Coherent is a Hammer Contorting the Datacenter into a Nail

Workshop Mo1C2

IMDD and Coherent in Short Reach Systems

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Chris Cole, II-VI Incorporated

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II-VI

Outline

- **Transport**
  - Chromatic Dispersion
  - Polarization Mode Dispersion
  - Insertion Loss
  - Spectral Efficiency
- Datacenter
  - Chromatic Dispersion
  - Polarization Mode Dispersion
  - Insertion Loss
  - Spectral Efficiency
- Summary
- Appendix: IMDD vs Coherent SNR

Transport Chromatic Dispersion (CD)

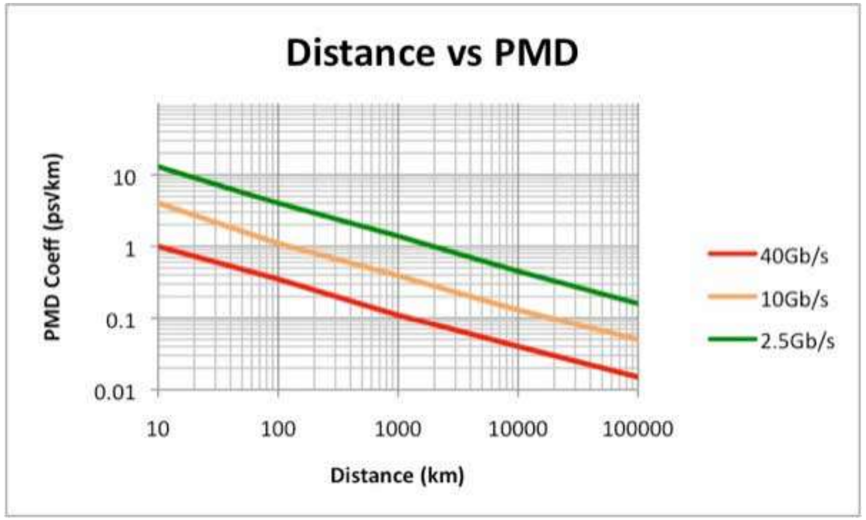
G.652 SMF DWDM Transport C-band CD Specs

- nom: 17ps/nm-km
- max: 20ps/nm-km
- CD penalty is huge and different for each link reach
- IMDD DCF EQ: each link requires unique length (bulky, operationally expensive)
- Coherent DSP EQ: adapts to all links

Transport Polarization Mode Dispersion (PMD)

G.652 SMF DWDM Transport C-band PMD_Q Specs

- A&C nom: 0.5ps/√km
- B&D nom: 0.2ps/√km
- DGD is significant over long reaches
- Coherent DSP EQ: tracks polarization



Transport Insertion Loss (IL)

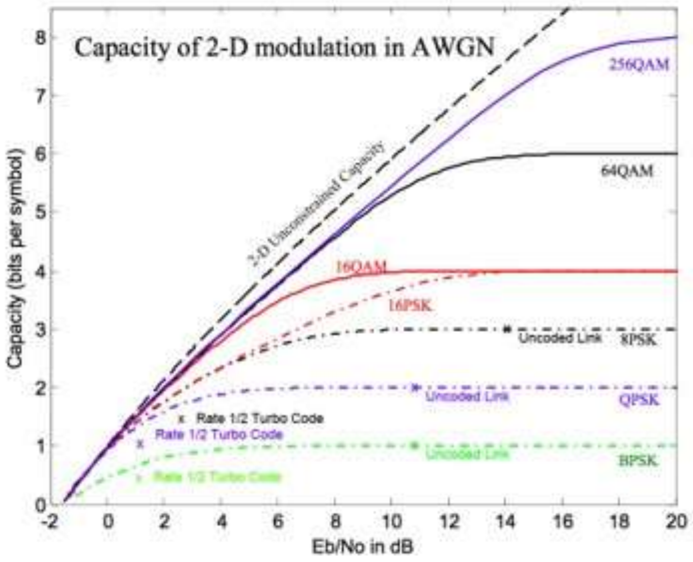
G.652 SMF DWDM Transport C-band IL Specs

- nom: 0.20dB/km
- max: 0.28dB/km
- link SNR IF only determined by IL
  - Coherent SNR ≈ 2 x IMDD SNR, in dB
  - → Coherent reach ≈ 2 x IMDD reach
  - → ½ x optical amplifier cost

Transport Spectral Efficiency (SE)

G.652 SMF DWDM Transport C-band BW Specs

- G.694.1 channel bandwidth (BW): 25, 50, 100GHz
- BW limits imposed by End Users to only use deployed SMF
- NRZ IMDD: 1 bit/Hz
- Coherent: 2 – 8 bits/Hz



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Datacenter Chromatic Dispersion (CD)

- G.652 1km SMF CWDM4 CD O-band Specs
- min: -6ps/nm
- nom min: -4ps/nm
- nom max: 4ps/nm
- max: 5ps/nm
- CD penalty is typically under a dB; TX dominates TDP
- Coherent proposals optimized for intra-datacenter applications drastically reduce, or eliminate CD EQ entirely like in an analog RX

Datacenter Polarization Mode Dispersion (PMD)

G.652 1km SMF CWDM4 O-band PMD_Q Specs

- A&C nom: 0.5ps
- B&D nom: 0.2ps
- DGD penalty is a fraction of a dB
- Regardless, Coherent RX must track polarization

Datacenter Insertion Loss (IL)

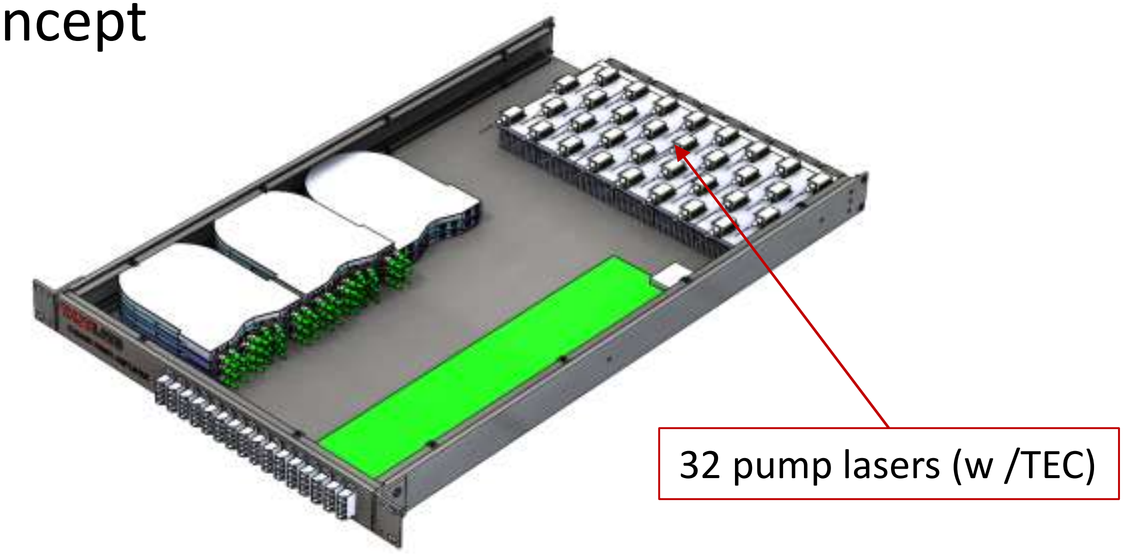
G.652 1km SMF CWDM4 O-band Spec Limits

- nom: 0.35dB
- max: 0.47dB
- SMF IL is minor portion of link budgets
- Connectors and other passives dominate
- Typical IL link budget: 4dB
- For IL < ~10dB, IMDD is more power efficient than Coherent (see Appendix)

Datacenter Insertion Loss (IL) 2

- What if End Users want high IL links, for example w/ 7dB IL optical switches?
- For IL > ~10dB, Coherent is more power efficient than IMDD (see Appendix)
- IMDD can increase link budget through amplification:
    - SOA
    - PDFA
- Example: Thor Labs 10dB Gain PDFA concept

1RU 32-Channel 10dB Gain PDFA



Datacenter Spectral Efficiency (SE)

G.652 1km SMF BW O-band Specs

- Low CD penalty span BW: ~10THz
- SMF SE is not important
- Consequence of low IL & SE links is that IMDD is lower cost than Coherent

Metric	Low SE IMDD	High SE Coherent
Laser cost	low	high
TX & RX component loss	low	high
Assembly/packaging cost	low	medium
Testing	simple	complex

Datacenter Spectral Efficiency (SE) 2

- What if End Users impose a 4λ limit because they prefer CWDM4?
- Ex.: 1.6 & 3.2 Tb/s transceivers 4λ w/ 4-level modulation symbol rate

4λ Transceiver	modulation format	data rate		unit
		1.6Tb/s	3.2Tb/s	
IMDD	PAM4	200	400	GBaud
Coherent	QAM16	50	100	GBaud

- CWDM4 IMDD is not practical in the time frame of interest

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➢**Summary**

- Appendix: IMDD vs Coherent SNR

IMDD vs Coherent in the Datacenter

- Transport Coherent performance advantages do not matter in the Datacenter
- For typical Datacenter links, cost and power of IMDD are lower than of Coherent
- Exception 1: high IL links
  - Ex.: w/ optical switches
  - requires detailed cost and power analysis of amplified IMDD vs Coherent specific implementations (beyond the scope of this presentation)
- Exception 2: high SE imposed by End Users
  - Ex.: CWDM4
  - Impractically high IMDD Baud Rate for $\geq$1.6T 4λ transceivers in the time frame of interest

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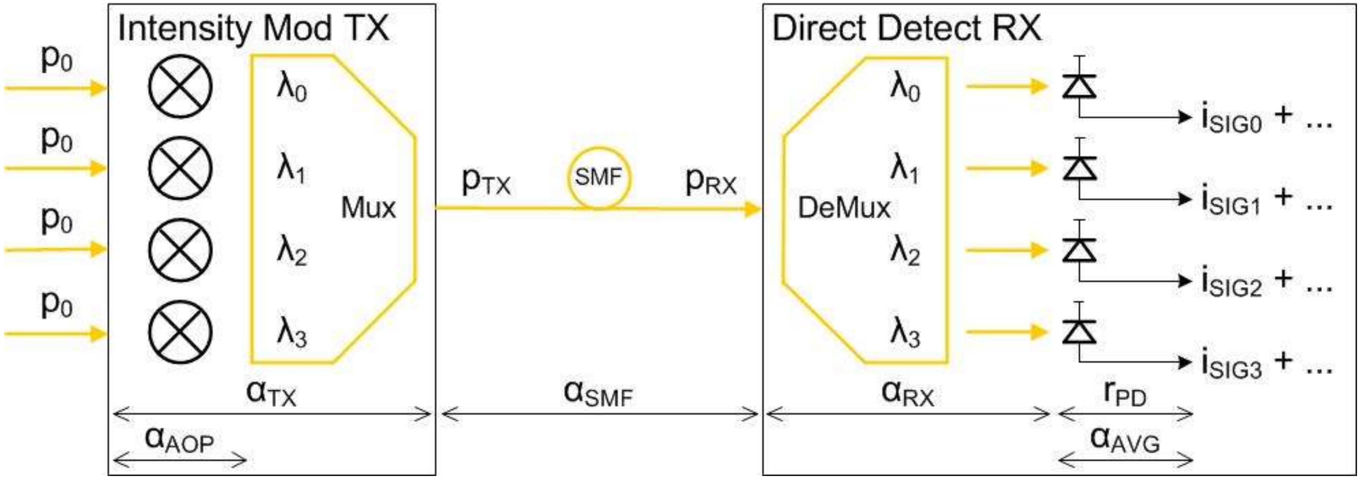
➢**Appendix: IMDD vs Coherent SNR**

Direct Detection (DD) IL Signal Path



$p_{IN\text{-}TX} = 4\, p_0$

$p_{RX} = \alpha_{SMF}\, p_{TX}$

$p_{TX} = \alpha_{TX}\, \alpha_{AOP}\, p_{IN\text{-}TX}$

$p_{PD} = \alpha_{RX}\, p_{RX} / 4$

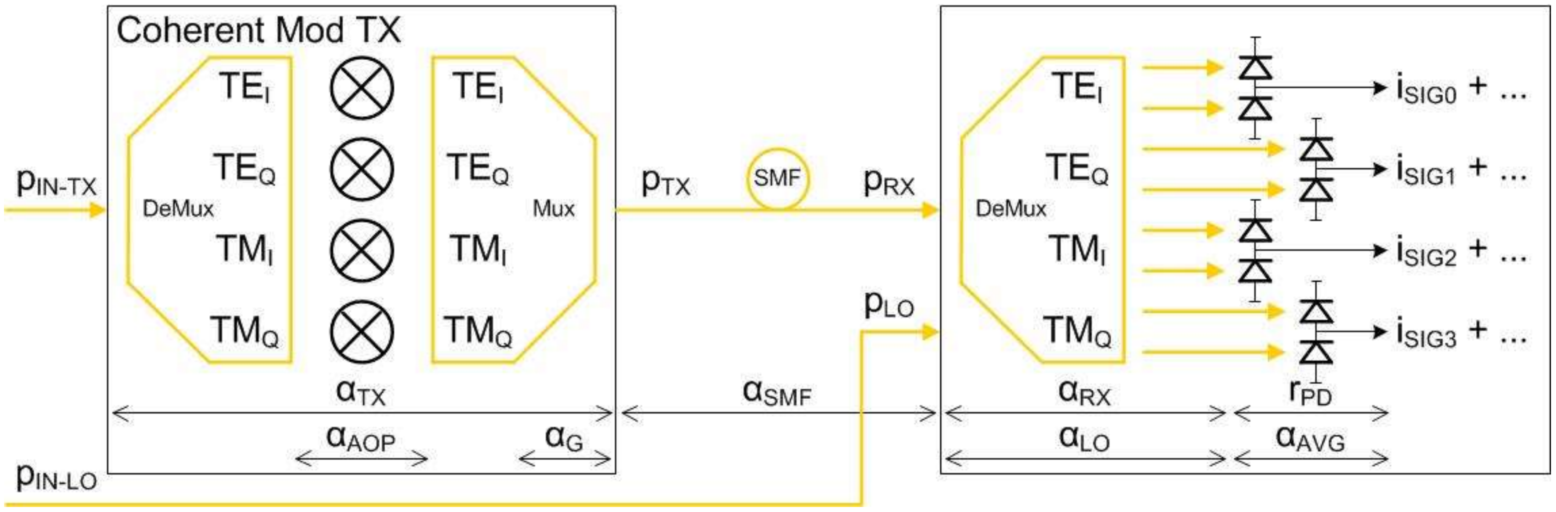
$i_{SIG} = \alpha_{AVG}\, r_{PD}\, p_{PD}$

$i_N = \alpha_N\, i_0 \sqrt{BW}$

$\sqrt{snr} = \alpha_{AVG}\, \alpha_{RX}\, \alpha_{SMF}\, \alpha_{TX}\, \alpha_{AOP}\, r_{PD}\, p_0 / (\alpha_N\, i_0 \sqrt{BW})$

C. Cole, “Inside the Datacenter is not yet a Nail for the Coherent Hammer”, WS05, Data Centers 1, Session 1, ECOC 2018, Rome, Italy, 23 Sep. 2018, and subsequent OFC and ECOC presentations.

Coherent (CH) IL Signal Path



$p_{IN-TX} = 4\,\alpha_{LS}\,\alpha_{TEC}\,p_0$ $p_{RX} = \alpha_{SMF}\,\alpha_{TX}$

$p_{TX} = \alpha_G\,\alpha_{TX}\,\alpha_{AOP}\,p_{IN-TX}$ $p_{PD-RX} = \alpha_{RX}\,p_{RX} / 4$

$p_{IN-LO} = 4\,(1 - \alpha_{LS})\,\alpha_{TEC}\,p_0$ $p_{LO} = p_{IN-LO}$ $p_{PD-LO} = \alpha_{LO}\,p_{LO} / 4$

$i_{SIG} = \alpha_{AVG}\,r_{PD}\,2\sqrt{(p_{PD-RX}\,p_{PD-LO})}$ $i_N = \alpha_N\,i_0\sqrt{BW}$

$\sqrt{snr} = \alpha_{AVG}\,\alpha_{RX}\sqrt{(\alpha_{SMF}\,\alpha_G\,\alpha_{TX}\,\alpha_{AOP})}\,\alpha_{TEC}\,r_{PD}\,p_0 / (\alpha_N\,i_0\sqrt{BW})$

Optical $\Delta SNR_{DD\text{-}CH} = SNR_{DD} - SNR_{CH}$ dB

$A \triangleq$ loss in optical -dB

$A = -10\log_{10}(\alpha)$

$\Delta SNR_{DD\text{-}CH} = SNR_{DD} - SNR_{CH} = 10\log_{10}(snr_{DD} / snr_{CH})$

$$
\begin{aligned}
\Delta SNR_{DD\text{-}CH} / 2 = & - (A_{AOP\text{-}DD} + A_{TX\text{-}DD} + A_{SMF}) \\
& + (A_{AOP\text{-}CH} + A_{TX\text{-}CH} + A_G + A_{SMF}) / 2 + A_{TEC} \\
& - (A_{AVG\text{-}DD} + A_{RX\text{-}DD} - A_{N\text{-}DD}) \\
& + (A_{AVG\text{-}CH} + A_{RX\text{-}CH} - A_{N\text{-}CH})
\end{aligned}
$$

$A_{TXT\text{-}DD} = A_{AOP\text{-}DD} + A_{TX\text{-}DD}$ $\quad$ $A_{RXT\text{-}DD} = A_{AVG\text{-}DD} + A_{RX\text{-}DD} - A_{N\text{-}DD}$

$A_{TXT\text{-}CH} = A_{AOP\text{-}CH} + A_{TX\text{-}CH} + A_G + 2A_{TEC}$ $\quad$ $A_{RXT\text{-}CH} = A_{AVG\text{-}CH} + A_{RX\text{-}CH} - A_{N\text{-}CH}$

$\Delta SNR_{DD\text{-}CH} = (A_{TXT\text{-}CH} + A_{SMF} + 2A_{RXT\text{-}CH}) - 2(A_{TXT\text{-}DD} + A_{SMF} + A_{RXT\text{-}DD})$

Optical $\Delta SNR_{DD\text{-}CH}$ dB Comparison

- Example: Equal total input AOP from laser source (TEC ignored):

$$\Delta SNR_{DD\text{-}CH} = (A_{TXT\text{-}CH} + A_{SMF}) - 2(A_{TXT\text{-}DD} + A_{SMF}) + 2(A_{RXT\text{-}CH} - A_{RXT\text{-}DD})$$

ex.	Link reach only	or 2km reach w/ optical switch loss	Link loss	TX & RX Total loss				$\Delta SNR_{DD\text{-}CH}$	unit
			A_{SMF}	$A_{TXT\text{-}DD}$	$A_{TXT\text{-}CH}$	$A_{RXT\text{-}DD}$	$A_{RXT\text{-}CH}$		
1	2km	0	4	5	17	2	4	7	dB
2	20km	7	11					0	
3	40km	14	18					-7	

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Thank you