Annex 200B (Informative)
Super-PON black link implementation

200B.1 Example of Super-PON black link implementation

Figure 1 shows an example of Super-PON black link implementation, able to satisfy the Super-PON objectives. In this arrangement, the MUX/Amp module contains all the discrete optical components needed for Super-PON, including the mux/demux, amplifiers, and band mux. The MUX/Amp is expected to reside inside the central office (CO). Each set of wavelengths is aggregated into a simplex fiber before connecting to the optical distribution network (ODN). Packaging of the components inside the MUX/Amp module is at the discretion of the operator. They are grouped into a single module only as an example implementation that simplifies deployment. These components could also be deployed as individual components if desired.

The wavelength router and the power splitters are expected to both be a part of the outside plant, or optical distribution network. The wavelength router is expected to be a passive component that is temperature stabilized enough to operate over a sufficiently wide temperature range to be placed outside in a temperature uncontrolled environment.

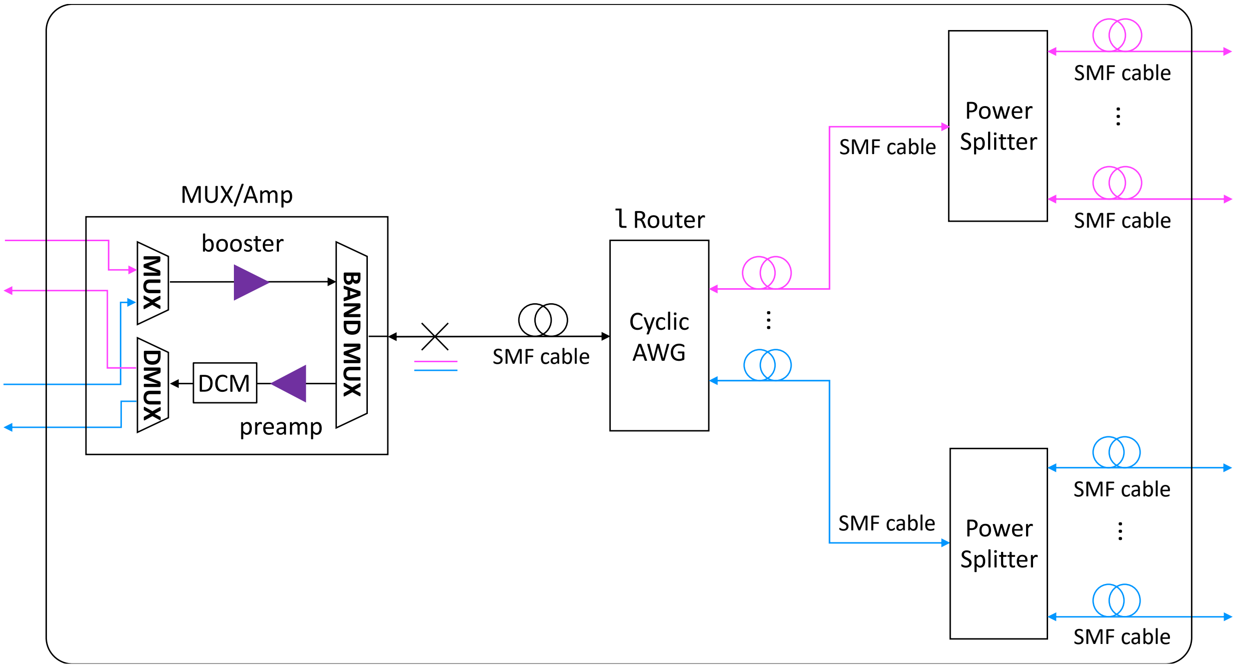

Figure 1 - Example of Black Link Implementation

Table 1 shows the expected loss of a 50 km Super-PON passive ODN link, which is defined to be from the MUX/Amp module to an ONU. 41 dB is the maximum link loss supported by the black link implementation described in this Annex.

Table 1 - Expected loss of a 50 km Super-PON access link

Component	Count	Typical loss [dB]	Worst case loss [dB]	Total loss [dB]
Fiber [km]	50	0.24	0.24	12
Connectors[1]	6	0.2	0.5	1.5
Splices[2]	17	0.05	0.2	1

CAWG[3]	1	4	4	4
1:64 Splitter[4]	1	20.5	20.5	20.5
Margin	1	2	2	2
Total				**41**

[1] Assumes 1 bad connector and 5 good ones per link.
[2] Assumes 10 inline splices and 7 for components/cables changes.
[3] Assumes low-loss design [30].
[4] Assumes premium grade optical splitters.

200B.2 MUX/Amp

The following subclauses describe an example implementation of the MUX/Amp. The characteristics of the MUX/Amp components are described below. The arrangement of these components is shown in Figure 1.

200B.2.1 MUX/DEMUX characteristics

The mux and demux are both assumed to be implemented using arranged waveguide gratings (AWG). The mux and demux functions in the MUX/Amp do not require cyclical properties so these should be designed to have a free spectral range (FSR) significantly wider than the defined frequencies of operation. Each AWG operates over one 16-channel wavelength band: the mux operates over the C-band 1; the demux operates over the L-band 1.

Some key AWG specifications enabling the construction of a conforming black link are shown in Table 2.

Table 2 - MUX/DEMUX specifications

Parameter	Conditions	Min	Max
Type of AWG	Athermal flat-top		
Number of channels		16	
Number of bands		1	
Channel spacing (MUX) [GHz]		98.8	
Operational wavelength (MUX) [nm]		1547.715	1563.047
Channel spacing (DEMUX) [GHz]		100.0	
Operational wavelength (DEMUX) [nm]		1583.907	1599.594
Clear pass band (CPB) [GHz]	relative to nominal	-15	+15
In-channel ripple	over CPB for all SOP		1.0
Insertion loss (IL) [dB]	over CPB for all SOP		5.5
Adjacent channel crosstalk [dB]	over CPB of adjacent channels	-23	
Non-adjacent channel crosstalk [dB]	over CPB of non-adjacent channels	-28	
Total integrated crosstalk [dB]	Sum of all crosstalk	-20	
Operating temperature [C]			

200B.2.2 Booster optical amplifier characteristics

The booster optical amplifier is assumed to be a high-power erbium-doped fiber amplifier (EDFA). Gain flattening is required over the 16-channel operational range to minimize the imbalance between wavelength channels after amplification. The required specifications for the reference link budget are shown in Table 3.

Table 3 - Booster optical amplifier specifications

Parameter	Conditions	Min	Max
EDFA type	Constant Gain until saturating		
Operating wavelength range [nm]		1547.715	1563.047
Single channel input power [dBm]		-8	-5
Number of channels		1	16
Small signal gain [dB]	Over all SOP	21	
Gain ripple [dB]	16-channel input, over all input powers		2
Saturation power [dBm]		26.5	
Noise figure [dB]			12

200B.2.3 Band MUX characteristics

The band MUX is responsible for combining the multiplexed downstream and upstream signals into a bidirectional signal for transmission over a single fiber ODN. Since the wavelengths for the next-generation system are already defined, the band-mux also has expansion ports to allow the next generation system to be inserted without needing to interrupt service. The required specifications are shown in Table 4.

Table 4 - Band multiplexer specifications

Parameter	Conditions	Min	Max
Device type	Thin Film Filter		
Number of ports	(not including common)	4	
Channel wavelengths	L-band 1 L-band 2 C-band 1 C-band 2	1583.907 1565.602 1547.715 1530.233	1599.594 1581.109 1563.047 1545.393
Insertion loss [dB]			1
In-band ripple [dB]			1
Channel uniformity [dB]			1
Adjacent channel crosstalk [dB]		-40	
non-adjacent channel crosstalk [dB]		-40	

200B.2.4 Preamp characteristics

The optical preamplifier is assumed to be a gain-clamped EDFA. Gain clamping is required to avoid gain variations for the burst-mode upstream signals. There are multiple methods for optical gain clamping; the exact implementation is not prescribed. The required specifications of the key parameters are shown in Table 5.

Table 5 - Preamp specifications

Parameter	Conditions	Min	Max
EDFA type	Constant Gain, gain clamped		
Operating wavelength range [nm]		1583.907	1599.594
Single channel input power [dBm]	Continuous power	-38	-18
Number of channels		1	16
Small signal gain [dB]	Over all SOP	25	
Gain ripple [dB]	16-channel input, over all input powers		2
Saturation power [dBm]	For all 16 channels	10	
Noise figure [dB]			5.5
Burst length [us]		0.2	125
Burst mode settling time [ns]			TBD
Burst-mode gain excursion [dB]			0.5

The input power into this EDFA is expected to be very low. Therefore, the noise figure (NF) and gain are critical to Super-PON. The required output power is low, thus simplifying the gain clamping implementation.

200B.2.5 DCM characteristics

The dispersion compensation module (DCM) can be implemented using any technology. Known solutions that will work include:

- Fiber Bragg Grating (FBG) DCMs; and
- Negative Dispersion Fiber DCMs.

FBG DCMs are channelized and able to cover the full C- and L-bands. They have a fixed insertion loss and a fixed latency. The latency of FBG DCMs is very small (i.e., <0.025 µs). This means the optical line terminal's (OLT) calculation of the length from the ranging will be unaffected by the DCM. FBG DCMs are likely to be channelized. Therefore, it is important to make sure the amplitude and phase ripple are minimal between ±15 GHz of the nominal channel frequency

For a fiber-based DCM, insertion loss and latency is dependent on the length of the fiber used to build them and they are not channelized. To compensate for 50 km of standard single-mode fiber, around 10 km of dispersion compensating fiber (DCF) is required. This results in around 25 µs of latency. Because a DCM is only required for the upstream (US) direction, there will be imbalance in the latency, with greater latency in the upstream direction. PON protocols are tolerant of latency asymmetry so this will not cause a problem. However, this will lead the OLT to overestimating the link length by ~5 km.

Add a note that this could break time transport protocols. Look at 802.1as clause 13.

200B.3 λ Router (CAWG)

The cyclical wavelength router is best implemented using a cyclical AWG. AWGs are naturally cyclical. The repetition frequency is referred to as the free spectral range (FSR). For the Super-PON wavelength router, the FSR for the CAWG should be approximately 2200 GHz, the width of each wavelength band including all the unused channels. The response is defined only for the channels in the four wavelength-bands used in Super-PON. However, the cyclical nature of the AWG will actually repeat for many more cycles. It is possible to use those additional cycles for applications not defined in this standard, such as OTDR for example.

The required specifications of the key parameters are shown in Table 6.

Table 6 - CAWG specifications

Parameter	Conditions	Min	Max
Type of AWG	Athermal flat-top		
Number of channels		16	
Number of bands		4	
Channel spacing (MUX) [GHz]	L-band 1	97.7	
	L-band 2	98.8	
	C-band 1	100.0	
	C-band 2	101.2	
Operational wavelength (MUX) [nm]*	L-band 1	1583.907	1599.594
	L-band 2	1565.602	1581.109
	C-band 1	1547.715	1563.047
	C-band 2	1530.233	1545.393
Clear pass band (CPB) [GHz]	relative to nominal	-15	+15
In-channel ripple	over CPB for all SOP		1.0
Insertion loss (IL) [dB]	over CPB for all SOP		4.0
Adjacent channel crosstalk [dB]	over CPB of adjacent channels	-23	
Non-adjacent channel crosstalk [dB]	over CPB of non-adjacent channels	-28	
Total integrated crosstalk [dB]	Sum of all crosstalk	-20	
temperature range			

*full wavelengths listed in ...

200B.4 Power splitter

The power splitters for Super-PON are the same as those used in other PON standards. In order to minimize the link loss, premium low-loss splitters are required for links approaching 50-km to keep the total link loss below 41 dB. The required insertion loss of 20.5 dB is not exotic and can be achieved simply by most splitter manufacturers by selecting the lower loss units from a batch.

200B.5 Link budget analysis

200B.5.1 Downstream

Figure 2 shows the downstream link components and expected losses/gains for each component. At the bottom of the figure, the expected minimum power is shown for different locations in the ODN. For simplicity, all connector, splice and link aging losses are lumped together right before the receiver (ONU).

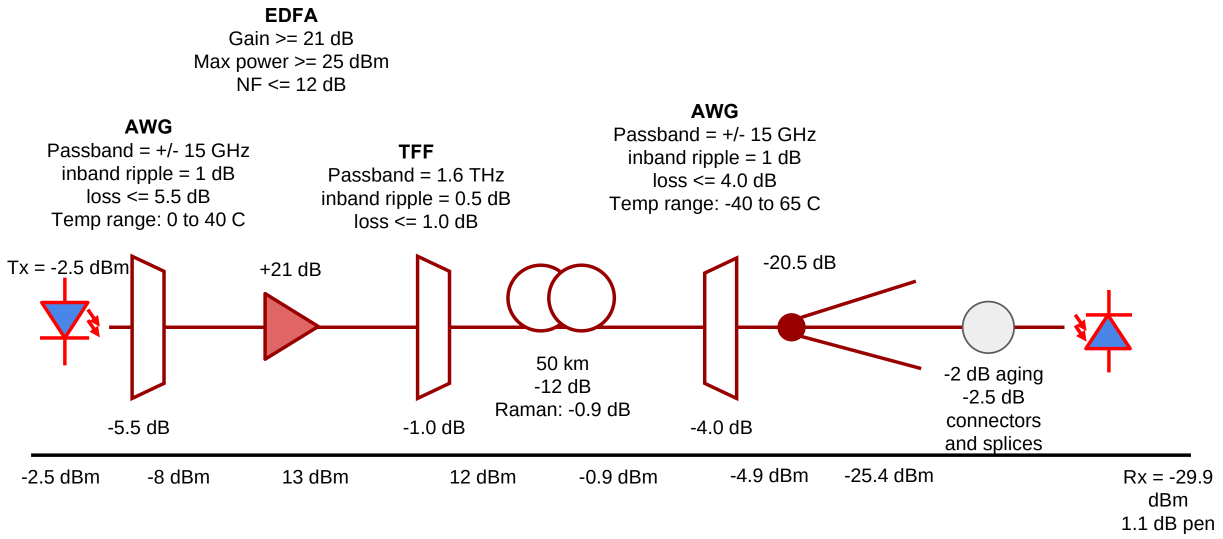

Figure 2 - Downstream link budget

200B.5.2 Upstream

Figure 3 shows the upstream link components and expected losses/gains for each component. At the bottom of the figure, the expected minimum power is shown for different locations in the ODN. For simplicity, all connector, splice and link aging losses are lumped together right before the transmitter (ONU).

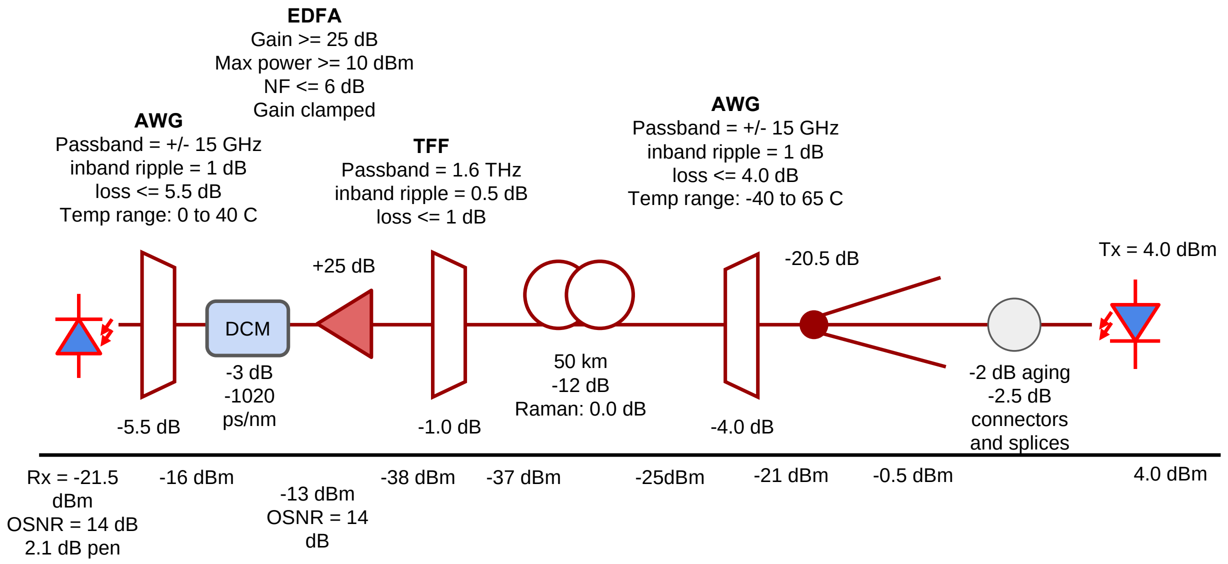

Figure 3 - Upstream link budget

200B.5.3 Raman Effect Penalty

The Stimulated Raman Scattering (SRS) transfers power from shorter wavelength channels to the longer wavelength channels. The downstream channels are emitted at a much higher power than the upstream channels; the Raman effect is determined by the power and number of downstream channels only.

Using L-band wavelengths for upstream, the Raman effect transfers power to the upstream signals. This is illustrated by the negative Raman penalty in Figure 4. This calculation assumed the use of 16 channels for both US and DS. The channel with the highest Raman penalty is shown. A negative penalty means that power is transferred into the channel via SRS, thus receiving gain.

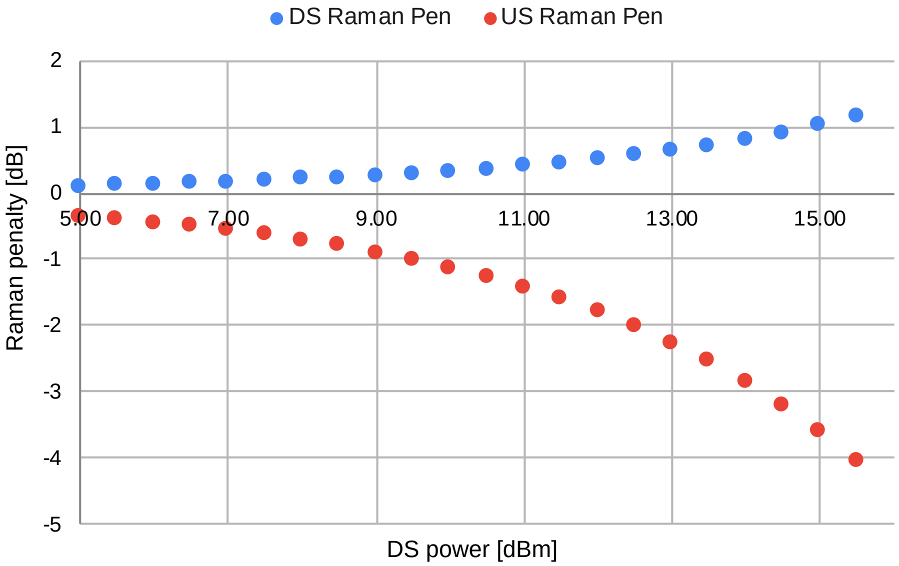

Figure 4 - Raman penalty

This Raman gain cannot be relied upon for two reasons:

- the gain in power will only be a fraction if fewer wavelengths are used; and
- gain from a modulated pump will also result in additional noise.

Therefore, the Raman gain/penalty is assumed to be zero when calculating the required upstream powers for upstream operation.

The Raman effect between the 16 downstream channels causing the longer wavelength channels to steal power from the shorter wavelength channels. However, this effect is weaker due to the close pump-stokes separation. The predicted downstream penalty can be handled by increasing the gain and maximum power of the downstream EDFA in the MUX/Amp module. In the downstream link budget, the expected Raman power penalty is added to the loss of the fiber.

Figure 5 shows the required power levels as a function of the link budget, assuming a 2.1 dB transmission penalty for the upstream and 1.1 dB transmission penalty for the downstream. A 41 dB link budget requires an upstream launch power level of 4.0 dBm at 10Gb/s.

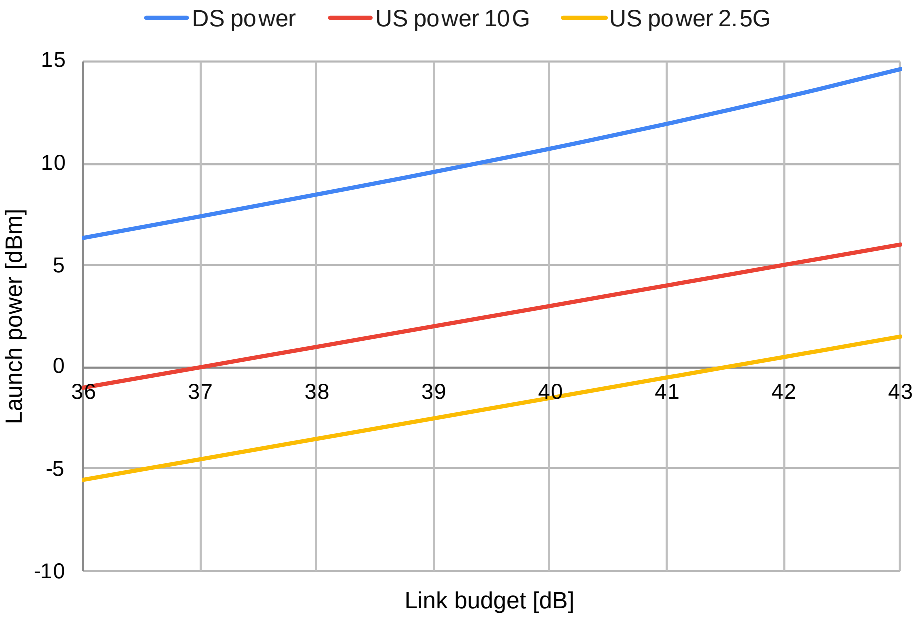

Figure 5 - ONU power levels

All Raman penalties are calculated assuming the power on all downstream channels is 2 dB higher than the minimum required downstream power. This allows for there to be some channel imbalance in the downstream system without causing an excessively large penalty on the lowest power channels. Note that the typical allowed variation in OLT output power is 4 dB. The 2-dB imbalance assumption therefore assumes (and requires) an operator will perform closed loop balancing of channel powers for each ODN.

200B.5.4 Dispersion compensation

The required operational dispersion range selected was based on the following needs of the project:

- Desire to enable both DML and EML solutions,
- Need to minimize the total penalty from transmission for all transmitter types.

DMLs typically have a high positive chirp, which is very difficult to avoid. This causes a large transmission penalty if there is substantial positive residual chromatic dispersion (CD) in the link. DML transmitters will need CD compensation to operate in a 50-km link.

For EML transmitters, the chirp is typically determined by the bias point of the modulator. A low bias results in higher transmission powers, positive chirp, and lower extinction ratio (ER). A high bias results in lower transmission powers, low or even negative chirp, and higher ER. Our requirement of 4-dBm output power is relatively high for EML transmitters, so will likely require a moderately low modulator bias point, resulting in a positive chirp.

The performance of typical DML and EML solutions for different residual chromatic dispersion is shown below. Both solutions are positively chirped so perform better with negative residual dispersion. The higher chirp factor of the DML transmitter results in a lower tolerance in both the extreme positive and negative residual dispersion bounds at 1-dB penalty. These results suggest that a residual dispersion between -600 ps/nm and +50 ps/nm will allow both the EML and DML transmitters to operate within 1-dB penalty.

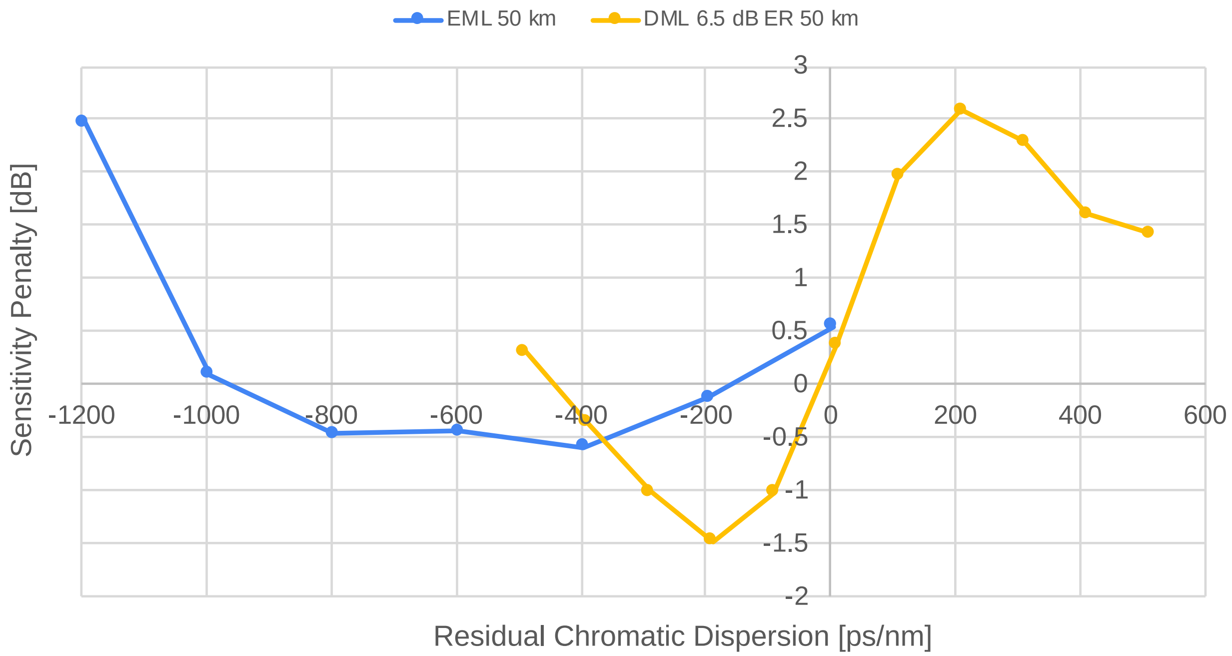

Figure 6 - CD penalty for DML and EML transmitter