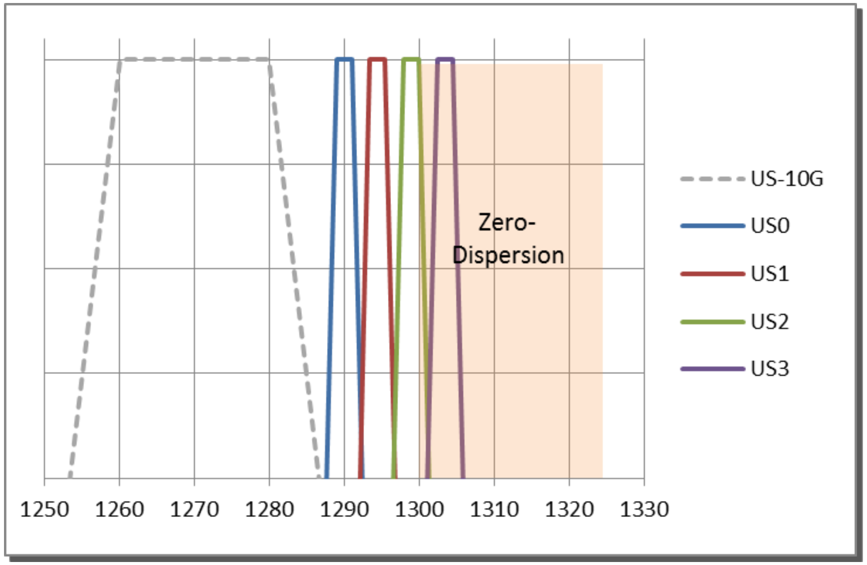
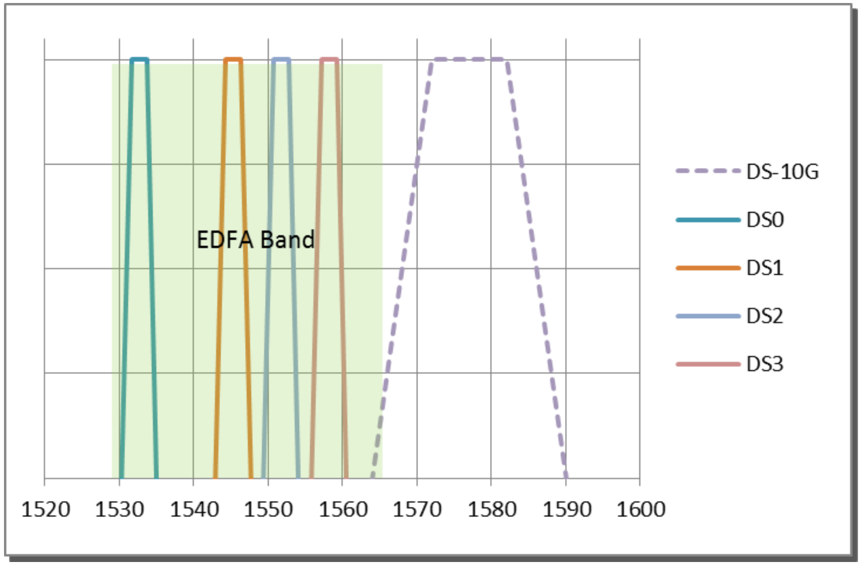
Wavelength Plan D advantages

- The wide US-DS gap in EPON and 10G-EPON is a key enabler of low-cost focused-beam BOSA construction. NG-EPON plans with all channels in O-band suffer from much narrower US-DS gap, increasing BOSA cost by ~1.3X not including 25G parts (liu_3ca_2_0516)
  - Diplexers must be implemented with collimated beam optics
  - Order of magnitude tighter filter and assembly tolerances
  - Even entry-level 25/10G and 25/25G ONUs must pay this price
  - Plan D retains the proven low-cost diplexer technology enabled by splitting US and DS into separate bands.
- Using O-band for US has the advantages of low-dispersion 25Gb/s NRZ transmission using high-power cooled 25G DMLs for low-cost ONUs.
  - Plan D retains the proven advantage of low-cost, high-power DML-based ONUs.
- The advantages of using O-band for OLT TX are low dispersion and the existence of 25G EMLs for 100G-LR4 optics, but these are small.
  - Nearly all spans are <10km (migeulez_3ca_1a_0516) so the low dispersion advantage only applies to a small fraction of networks.
  - 10km NRZ or EDB transmission in C-band is possible without dispersion compensating fiber (DCF) – see harstead_3ca_3_0916.
  - High-power 10G EMLs exist for C/L-band and can be easily adapted for 25G.
- Other advantages of C-band include reduced fiber loss and the availability of high-power booster EDFAs to enable relaxed ONU receiver specs.

Proposed Wavelength Plan D





	Center Freq (THz)	Center WL (nm)
US0	232.40	1289.98
US1	231.60	1294.44
US2	230.80	1298.93
US3	230.00	1303.45
DS0	195.600	1532.681
DS1	194.000	1545.322
DS2	193.200	1551.721
DS3	192.400	1558.173

Key features of Plan D

- Same US wavelength plan as Plan A: O$^-$ Band, 800GHz grid, cooled DML TX, no coherent FWM impairment.
- WDM coexistence with 10G-EPON US and DS. TDM US possible for 25G OLT
- DS lanes on 800GHz grid with 1.6THz gap between DS0 and DS1 for relaxed 25G ONU blocking filter (WBF).
- US-DS gap > 200nm enables low-cost focused-beam 45º diplexers
- DS channels in EDFA amplifier band

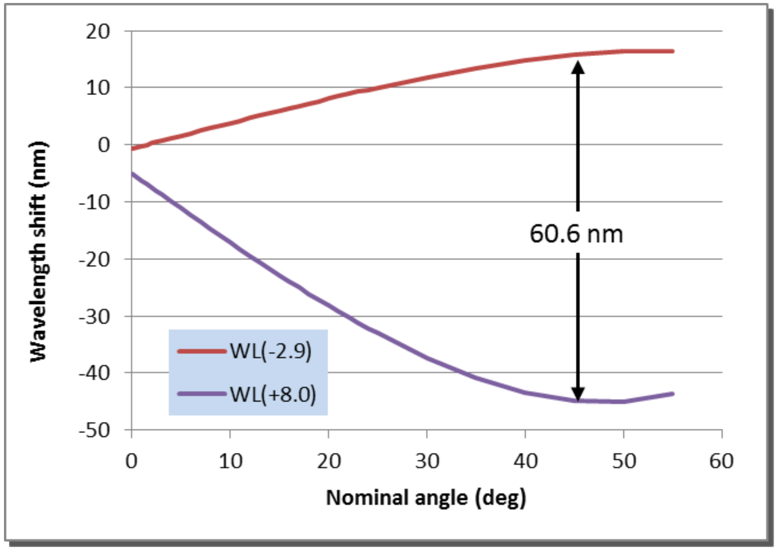
Thin film diplexer filters

- The wavelength shift of an interference filter as a function of angle is given by:

$$\lambda(\theta) = \lambda_0 \sqrt{1 - \left(\frac{\sin\theta}{n_2}\right)^2}$$

- A diverging beam contains all angles between 0 and ~asin(NA).
  - The actual filter shape is an integral over all angles weighted by the power in the beam (~Gaussian)
- Typical EPON TO-can has NA = 0.14 (for SM fiber) for the RX and NA ~ 0.05 for the TX beam.
  - RX NA=0.14 gives ±8.0º beam angle and ± 44.8nm shift on reflection.
  - TX NA=0.05 gives ±2.9º beam angle and ±15.8nm shift on transmission.
  - Approximate minimum US-DS gap is the sum of the two cases, 60.6nm.
  - Assembly tolerance of ±0.5º results in additional ±1.4nm.

Wavelength shifts for NA=0.14 and 0.05



- This makes the use of focusing beam optics difficult for narrow US-DS guardband.
  - For conservative design using typical TOSA NA, > ~60nm gap is required.
  - Smaller gaps (~40nm?) may be possible with lower NA TOSA, longer BOSA, tighter tolerances, increased coupling loss and higher cost relative to EPON.
- Good topic for future contribution.

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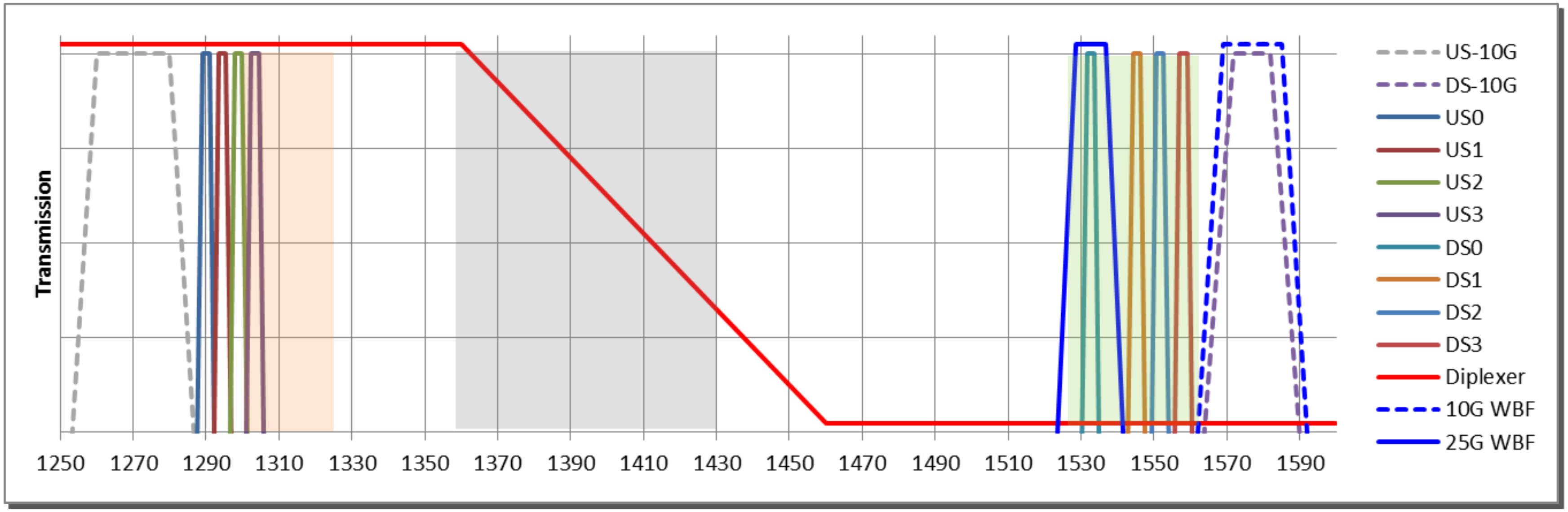
ONU filters



Plan D enables low-cost focused-beam 25/10G and 25/25G ONU BOSAs

Diplexer

- Standard 1/10G-EPON 45º diplexer filter
- Compatible with low-cost focusing beam optics
- Same for all ONU generations

25G Blocking filter

- Wide 1.6THz spacing between DS0 and DS1
- For ±1nm laser tolerance, guardband > 10nm.
- Compatible with low-cost focusing beam optics (liu_3ca_3_0716)

10G Blocking filter

- G.987.2 defines a 15nm wide guardband for XG-PON1: 1560-1575nm
- DS3 is below 1560nm
- Compatible with low-cost focusing beam optics (liu_3ca_3_0716)

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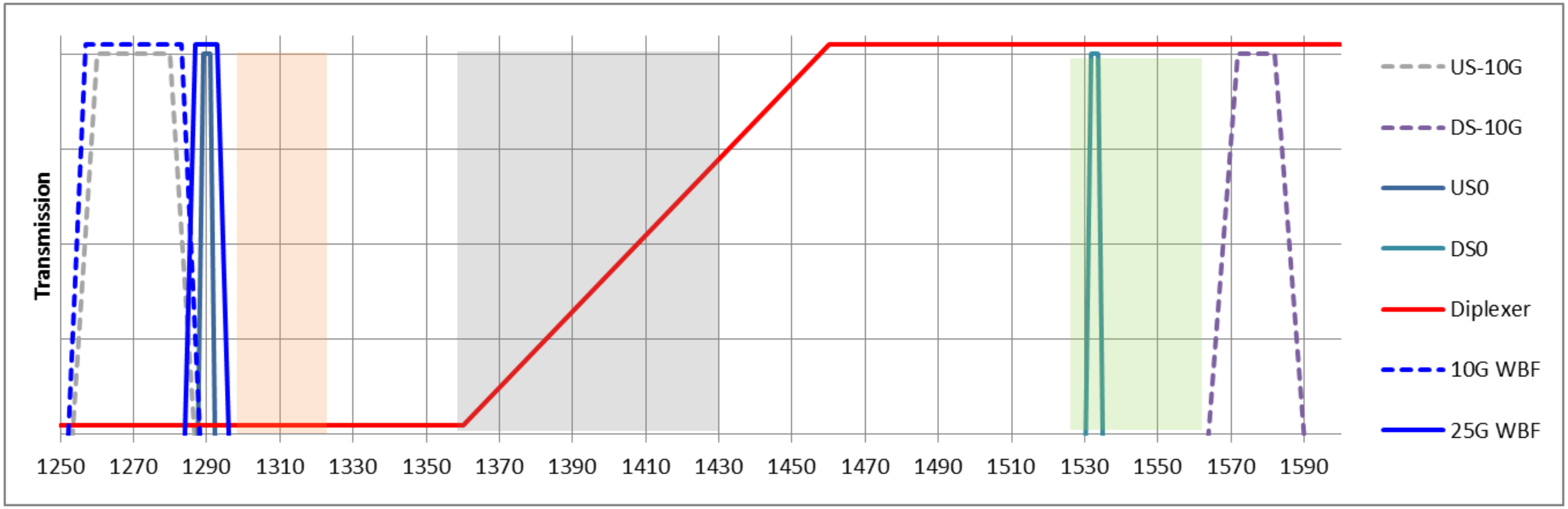
OLT filters



Plan D enables choice of WDM or TDM coexistence for 25G OLT

Diplexer

- Standard 1/10G-EPON 45º diplexer filter
- Compatible with low-cost focusing beam optics
- Same for all ONU generations

10/25G Blocking filters

- Blocking filters are needed for WDM coexistence.
- Guardband between 1270± 10nm and US0±1nm is 9nm
- Can use focusing beam optics with longer focal length ROSA at slightly higher cost

10/25G TDM option

- 25G OLT can optionally be configured for TDM coexistence
- Simpler TRISA with one ROSA, no WBF's
- Requires 10/25G dual-rate burst-mode receiver

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Transmitter optical power capability

	Cooled EML			Cooled DML			Uncooled DML			Unit
Number of wavelengths	**1**	**2**	**4**	**1**	**2**	**4**	**1**	**2**	**4**	
Extinction ratio	**8**	**8**	**8**	**6**	**6**	**6**	**5**	**5**	**5**	dB
AVP, single w/ diplexer	5.3	5.3	5.3	8.2	8.2	8.2	6.2	6.2	6.2	dBm
OMA, single w/ diplexer	6.92	6.92	6.92	8.98	8.98	8.98	6.37	6.37	6.37	dBm
Mux loss	0.0	1.0	2.5	0.0	1.0	2.5	0.0	1.0	2.5	dB
AVP, BOSA	5.30	4.30	2.80	8.20	7.20	5.70	6.20	5.20	3.70	dBm
OMA, BOSA	6.92	5.92	4.42	8.98	7.98	6.48	6.37	5.37	3.87	dBm

AVPmin (dBm)	number	mean	σ
EML	6	4.5	0.8
cooled DML	8	7.0	1.2
uncooled DML	6	4.7	1.5
ER (dB)			
EML	6	7.5	0.8
cooled DML	8	5.3	0.9
uncooled DML	6	4.7	1.0

When a range was given (maximum 1 dB), the higher value was chosen.

harstead_3ca_1a_0716

- Use vendor TX data of harstead_3ca_1a_0716
  - Vendors were asked to estimate commercial values for output power in a single-channel BOSA configuration including diplexer loss and manufacturing margin
  - Assume mean+1σ level as a view of future capability
  - Assume similar capability in O-band and C-band
- US channels will use cooled DML with ER = 6dB
  - 25G BOSA average output power = 8.2 dBm
  - Assume 100G mux loss = 2.5dB
- DS channels will use cooled EML with ER = 8dB
  - 25G BOSA average output power = 5.3dBm
  - Assume 100G mux loss = 2.5dB

Receiver sensitivity capability

	EML Transmitter, ER=8dB			DML Transmitter, ER=6dB			Units
Number of wavelengths	**1**	**2**	**4**	**1**	**2**	**4**	
TX extinction ratio	**8**	**8**	**8**	**6**	**6**	**6**	dB
Baseline ROSA sensitivity	-28	-28	-28	-28	-28	-28	dBm
Baseline ER	9	9	9	9	9	9	dB
Baseline OMA	-26.09	-26.09	-26.09	-26.09	-26.09	-26.09	dBm
APD noise penalty	0.00	0.00	0.00	1.00	1.00	1.00	dB
ROSA sensitivity	-28.00	-28.00	-28.00	-27.00	-27.00	-27.00	dBm
ROSA OMA @ TX ER	-26.38	-26.38	-26.38	-26.22	-26.22	-26.22	dBm
Diplexer loss	1.0	1.0	1.0	1.0	1.0	1.0	dB
Blocking filter loss	0.5	0.0	0.0	0.5	0.0	0.0	dB
Demux loss	0.0	1.0	1.5	0.0	1.0	1.5	dB
Total BOSA insertion loss	1.5	2.0	2.5	1.5	2.0	2.5	dB
Additional FEC gain	1.0	1.0	1.0	1.0	1.0	1.0	dB
Manufacturing margin	2.0	2.0	2.0	2.0	2.0	2.0	dB
BOSA sensitivity	-25.50	-25.00	-24.50	-24.50	-24.00	-23.50	dBm
BOSA OMA	-23.88	-23.38	-22.88	-23.72	-23.22	-22.72	dBm

- Assume 25G APD has typical AVP sensitivity equal to -28dBm at BER=10^{-3} in a simple ROSA package (without diplexer or blocking filter) with TX ER=9dB. Value to be refined as more data becomes available.
- Assume manufacturing margin = 2dB and additional +1dB FEC gain over RS(255,223).
- Combined diplexer and demux loss = 2.5dB for 100G RX
- Assume 1dB excess APD noise penalty for DML with low ER.
  - Note tanaka_3ca_1_0716 showed 2dB OMA penalty between DML ER = 7dB and EML ER=10dB which is larger than expected. It could be due to relative APD noise, TIA noise, eye quality or other factors. More study is needed.

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Power budget margin analysis

- Using the estimated transmitter powers and receiver sensitivities, we calculate the power margin for each PMD for the cases of 25G OLT/ONU and 100G OLT/ONU.
- An illustrative PMD with 25dB loss and 10km max span, “PR30S,” has been added per miguelez_3ca_1a_0916.
- Spans >10km will need DCF or use EDB line code.
  - In this analysis, a DCF loss of 1.5dB is included for 20km PMDs for illustration of the effect of DCF on the power budget.
- TDP assumptions for 10km span (or equivalent with DCF):
  - O-minus band DML < 1.5dB (tanaka_3ca_1_0716).
  - C-band EML < 2dB (umeda_3ca_1_0316).
- This power budget is only a straw-man analysis to illustrate the particular features of Plan D.
  - Most of the power challenges are common to all wavelength plans.
  - Additional analyses of technical and economic feasibility are needed once the Task Force has made a wavelength plan selection.

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Power margin analysis – 25G ONU and OLT

Parameter	PR10 DOWN	PR10 UP	PR20 DOWN	PR20 UP	PR30S DOWN	PR30S UP	PR30 DOWN	PR30 UP	PR40 DOWN	PR40 UP	Unit
Distance	10	10	20	20	10	10	20	20	20	20	km
Split ratio	16	16	16	16	32	32	32	32	64	64	
Insertion loss, min	5	5	10	10	11	11	15	15	18	18	dB
Insertion loss, max	20	20	24	24	25	25	29	29	33	33	dB
Transmitter - 25G	Cooled EML	Cooled DML	Cooled EML	Cooled DML	Cooled EML	Cooled DML	Cooled EML	Cooled DML	Cooled EML	Cooled DML	
ER, min	8	6	8	6	8	6	8	6	8	6	dB
AVP, min	5.30	8.20	5.30	8.20	5.30	8.20	5.30	8.20	5.30	8.20	dBm
OMA, min	6.92	8.98	6.92	8.98	6.92	8.98	6.92	8.98	6.92	8.98	dBm
DCF loss	0.0	0.0	1.5	0.0	0.0	0.0	1.5	0.0	1.5	0.0	dB
Rx Stressed OMA, min	-13.08	-11.02	-18.58	-15.02	-18.08	-16.02	-23.58	-20.02	-27.58	-24.02	dBm
TDP, max	2	1.5	2	1.5	2	1.5	2	1.5	2	1.5	dB
Rx OMA, min	-15.08	-12.52	-20.58	-16.52	-20.08	-17.52	-25.58	-21.52	-29.58	-25.52	dBm
Receiver - 25G											
AVP Sensitivity, min	-25.50	-24.50	-25.50	-24.50	-25.50	-24.50	-25.50	-24.50	-25.50	-24.50	dBm
OMA Sensitivity, min	-23.88	-23.72	-23.88	-23.72	-23.88	-23.72	-23.88	-23.72	-23.88	-23.72	dBm
Margin: 25G - 25G	8.80	11.20	3.30	7.20	3.80	6.20	-1.70	2.20	-5.70	-1.80	dB

> +1dB
0 ± 1dB
< -1dB

- PR10, PR20 and PR30S have positive margin – no amplification required.
- PR30 DS margin is negative so will require booster amplification such as EML with integrated SOA.
- PR40 needs amplification for DS and US.

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Power margin analysis – 100G ONU and OLT

Parameter	PR10 DOWN	PR10 UP	PR20 DOWN	PR20 UP	PR30S DOWN	PR30S UP	PR30 DOWN	PR30 UP	PR40 DOWN	PR40 UP	Unit
Distance	10	10	20	20	10	10	20	20	20	20	km
Split ratio	16	16	16	16	32	32	32	32	64	64	
Insertion loss, min	5	5	10	10	11	11	15	15	18	18	dB
Insertion loss, max	20	20	24	24	25	25	29	29	33	33	dB
Transmitter - 100G	Cooled EML	Cooled DML	Cooled EML	Cooled DML	Cooled EML	Cooled DML	Cooled EML	Cooled DML	Cooled EML	Cooled DML	
ER, min	8	6	8	6	8	6	8	6	8	6	dB
AVP, min	2.80	5.70	2.80	5.70	2.80	5.70	2.80	5.70	2.80	5.70	dBm
OMA, min	4.42	6.48	4.42	6.48	4.42	6.48	4.42	6.48	4.42	6.48	dBm
DCF loss	0.0	0.0	1.5	0.0	0.0	0.0	1.5	0.0	1.5	0.0	dB
Rx Stressed OMA, min	-15.58	-13.52	-21.08	-17.52	-20.58	-18.52	-26.08	-22.52	-30.08	-26.52	dBm
TDP, max	2	1.5	2	1.5	2	1.5	2	1.5	2	1.5	dB
Rx OMA, min	-17.58	-15.02	-23.08	-19.02	-22.58	-20.02	-28.08	-24.02	-32.08	-28.02	dBm
Receiver - 100G											
AVP Sensitivity, min	-24.50	-23.50	-24.50	-23.50	-24.50	-23.50	-24.50	-23.50	-24.50	-23.50	dBm
OMA Sensitivity, min	-22.88	-22.72	-22.88	-22.72	-22.88	-22.72	-22.88	-22.72	-22.88	-22.72	dBm
Margin: 100G - 100G	5.30	7.70	-0.20	3.70	0.30	2.70	-5.20	-1.30	-9.20	-5.30	dB

> +1dB
0 ± 1dB
< -1dB

- PR10 has positive margin – no amplification required.
- PR20 and PR30S have slightly negative DS margin – slightly higher TX power or a booster amplifier will be needed.
- PR30 and PR40 have negative margin DS and US – needs booster amplification for DS and pre-amplification for US.
- The need for OA for 29dB loss budget with 100G optics is independent of wavelength plan. Plan D has the advantage of being able to use EDFA for OLT booster.

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Summary of power margin analysis

Parameter	PR10 DOWN	PR10 UP	PR20 DOWN	PR20 UP	PR30S DOWN	PR30S UP	PR30 DOWN	PR30 UP	PR40 DOWN	PR40 UP	Unit
Distance	10	10	20	20	10	10	20	20	20	20	km
Split ratio	16	16	16	16	32	32	32	32	64	64	
Insertion loss, min	5	5	10	10	11	11	15	15	18	18	dB
Insertion loss, max	20	20	24	24	25	25	29	29	33	33	dB
25G OLT - 25G ONU	8.80	11.20	3.30	7.20	3.80	6.20	-1.70	2.20	-5.70	-1.80	dB
100G OLT - 100G ONU	5.30	7.70	-0.20	3.70	0.30	2.70	-5.20	-1.30	-9.20	-5.30	dB

No Amplifiers
OLT Booster Amp
OLT Booster & Preamp

- In all cases DS has less margin due to lower EML TX output power.
- Prefer all 25G-EPON systems to be without external OA.
  - For PR30 without DCF just need +0.2dB DS0 TX power, which is a reasonable stretch.
  - For PR30 >10km with DCF need EML+SOA for DS0 TX. This is only one lane, so may still be able to integrate in the module.
- Per harstead_3ca_1a_0516, 5dB mux+demux loss forces the use of amplification for 100G-EPON over PR30 PMD, regardless of wavelength plan.
- Intermediate (50G) and asymmetric bit rate deployments (100/25G) will fall somewhere between the two cases shown.
- For all NG-EPON generations and wavelength plans PR40 is not possible without OA.

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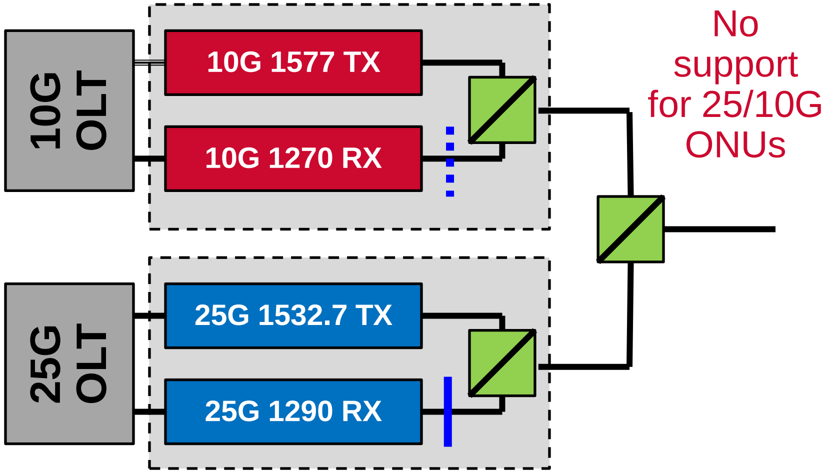
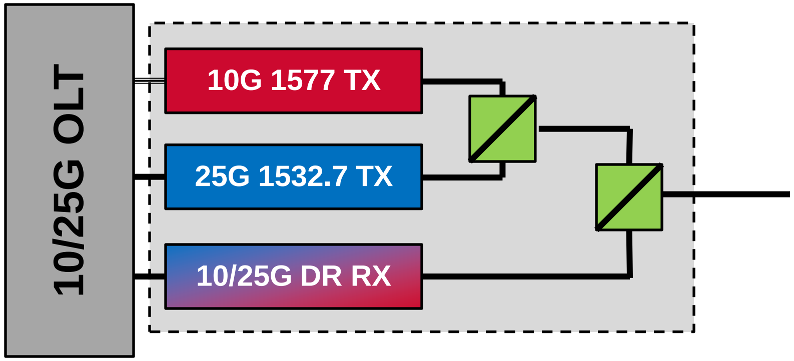
25G OLT configurations

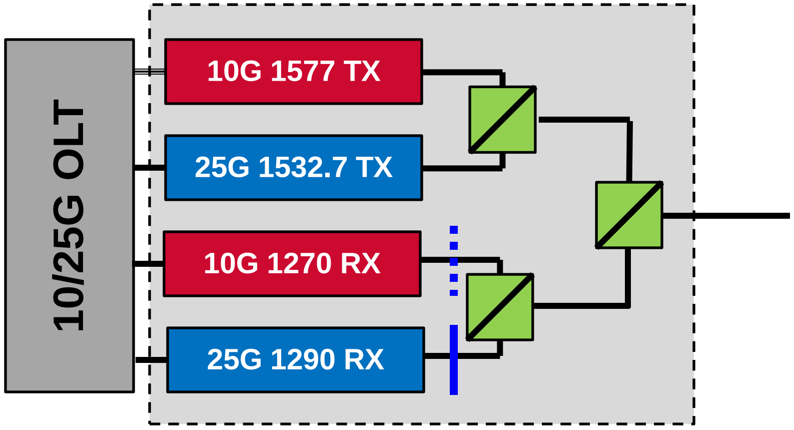
Separate 10/10G and 25/25G OLT BOSAs



TDM Coexisting 25/10G TRISA



WDM Coexisting 25/10G Quad OSA



- Three possible 25G OLT configurations depending on deployment scenario
  - Separate 10/10G and 25/25G OLTs with simple BOSA optics and external diplexer (no support for 25/10G ONUs)
  - Combined 10/25G OLT with Quad OSA optics (more complex optics, supports 25/10G ONUs)
  - Combined 10/25G OLT with TRISA optics with dual-rate RX for TDM coexistence (simpler optics, but more complex TIA).
- TDM coexistence has the advantage of support for 25/10G ONUs and simplifier TRISA optics without WBFs
  - Can't afford a sensitivity penalty for dual-rate TIA

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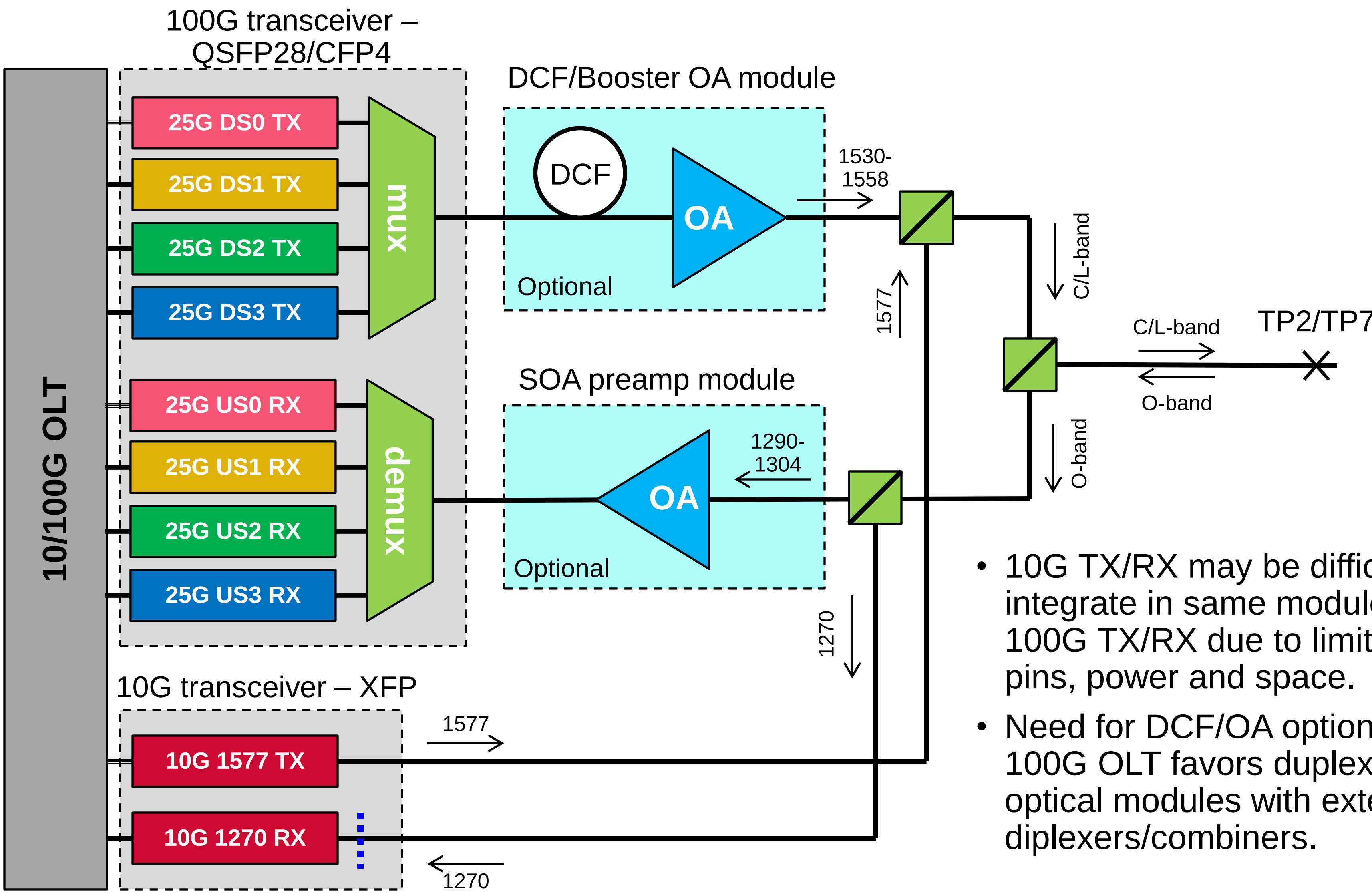
10/100G OLT with optional DCF/OAs



- 10G TX/RX may be difficult to integrate in same module as 100G TX/RX due to limits on pins, power and space.
- Need for DCF/OA option for 100G OLT favors duplex optical modules with external diplexers/combiners.

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Conclusions

- All O-band wavelength plans are attractive mainly because of the low fiber dispersion near the zero dispersion window.
  - In reality, only the lower half of O-band which allows the use of cooled DMLs for the ONU has significant value and should be retained for upstream.
  - The positive dispersion in the upper half of O-band requires higher cost EML transmitters – same as in S/C/L-band.
- Putting US and DS in O-band comes at a significant cost by forcing the use of expensive collimated beam optics in every ONU at every stage of deployment.
- By putting downstream lanes in C-band, focusing beam optics can be used enabling the same ONU diplexer cost structure as 1/10G-EPON.
  - This choice drives huge cost savings for all deployment generations and PMDs.
- The main disadvantage of using C-band, the need for DCF for spans >10km, is a much smaller overall cost since only a small fraction of networks will need it.
- The need for optical amplifiers for 100G-EPON to overcome mux/demux losses for PR30 is a constant, independent of the wavelength plan.
  - The availability of high power booster EDFAs in C-band is an additional advantage for C-band over O-band, where SOA booster output power is limited.
- Other than OA technology, all of the advantages above apply to using S-band downstream as well. This may be desirable for NG-PON2 coexistence.

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Thank You!