Defining inter-channel crosstalk in IEEE 802.3cw

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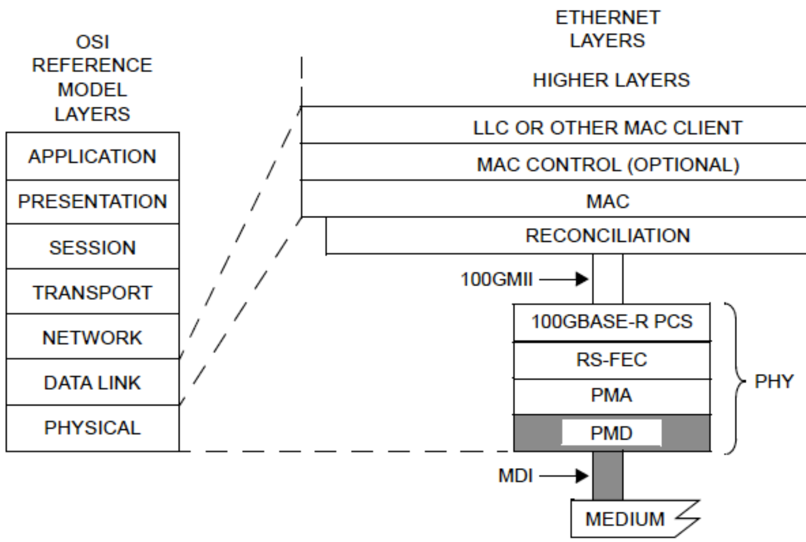
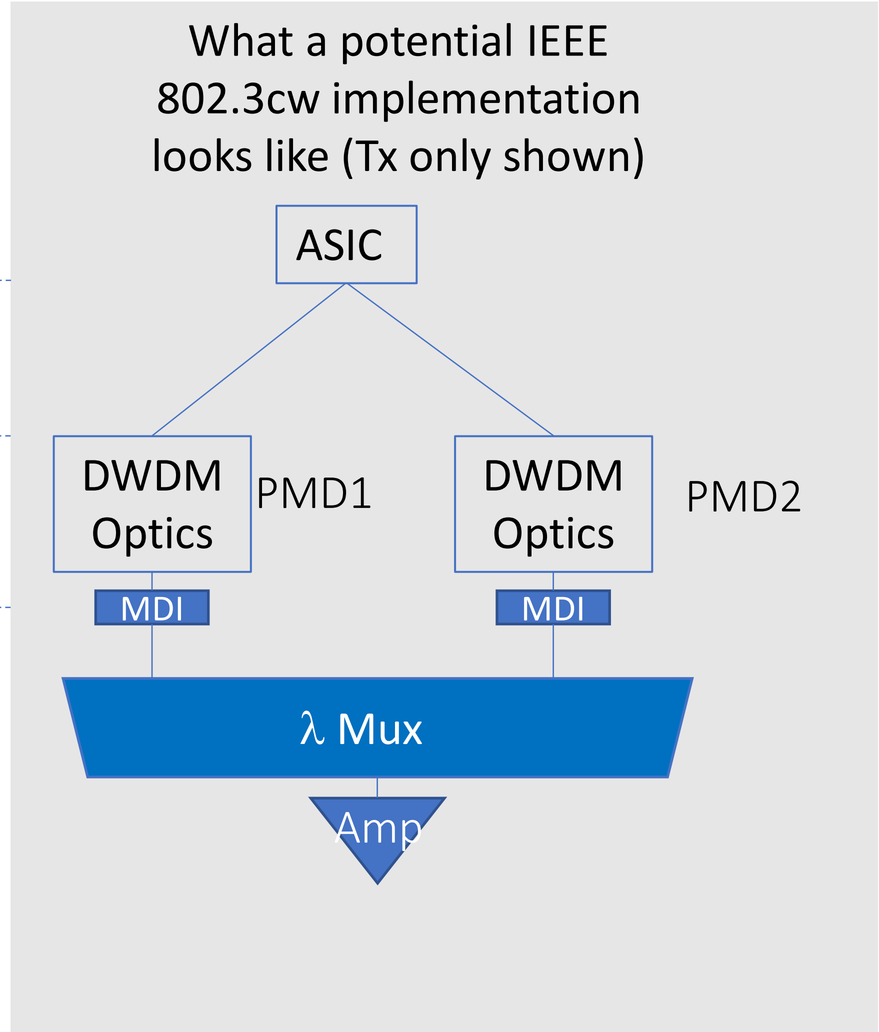
Scope of IEEE 802.3 specifications



Within Physical Layer Specification scope

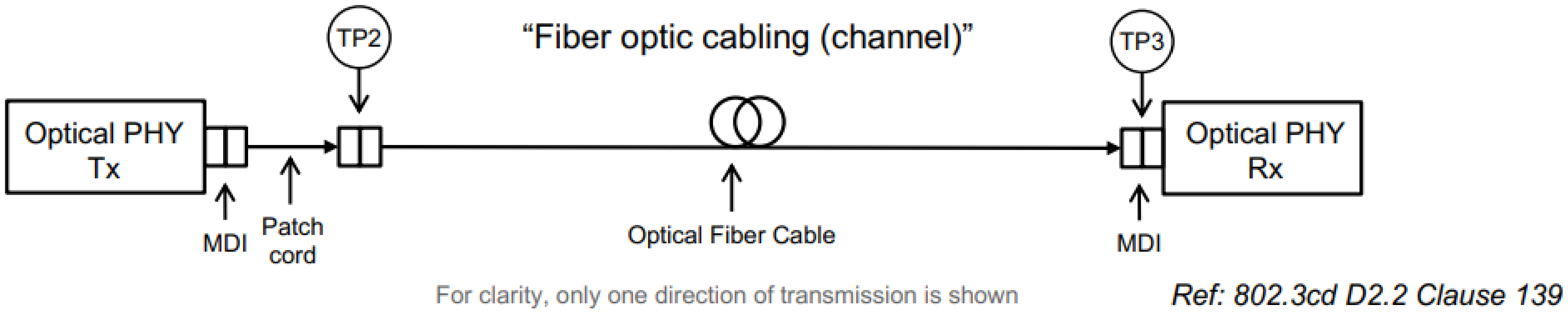
Outside Physical Layer Specification scope



Problem statements

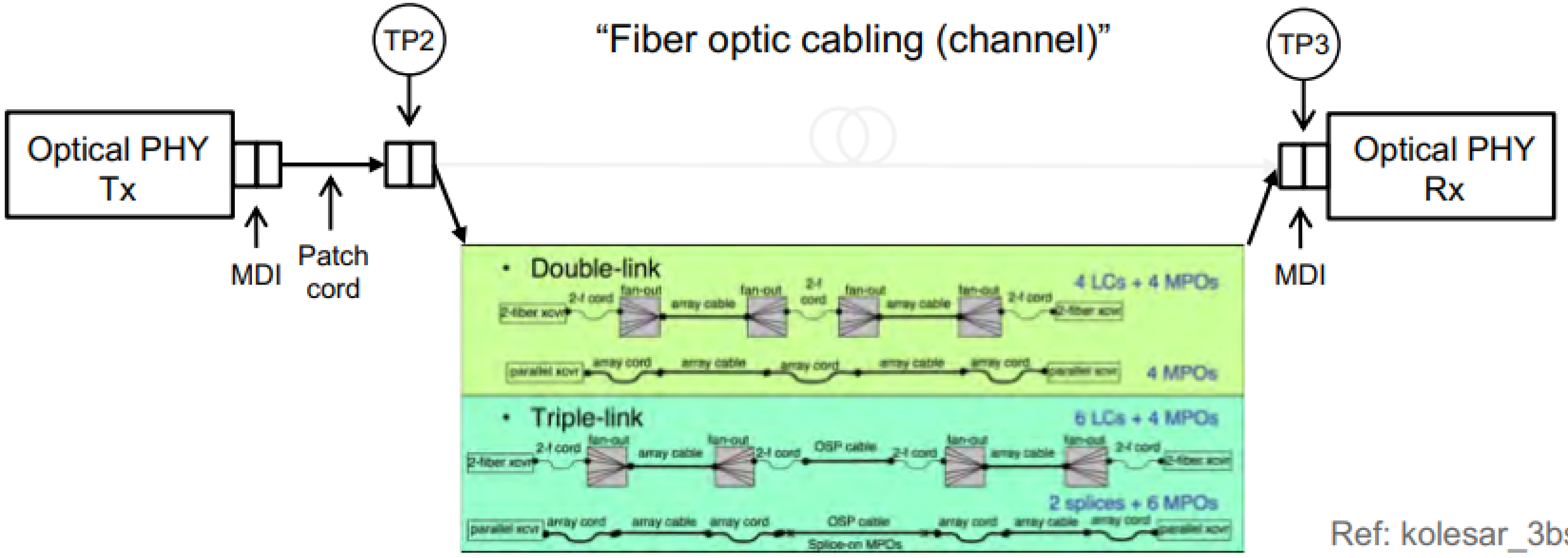
1. 400GBASE-ZR has a 60 Gbaud signal that will be operated over a multi-channel fiber at wavelengths that are 75 GHz spaced. Optical inter-channel crosstalk can and will happen.
    - The amount of cross talk and the penalty due to that cross talk is very dependent on the specifics of the wavelength selective devices within the channel AND of course the usual Tx and Rx PMD specifications that 802.3 would usually define in a PHY
2. 400GBASE-ZR needs specifications inside the cable plant (aka black link) that don’t currently exist

Recap - Traditional Ethernet optical PHY link model



- In current IEEE 802.3 PHYs the optical link between transmitter and receiver, i.e. between TP2 and TP3, is in the form of a passive connection over a "fiber optic cabling (channel)".
- The "fiber optic cabling (channel)" characteristics are normative and are defined in terms of a few key parameters, e.g. distance, loss, dispersion, DGD and return loss.
- The detailed implementation of the "fiber optic cabling (channel)" is not defined by the standard (e.g. number and locations of splices, connectors, etc), i.e. the "fiber optic cabling (channel)" is treated as a "black link".

Recap - Traditional Ethernet optical PHY link model

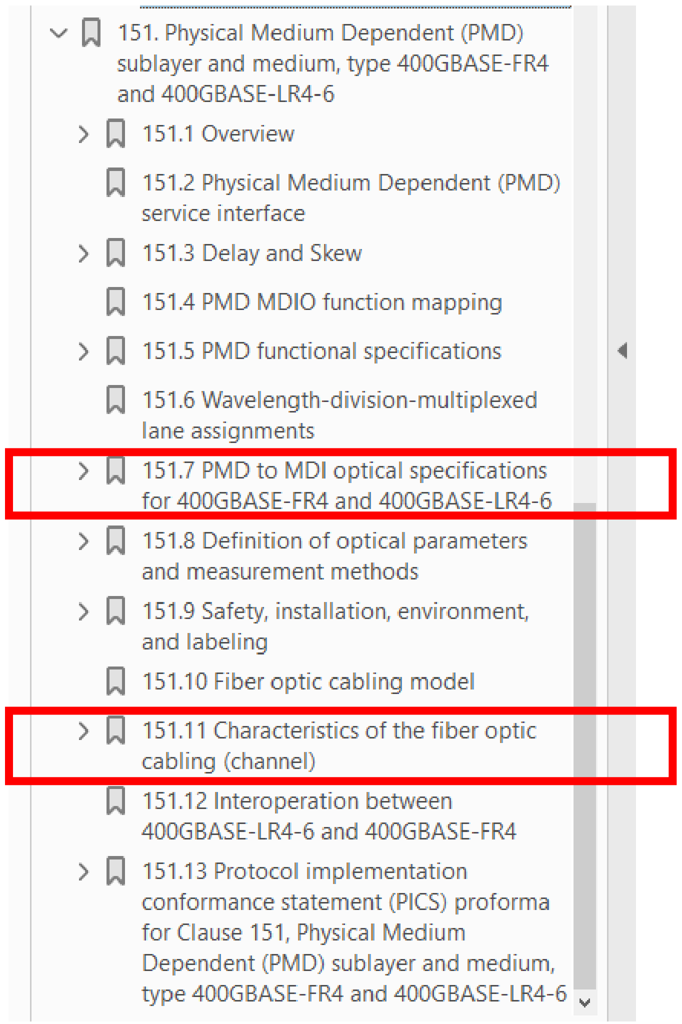


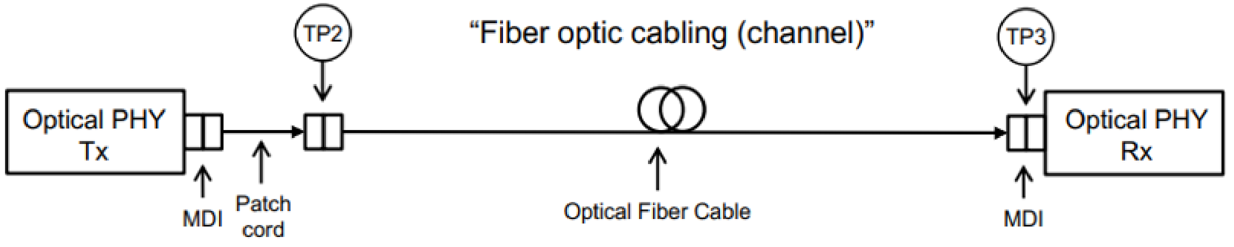
Ref: kolesar_3bs_01_0514

For clarity, only one direction of transmission is shown

- The “reference” channels in kolesar_3bs_01_0514 were used to help define the optical interface parameters at TP2 and TP3.
- However the “reference” channels in kolesar_3bs_01_0514 are not part of, nor included in, the IEEE specification.

How are link parameters defined in the spec ?





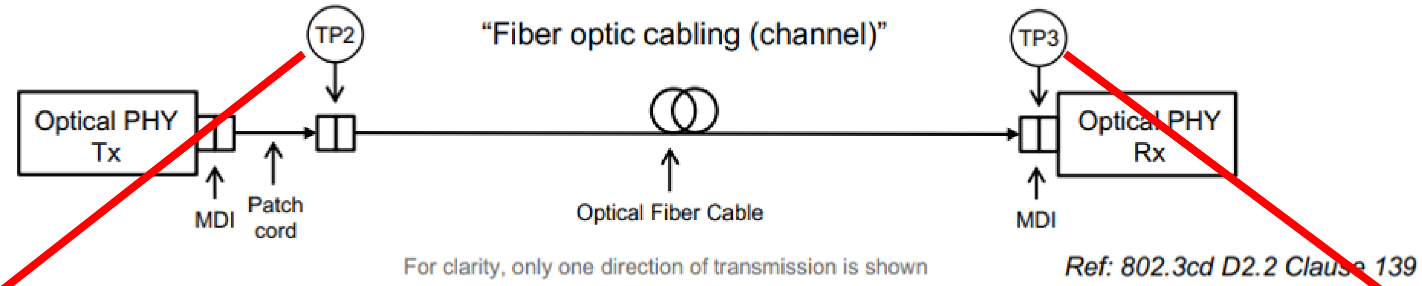
For clarity, only one direction of transmission is shown

Ref: 802.3cd D2.2 Clause 139

This section defines the normative optical parameters for the PMD at TP2 (transmitter) and TP3 (receiver).

This section defines the normative optical parameters associated with the "fiber optic cabling (channel)" or "black link" that the PMD operates over, but does not define or dictate what goes inside the "black link"

How are link parameters defined in the spec ?



Subclause 151.7.1 (Transmitter characteristics)

Table 151–7—400GBASE-FR4 and 400GBASE-LR4-6 transmit characteristics

Description	400GBASE-FR4	400GBASE-LR4-6	Unit
Signaling rate, each lane (range)	53.125 ± 100 ppm		GBd
Modulation format	PAM4		—
Lane wavelengths (range)	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		dB
Total average launch power (max)	10.4	11.1	dBm
Average launch power, each lane (max)	4.4	5.1	dBm
Average launch power, each lane[a] (min)	–3.2	–2.7	dBm
Outer Optical Modulation Amplitude (OMA_{outer}), each lane (max)	3.7	4.4	dBm
Outer Optical Modulation Amplitude (OMA_{outer}), each lane (min) for TDECQ <1.4 dB for 1.4 dB ≤ TDECQ ≤ 3.4 dB	 –0.2 –1.6 + TDECQ	 0.3 –1.1 + TDECQ	 dBm dBm
Difference in launch power between any two lanes (OMA_{outer}) (max)	3.9	4	dB
Transmitter and dispersion eye closure for PAM4 (TDECQ), each lane (max)	3.4	3.4	dB
Transmitter eye closure for PAM4 (TECQ), each lane (max)	3.4	3.4	dB
| TDECQ – TECQ | (max)	2.5	2.5	dB
Over/under-shoot (max)	22	22	%

Subclause 151.11 (Fiber optic cabling channel characteristics)

Table 151–13—Fiber optic cabling (channel) characteristics

Description	400GBASE-FR4	400GBASE-LR4-6	Unit
Operating distance (max)	2	6	km
Channel insertion loss[a,b] (max)	4	6.3	dB
Channel insertion loss (min)	0	0	dB
Positive dispersion[b] (max)	6.6	19.9	ps/nm
Negative dispersion[b] (min)	–11.7	–35.2	ps/nm
DGD_max[c]	2.3	4	ps
Optical return loss (min)	25	22	dB

[a] These channel insertion loss values include cable, connectors, and splices.
[b] Over the wavelength range 1264.5 nm to 1337.5 nm for 400GBASE-FR4 and 400GBASE-LR4-6.
[c] Differential Group Delay (DGD) is the time difference at reception between the fractions of a pulse that were transmitted in the two principal states of polarization of an optical signal. DGD_max is the maximum differential group delay that the system is required to tolerate.

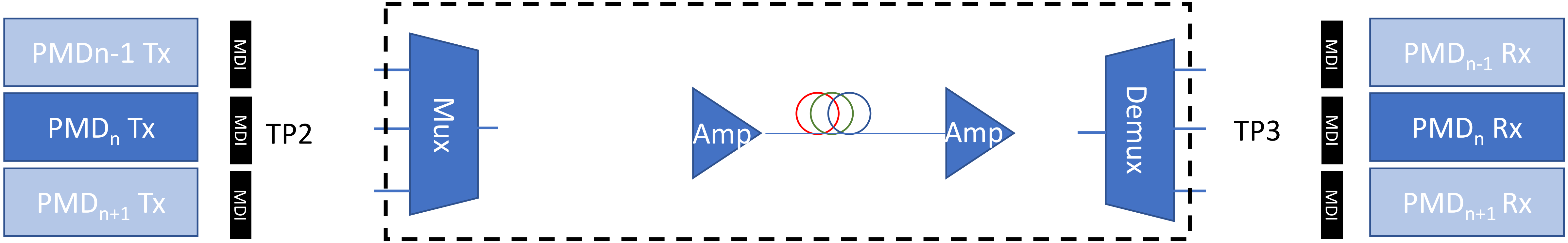
Subclause 151.7.2 (Receiver characteristics)

Table 151–8—400GBASE-FR4 and 400GBASE-LR4-6 receive characteristics

Description	400GBASE-FR4	400GBASE-LR4-6	Unit
Signaling rate, each lane (range)	53.125 ± 100 ppm		GBd
Modulation format	PAM4		—
Lane wavelengths (range)	1264.5 to 1277.5 1284.5 to 1297.5 1304.5 to 1317.5 1324.5 to 1337.5		nm
Damage threshold[a], each lane	5.4	6.1	dBm
Average receive power, each lane (max)	4.4	5.1	dBm
Average receive power, each lane[b] (min)	–7.2	–9	dBm
Receive power (OMA_{outer}), each lane (max)	3.7	4.4	dBm
Difference in receive power between any two lanes (OMA_{outer}) (max)	4.1	4.3	dB
Receiver reflectance (max)	–26		dB
Receiver sensitivity (OMA_{outer}), each lane (max) for TECQ < 1.4 dB for 1.4 dB ≤ TECQ ≤ 3.4 dB	 –4.6 –6 + TECQ	 –6.8 –8.2 + TECQ	 dBm dBm
Stressed receiver sensitivity (OMA_{outer}), each lane[c] (max)	–2.6	–4.8	dBm
Conditions of stressed receiver sensitivity test:[d]			
Stressed eye closure for PAM4 (SECQ), lane under test	3.4	3.4	dB
OMA_{outer} of each aggressor lane	1.4	–0.4	dBm

Note, all of these sections are normative and are referenced in the PICS

Coherent DWDM link budget



Has various TX parameters that affect performance.

Combines channels onto common fiber

May incorporate wavelength selective technology (usually does)

Optical amplifiers and (outside plant) fiber

Separates wavelength channels from common fiber

Does incorporate wavelength selective technology

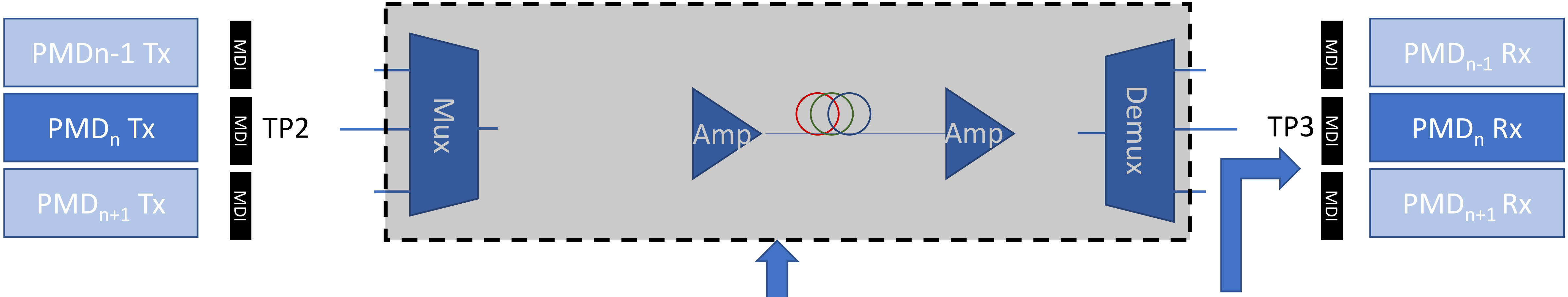
Has various Rx parameters that affect performance

IEEE Physical Layer Specified

IEEE Physical Layer Link budget can depend on parameters that arise from here but not normatively define or specify these implementation or components. Referencing industry specifications or informative annexes permissible

IEEE Physical Layer Specified

Coherent DWDM link budget



Loss (λ)
Dispersion (λ)
Optical Return Loss
Polarization Loss
Etc.

OSNR Penalty
Inter-channel Crosstalk
Etc.

*illustrative – not comprehensive

IEEE Physical Layer Specified

IEEE Physical Layer Link budget can depend on parameters that arise from here but not <u>normatively</u> define or specify these implementation or components. Referencing industry specifications or informative annexes permissible

IEEE Physical Layer Specified

Current 400GBASE-ZR black Link baseline

Table 156–10—400GBASE-ZR black link characteristics

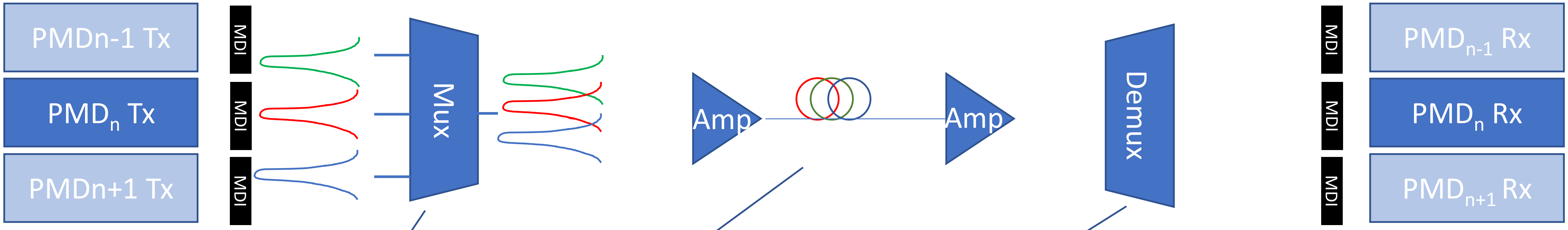
Description	Value	Unit
Channel spacing (min)	75	GHz
Ripple (max)	TBD	dB
Optical path OSNR penalty (max)	TBD	dB
Chromatic dispersion (max)	2000	ps/nm
Chromatic dispersion (min)	0	ps/nm
Fiber chromatic dispersion slope at channel center frequencies[a] (min)	TBD	ps/nm^2 km
Optical return loss at TP2 (min)	24	dB
Differential group delay, (DGD)[b] (max)	28	ps
Polarization dependent loss (max)	2.0	dB
Polarization rotation speed (max)	50	krad/s
Inter-channel crosstalk at TP3 (max)	TBD	dB
Interferometric crosstalk at TP3 (max)	TBD	dB

[a]The applicable channel center frequencies are specified in Table 156–6.
[b]Differential Group Delay (DGD) is the time difference at reception between the fractions of a pulse that were transmitted in the two principal states of polarization of an optical signal. DGD_max is the maximum differential group delay that the system must tolerate.

https://www.ieee802.org/3/ct/public/tf_interim/20_0917/issenhuth_3cw_01a_200917.pdf

Inter-channel Crosstalk (background)

Coherent Rx Local oscillator acts as a very effective RF filter



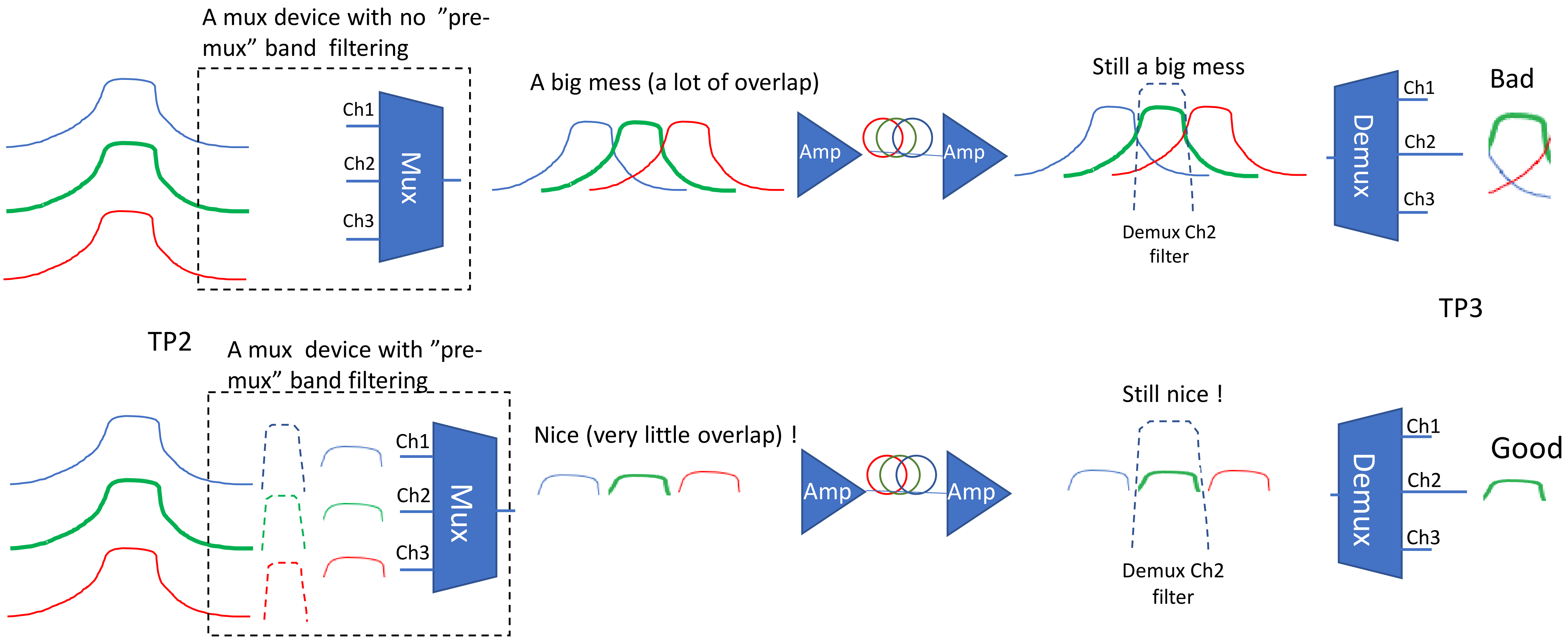
Once in the multiplexed fiber, impairments happen

The Mux is where the inter-channel crosstalk predominatly happens.

And is the <u>only</u> place it can be minimized or mitigated – hence the use of filters to limit an individual Tx spectrum to keep it out of band of adjacent channels

Demux filters out any broadband noise (ASE) and separates wavelengths to individual fibers. Once xtalk is in the channel, demux filtering can not undo

How mux & demux options impact inter-channel crosstalk

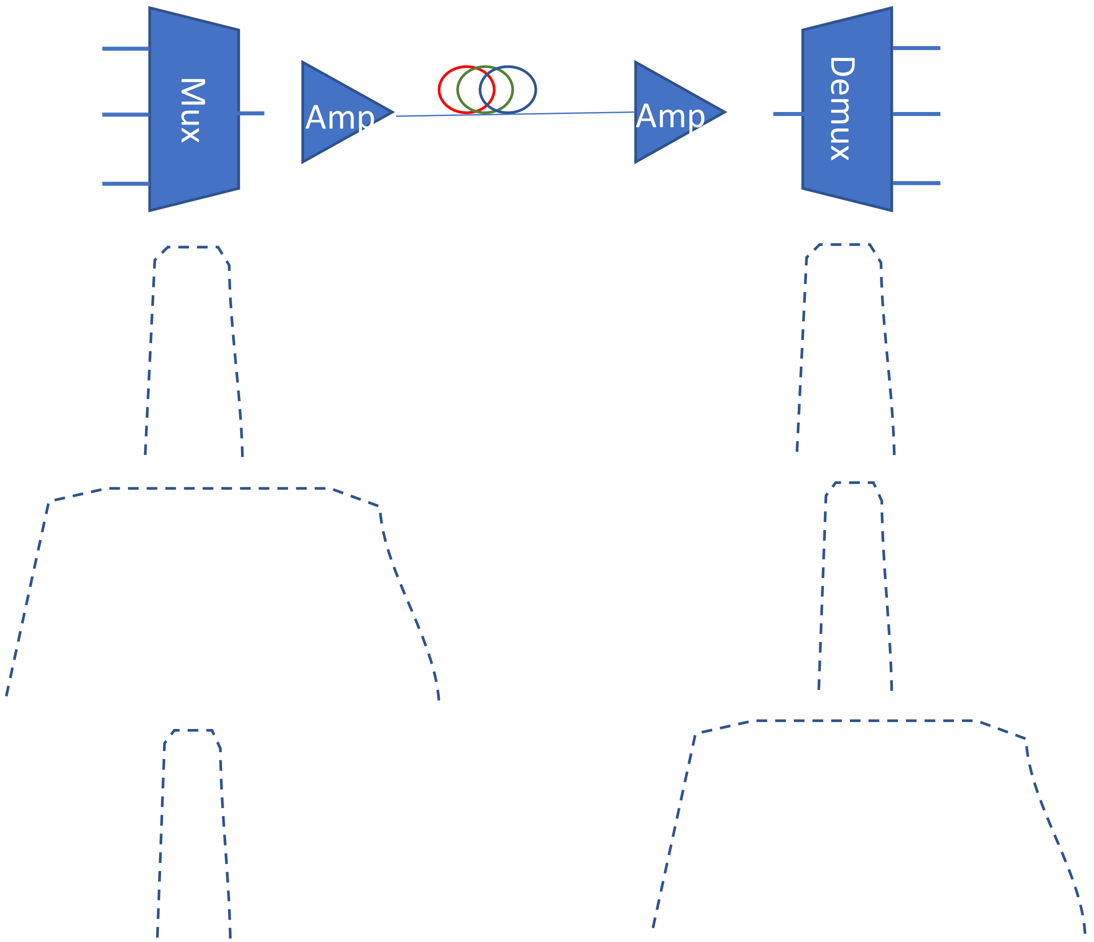


The key point is that to avoid interchannel crosstalk you need to band limit (filter) the individual channels **BEFORE** they are ever multiplexed together (too late afterwards) , and practically this pre-mux filtering would be included as part of the "mux device" (and hence some of the confusion)

Mux & Demux considerations

- Mux and Demux do not have to be matched in a real deployment
- Simplest mux is a simple power combiner (which has no filtering) but would introduce the maximum inter-channel crosstalk
- For 400GBASE-ZR, the individual details of the Mux and Demux matter due to tight spacing and broad spectrum
  - As an aside, other 100 Gb/s DWDM specifications or wider spaced 400 Gb/s specifications (OIF's 400ZR) are more relaxed and don't result in as much inter-channel crosstalk
- The challenge with the Black Link approach is it would concatenate the effects of the filters blurring the potential effects and risking breaking interop.
  - Specific constraints on <u>Both</u> Mux and Demux are needed in order to determine the inter-channel xtalk penalty which is needed to develop the link budget

Mux & Demux considerations



<u>Scenario</u>

Optimized Mux and Demux filter shapes

Broad Mux and narrow Demux filter shapes

Narrow Mux and Broad Demux filter shapes

While the black link concatenated equivalent might be the same in the 3 scenarios, the resultant interchannel crosstalk penalty could be quite different

Recap

- 400GBASE-ZR
  - Wider optical transmit spectrum (60GBaud)
  - Narrower channel bandwidth per target channel (75 GHz)
  - Much tighter than previous industry 100 Gb/s or 400 Gb/s specs
- Therefore inter-channel crosstalk penalty is a more significant penalty that needs to be considered accurately in link budget
- Very valid to accommodate this penalty parameter in an IEEE Physical Layer link budget specification
  - BUT – assumptions behind the how that specific parameter value chosen are very dependent on knowing details of transmitter and receiver parameters AND on mux/demux specifications (which are outside of IEEE 802.3 Scope) in order to define
- Therefore – at most we can clarify the assumptions of the mux/demux spec in an informative annex

Have we dealt with this before?

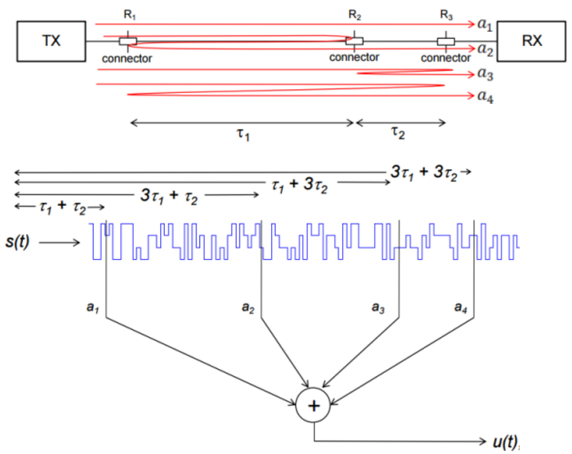
- Very similar analogy to MPI penalty used in many of 100G Lambda PMD specs
  - Task Force made assumptions on the "worst case" connector details in the channel in order to calculate a penalty
    - Number of connectors, return loss, location and inter-connector loss
  - That penalty was agreed upon by the TF after considerable analysis and is used in the link budget calculations
    - but these MPI Penalty assumptions do not appear in the specification (and perhaps it should have). Actually the MPI penalty is lumped into "Additional Penalties"
- Proposal for inter-channel xtalk is to follow similar approach but this time it needs to be included as an informative annex to document these assumptions

Proposal

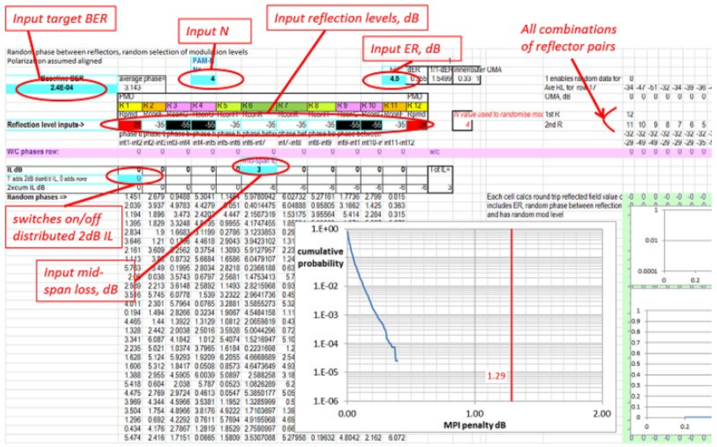
- Interchannel xtalk penalty parameter to be defined and used as part of the link budget specification for 400GBASE-ZR
- Informative Annex to include the assumptions used to determine this parameter value
    - This could (should) include filter mask shapes
    - This could (should) include details on assumptions of location of filtering (mux vs demux)
    - And whatever else is relevant (i.e. compliance testing methodology)
- These mux/demux specs will NOT be normative and are outside the scope of IEEE 802.3 to define
    - No issue though with a different standards group wanting to define it in a spec. And if they are done sooner, we could just reference.

Recap – How did we deal with MPI ?

Ref: bhatt_3bs_01a_0116.pdf



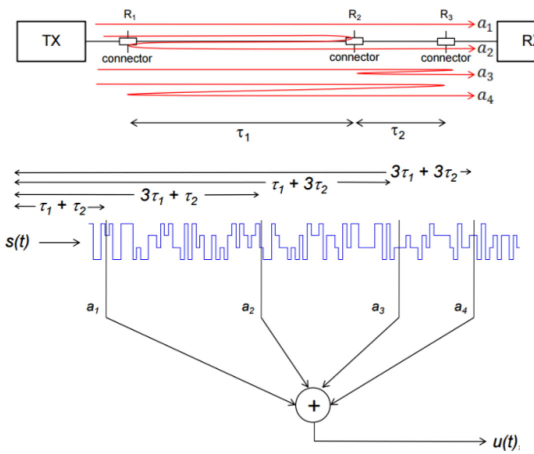
The received signal $u(t)$ is the sum of these delayed replicas of transmitted signals. Received power is $|u(t)|^2$.



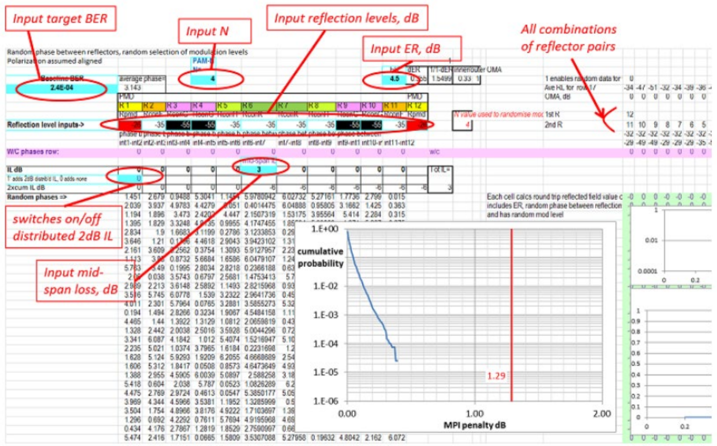
- MPI (Multi Path Interface) is a link penalty that became more important with the introduction of PAM4 (multi-level) signaling.
- MPI proved to be very challenging because unlike other link penalties it is not just dependent on a single characteristic associated with the "black link". Instead it is very dependent on the structure **inside** the black link, i.e. the number and locations of optical connectors and the fiber loss between them.
- This goes against the basic IEEE 'black link" philosophy of not defining the implementation inside the "black link" or the "fiber optic cabling (channel)".

Recap – The solution for MPI

Ref: bhatt_3bs_01a_0116.pdf



The received signal $u(t)$ is the sum of these delayed replicas of transmitted signals. Received power is $|u(t)|^2$.



- In the end we derived "worst case" MPI penalties that were accounted for in the link budget, based on assumptions around "worst case" links derived from the Kolesar reference channels:
  - 0.1dB for 500m, 0.3dB for 2km and 0.5dB for 10km.
- The MPI penalties and the assumptions used to them were not documented in the specification.
- It is possible to come with an implementation of an optical link that would meet all of the normative specs for the "black link" defined in the specification, but that exceeds the MPI penalties assumed in the link budget

Summary

In order to successfully define 400GBASE-ZR over 75 GHz spaced channels, the black link approach is preferred

- Some details within the black link need to be additionally defined (which sort of breaks the black link approach). But…
- Propose to do this work within an Informative Annex and use the resultant penalty within the Physical Layer specification

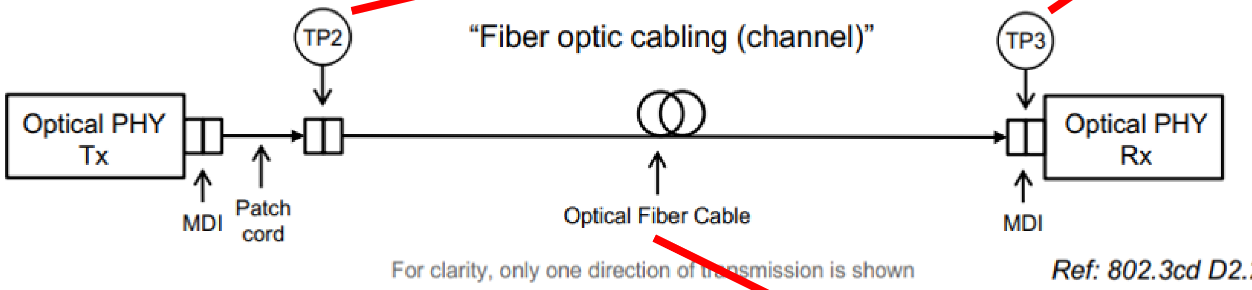
Black Link approach still in effect (with caveats)

References

- https://www.ieee802.org/3/B10K/public/18_01/nicholl_b10k_01a_0118.pdf
- https://www.ieee802.org/3/bs/public/16_01/bhatt_3bs_01a_0116.pdf

Ref: P802.3cu Clause 151

The PICS perspective



Ref: 802.3cd D2.2 Clause 139

Subclause 151.13.4.3

151.13.4.3 PMD to MDI optical specifications for 400GBASE-FR4

Item	Feature	Subclause	Value/Comment	Status	Support
FRF1	Transmitter meets specifications in Table 151–7	151.7.1	Per definitions in 151.8	FR4:M	Yes [ ] N/A [ ]
FRF2	Receiver meets specifications in Table 151–8	151.7.2	Per definitions in 151.8	FR4:M	Yes [ ] N/A [ ]

151.13.4.4 PMD to MDI optical specifications for 400GBASE-LR4-6

Item	Feature	Subclause	Value/Comment	Status	Support
LRF1	Transmitter meets specifications in Table 151–7	151.7.1	Per definitions in 151.8	LR4-6: M	Yes [ ] N/A [ ]
LRF2	Receiver meets specifications in Table 151–8	151.7.2	Per definitions in 151.8	LR4-6: M	Yes [ ] N/A [ ]

Subclause 151.13.4.7

151.13.4.7 Characteristics of the fiber optic cabling and MDI

Item	Feature	Subclause	Value/Comment	Status	Support
OC1	Fiber optic cabling	151.11	Meets requirements specified in Table 151–13 and Table 151–14	INS:M	Yes [ ] N/A [ ]
OC2	Maximum discrete reflectance	151.11.2.2	Meets requirements specified in Table 151–15	INS:M	Yes [ ] N/A [ ]
OC3	MDI Requirements	151.11.3	Meets IEC 61753-1 and IEC 61753-021-2	INS:M	Yes [ ] N/A [ ]