IMDD vs Coherent
Will Datacenter be the New Battleground?

Summer Topicals 2020 Virtual Conference

Tutorial TuA2.2 10:45AM – 11:30AM MDT

14 July 2020

Chris Cole

Outline

- **NRZ vs HOM**
- Serial vs WDM
- Coherent in Telecom
- Coherent in Datacom
- IMDD vs Coherent SNR
- Intra Datacenter Optics
- Appendices

Shannon-Hartley Theorem

$C = B \log_2 (1 + S/N)$

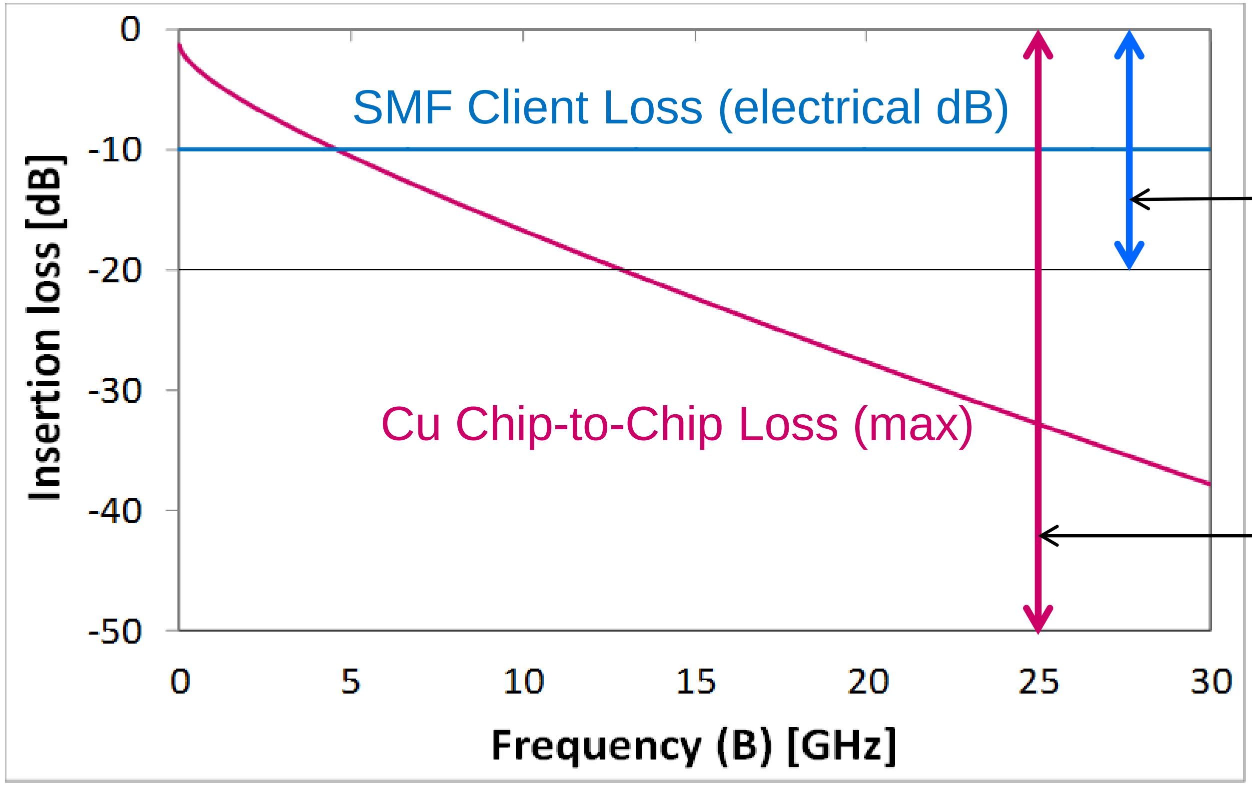
- $C \triangleq$ Channel capacity
- $B \triangleq$ Bandwidth
- $S \triangleq$ Signal Power
- $N \triangleq$ Noise Power

Guidance to increase C:

- If B limited, use S/N to increase modulation order
- If S/N limited, use B to increase Baud rate

C. Cole, “SMF PMD Modulation Observations”, 400 Gb/s Ethernet Task Force, IEEE 802.3 Plenary Session, Berlin, Germany, 10-12 March 2015cc

Cu C2C SerDes & SMF Client TRX S/N (BtB, no FEC)



SMF client TRX:
- low S/N
- high B

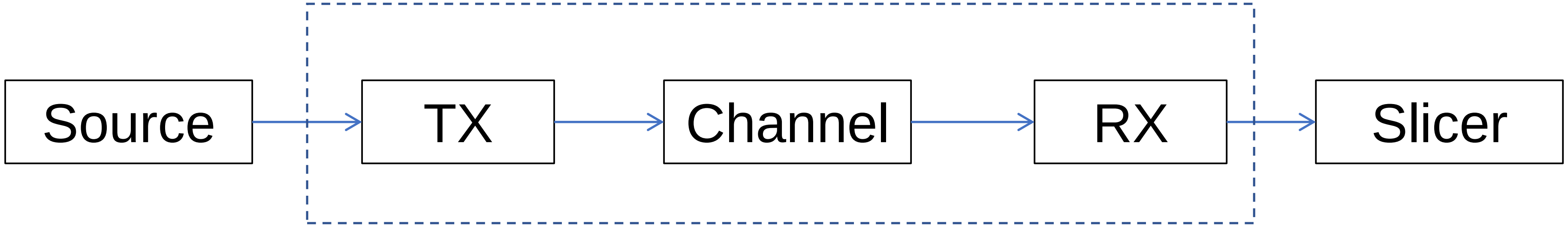
Shannon says: use NRZ

Cu C2C SerDes:
- high S/N
- low B

Shannon says: use HOM

HOM ≙ Higher Order Modulation

Ideal SMF Client System Model



- SMF client channel ideal
- (TX $*$ Channel $*$ RX) modelled as 4th order BT filter
- B = α bit-rate
- Ex. bit rate = 56Gb/s

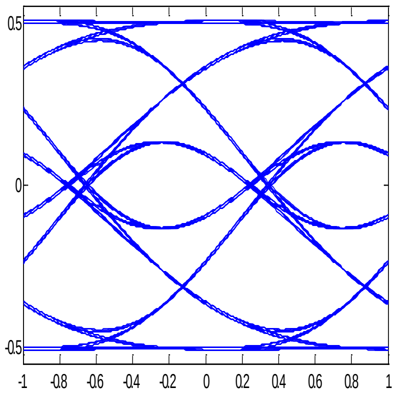
  ex. 1: α = 0.25 → B = 14GHz

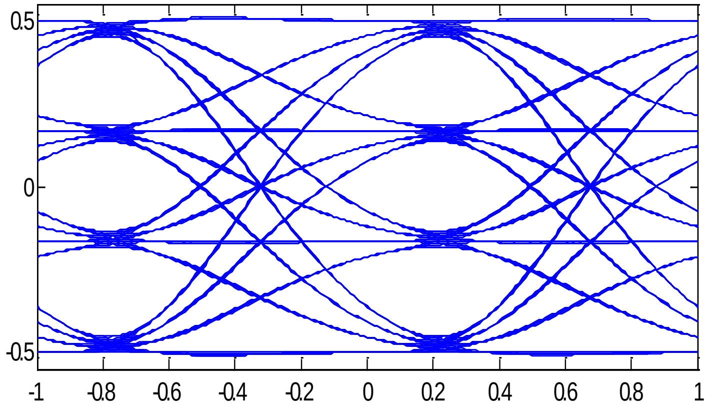
  ex. 2: α = 0.30 → B = 17GHz

Slicer Input Eyes of Ideal Noiseless SMF Client System

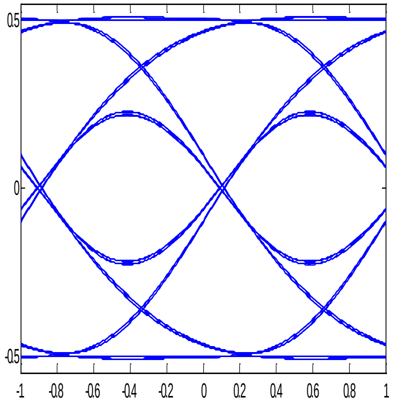
NRZ | PAM-4

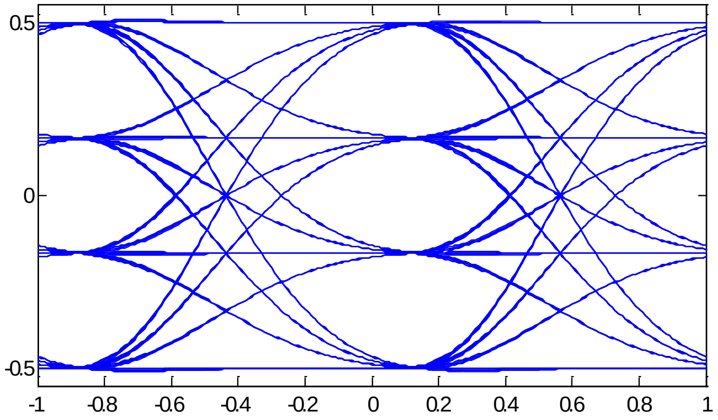
Ex. 1. α = 0.25 (14GHz)
NRZ VEC ≈ PAM4 VEC



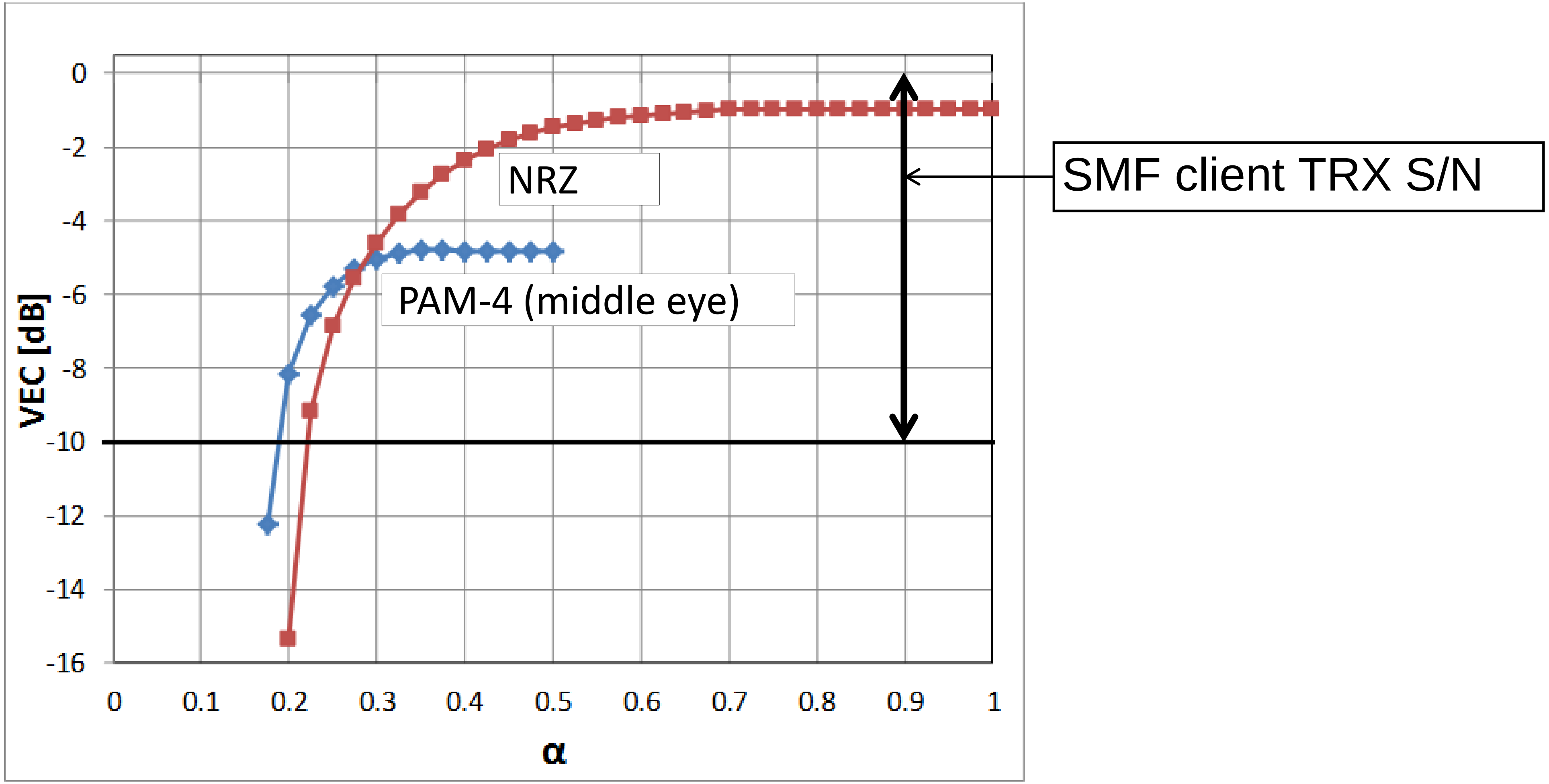


Ex. 2. α = 0.30 (17GHz)
NRZ VEC < PAM4 VEC





Vertical Eye Closure at Slicer Input w/ Noise Normalization



IEEE Modulation Choice for 50Gb/s and Faster Rates

- Optics is the tail on the IC industry dog
  - 50G PAM4 ASIC SerDes was first developed for the Cu channel
  - IC Vendors wanted to maximize their ADC and DSP investment
- IC dog wagged the optics tail
  - IEEE ignored Shannon
  - PAM4 standardized for 50G and 100G Ethernet optical lane rates
  - 200G (4x50G PAM4) FR4 will soon ship in the millions
- Optics & electronics today easily support 50G NRZ
  - Extra cost and power of 50G PAM4 ADC, DSP, SNR locked-in forever

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Ethernet Optics History: 1 & 10GbE

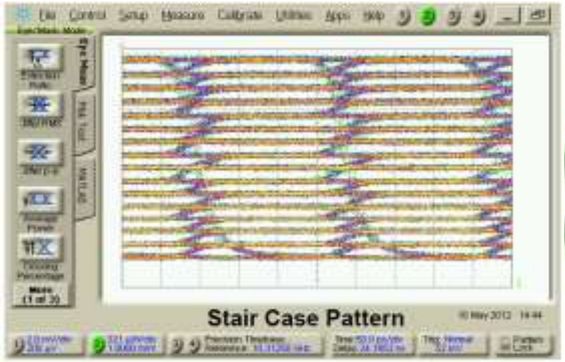
- 1GbE standard adopted in 1998
  - 1λ Serial NRZ (LX)
  - Shipped in the millions
- 10GbE standard adopted in 2002
  - 4λ WDM NRZ (LX4)
  - 1λ Serial NRZ (LR4)
  - 5-year delay in 10GbE adoption after 90's Tech bubble collapse
  - 10GBaud optics & electronics matured to easily support 10G NRZ
- 10G LR4 shipped in the millions
- 10G LX4 became a sad footnote in Ethernet optics history
- "Serial is always cheaper" myth is born

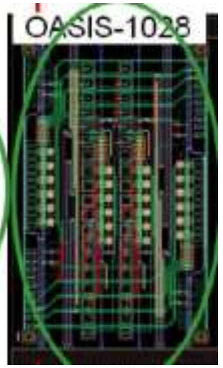
Ethernet Optics History: 40GbE

- 40GbE standard adopted in 2010
    - “Serial is always cheaper” myth well established
    - Fierce debate in the IEEE between:
        - 4λ WDM NRZ (LR4) vs.
        - 1λ Serial NRZ (FR)
        - IEEE split the baby, adopted both
- 40G LR4 shipped in the millions
- 40G FR became a sad footnote in Ethernet optics history

Ethernet Optics History: 100GbE

- 100GbE standard, targeted at the datacenter, adopted in 2015
  - “Serial is always cheaper” myth going strong
  - Fierce debate in the IEEE about duplex SMF spec between:
    - 4λ CWDM NRZ (FR4)
    - 1λ Serial PAM16/8 (FR)
    - IEEE could not reach agreement, and neither was adopted
- 100G CWDM4 spec developed immediately after in an MSA in 6 months
  - Shipped in the millions
- 100G PAM16/8 became a sad footnote in Ethernet optics history
- $240M SNR math lesson for Cisco





Ethernet Optics History: 400GbE

- 400GbE standard adopted in 2017
  - “Serial is always cheaper” myth unwavering
  - Fierce debate in the IEEE between:
    - 2λ*50G WDM for 100G FR2 and 8λ*50G LWDM 400G LR8
    - 1λ*100G Serial for 100G FR and 400G PSM DR4
    - IEEE split the baby, adopted 400G LR8 and DR4, but no 100G FR2
- 400G 8λ*50G LWDM LR8 shipped in low volume into early Telecom apps
- 400G 4λ*100G CWDM FR4 standardized soon afterwards

Ethernet Optics History: 400GbE (2)

- Ethernet optics sad story 1: no Web2.0 deployment of 400GbE
  - Huge industry R&D investment into 1st Gen 400GbE DR4 & FR4 with no ROI
  - 2nd Gen 400GbE will start shipping in volume in 2023 or later when Ethernet switches ship with 100G I/O
- Ethernet optics sad story 2: no low-cost, low-power 2λ 100GbE optics matched to today's Ethernet switches with 50G I/O, forcing shipment of:
  - 4λ 100G CWDM4 with 1:2 reverse gearbox (most Web2.0s), or
  - 1λ 100G FR with with 2:1 forward gearbox (Amazon mainly)
  - Either way, significant cost and power added to 100G Ethernet optical links

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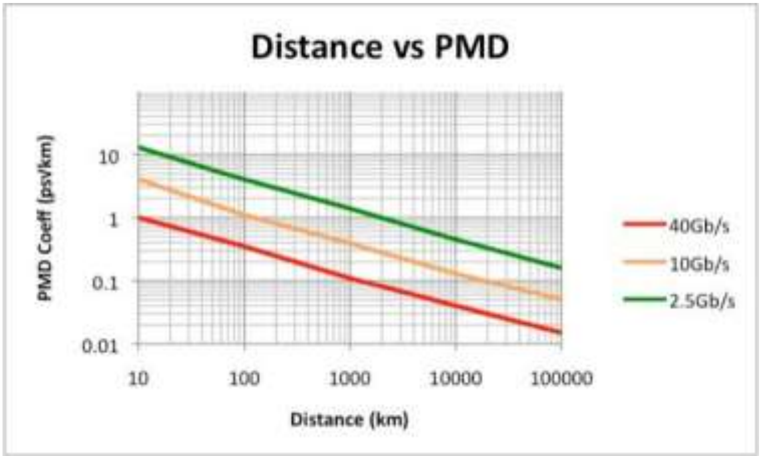
G.652 SMF DWDM Transport C-band Spec Limits

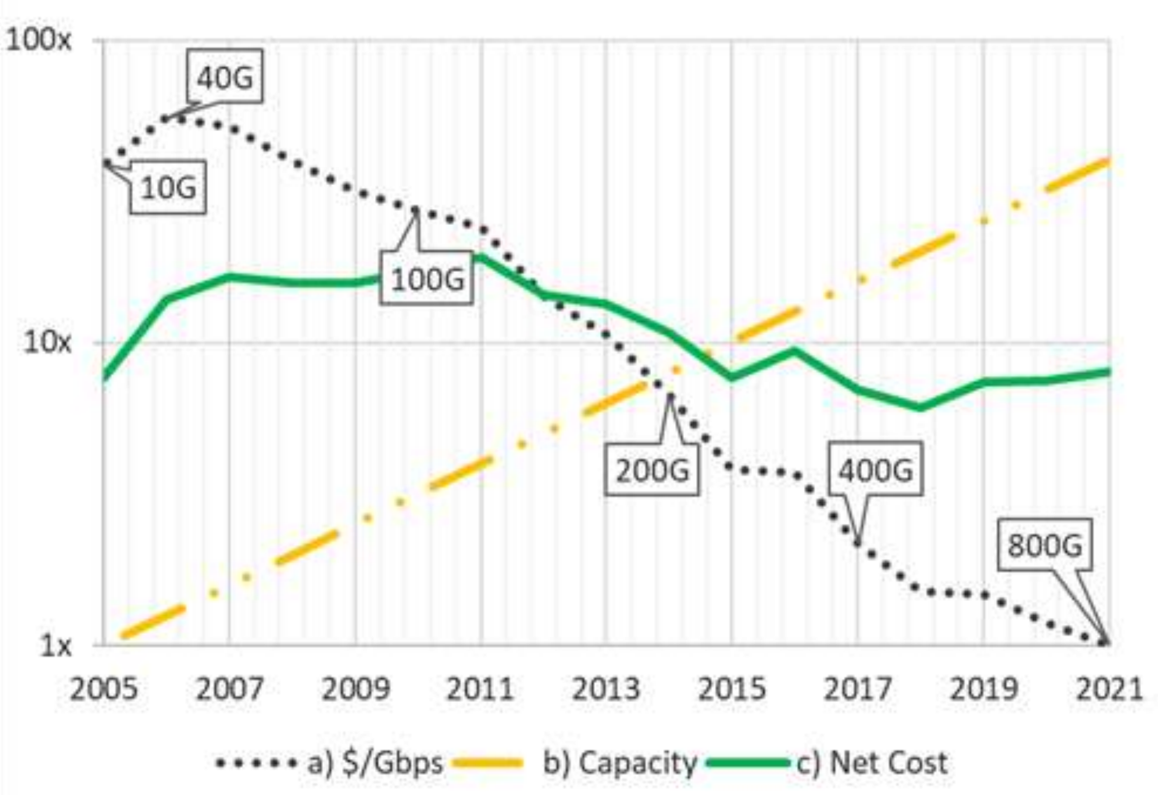
- Loss
  - nom, max: 0.2, 0.28dB/km
  - IF link SNR was only determined by link loss
    - Coherent SNR ≈ 2x IMDD SNR, in dB
    - Coherent reach ≈ 2x IMDD reach, i.e. half the amplifier cost
- Bandwidth (B)
  - Spectral Efficiency is key metric because of fiber deployment cost
  - G.694.1 channel bandwidths: 25 to 100GHz
  - Coherent has 4 orthogonal channels: I, Q, TE, TM
  - Shannon says: If B limited, use S/N to increase modulation order

G.652 SMF DWDM Transport C-band Spec Limits (2)

- Chromatic Dispersion (CD)
  - nom, max: 17, 20ps/nm-km
  - CD penalty variable with link reach
  - IMDD Fixed EQ: unique CDF length for each link
  - Coherent adaptive EQ: common for all links
- Polarization Mode Dispersion Q (PMDQ)
  - A&C nom: 0.5ps/√km
  - B&D nom: 0.2ps/√km
  - DGD is important over long reaches
  - Coherent adaptive EQ tracks polarization



Transport Cost vs Time



10G - 40G: IMDD

100G - 800G: Coherent

"A straight line will continue indefinitely as a straight line"

Optical Networks Forecast: 2018 – 2023, Jan 2019 Representative cost of optical transport capacity over time and transponder generations based on historical average sales price (ASP) of DWDM line card data from Ovum.

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

- Loss
  - max: 0.47dB
  - Connectors and other passives determine link loss
  - Nom link loss budget: 4dB
  - SMF loss is not important
- Bandwidth (B)
  - 4 wavelength band: 10THz
  - 1 wavelength channel: 800GHz
  - Shannon says: If S/N limited, use B to increase Baud rate
  - SMF bandwidth is not important

G.652 1km SMF CWDM4 O-band Spec Limits (2)

- Chromatic Dispersion (CD)
  - min: -6ps/nm
  - max: 3ps/nm
  - SMF CD penalty is not important
- Polarization Mode Dispersion Q (PDM_Q)
  - A&C nom: 0.5ps
  - B&D nom: 0.2ps
  - SMF DGD penalty is not important

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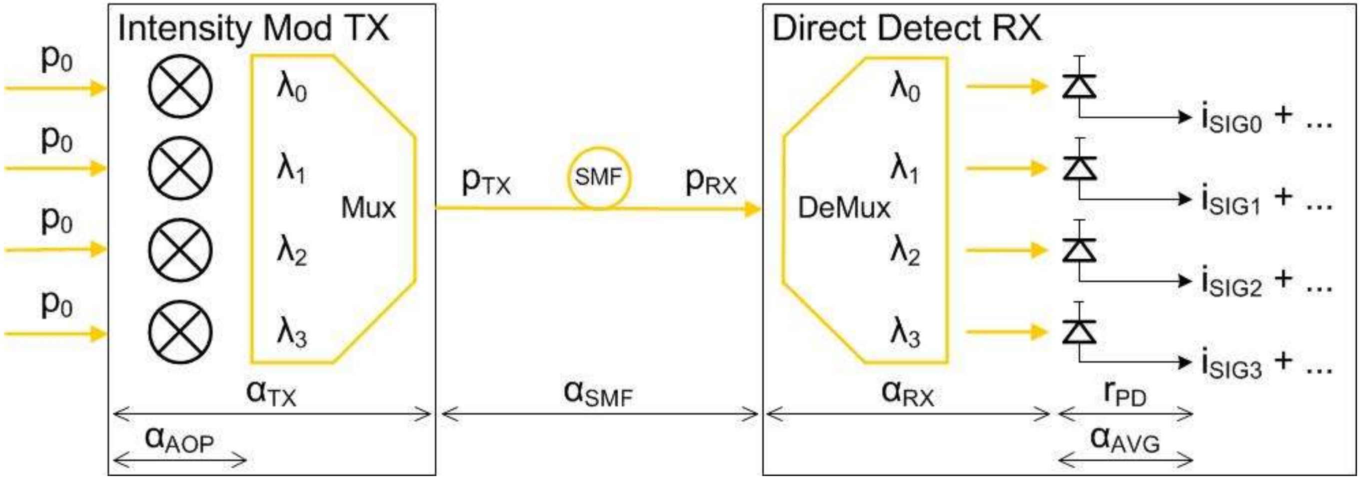
Direct Detection (DD) Signal Path



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

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

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

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

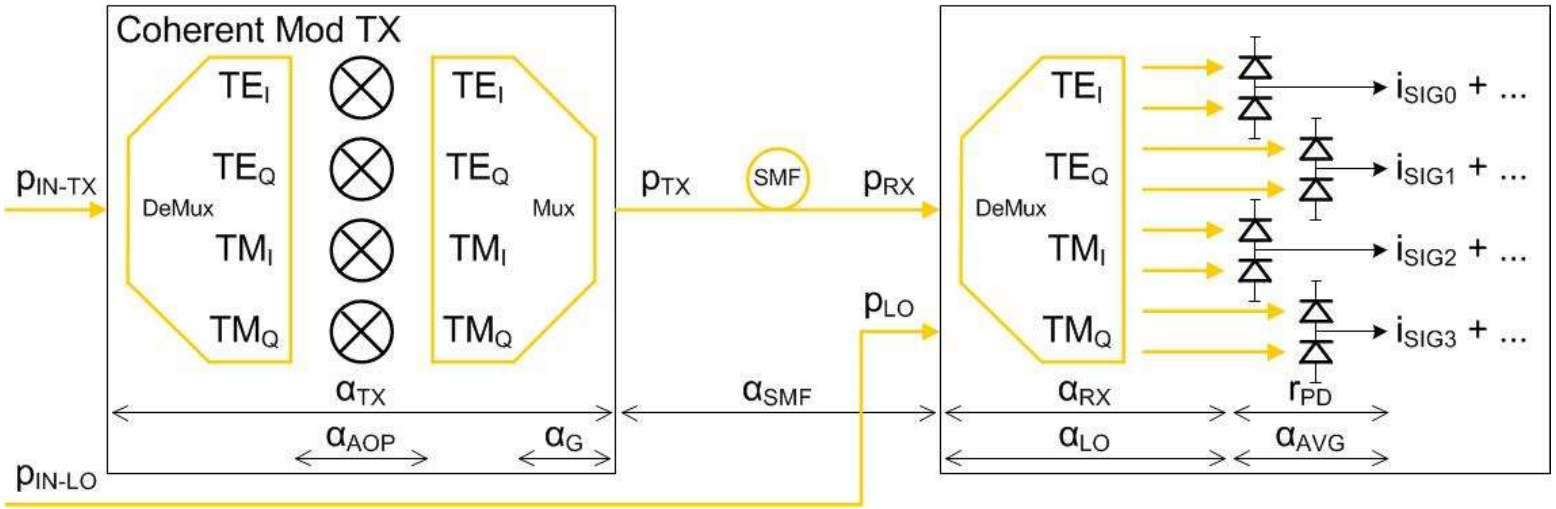
$p_{RX} = \alpha_{SMF}\, p_{TX}$

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

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

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.

Coherent (CH) Signal Path



$p_{IN\text{-}TX} = 4\ \alpha_{LS}\ \alpha_{TEC}\ p_0$

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

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

$i_{SIG} = \alpha_{AVG}\ r_{PD}\ 2\ \sqrt{(p_{PD\text{-}RX}\ p_{PD\text{-}LO})}$

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

$p_{PD\text{-}RX} = \alpha_{RX}\ p_{RX} / 4$

$p_{LO} = p_{IN\text{-}LO}$

$p_{PD\text{-}LO} = \alpha_{LO}\ p_{LO} / 4$

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

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

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

$A \triangleq$ loss in optical -dB

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

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

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

$A_{TXT\text{-}DD} = A_{AOP\text{-}DD} + A_{TX\text{-}DD}$

$A_{TXT\text{-}CH} = A_{AOP\text{-}CH} + A_{TX\text{-}CH} + A_G + 2A_{TEC}$

$A_{RXT\text{-}DD} = A_{AVG\text{-}DD} + A_{RX\text{-}DD} - A_{N\text{-}DD}$

$A_{RXT\text{-}CH} = A_{AVG\text{-}CH} + A_{RX\text{-}CH} - A_{N\text{-}CH}$

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

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

- Equal laser input AOP (TEC ignored):

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

- 100G EML NRZ CWDM4 IMDD vs 100G SiPIC QPSK Coherent
- Ex.1: **4dB** Link Loss (2km, typical intra datacenter)

  $\Delta SNR_{DD\text{-}CH} = ((17 + 4) - 2(5 + 4)) + 2(4 - 2)$ = **7dB**

- Ex.2: **11dB** Link Loss (20km, or 2km & one 7dB loss optical switch)

  $\Delta SNR_{DD\text{-}CH} = ((17 + 11) - 2(5 + 11)) + 2(4 - 2)$ = **0**

- Ex.2: **18dB** Link Loss (40km, or 2km & two 7dB loss optical switches)

  $\Delta SNR_{DD\text{-}CH} = ((17 + 18) - 2(5 + 18)) + 2(4 - 2)$ = **-7dB**

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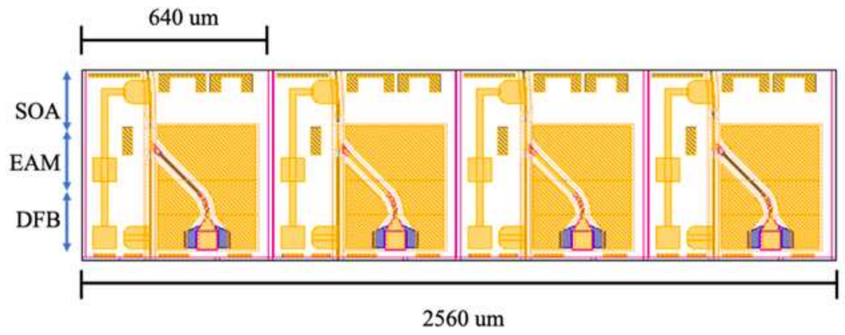
Intra Datacenter Optics Requirements

- What's important?
  - Cheap laser(s)
  - Cheap SNR (low loss components)
  - Cheap assembly and packaging
  - Cheap testing
- What does Coherent offer?
  - Expensive Laser
  - High loss components
  - Best case comparable packaging cost to IMDD
  - Complex testing

TX Modulator Size Comparison

- IMDD InP EML length:
  - 400 - 500um (EA ≈ 120um)
- Coherent Si MZM length:
  - 2 - 4mm
- 4 channel Coherent to IMDD TX area ratio:
  - 10 - 20x



Teriphic project, 4x100G PAM4 EML TX

Intra Datacenter Optics Today: Pluggable

- Characteristics
  - \$1 - \$2/Gb
  - ~30pJ/bit
  - IMDD DML or EML uncooled TX
  - 4λ CWDM NRZ or PAM4
  - Link budget: 4dB
- IMDD vs. Coherent SNR, equal laser DC Power (TEC included):

  100G EML NRZ CWDM4 IMDD vs 100G SiPIC QPSK Coherent

  $\Delta SNR_{DD\text{-}CH} = 11.5dB$

  (same result for PAM4 IMDD vs QAM16 Coherent)

Intra Datacenter Optics Tomorrow: Co-packaged

- Requirements
  - Co-packaged with Ethernet Switch ASIC
  - 256 - 512 data lanes
  - <$1/Gb
  - <10pJ/bit
  - Link budget: 4dB
- IMDD vs. Coherent SNR, equal laser DC Power (TEC included):

  100G SiPIC NRZ CWDM4 IMDD vs 100G SiPIC QPSK Coherent

  $\Delta SNR_{DD\text{-}CH}$ = 1.5dB

  (same result for PAM4 IMDD vs QAM16 Coherent)

Summary

- Coherent advantages in Transport are unimportant in Intra Datacenter
- Coherent indefinitely locks in the cost and power of ADCs and DSPs
  - This is what PAM4 did for >100G Ethernet optics
  - Good for IC vendors, bad for everyone else as optics improve
- “Serial is always cheaper” is a myth for leading data rates
  - 10GbE was the last time it was true
  - 1λ Coherent is higher cost and power than 4λ IMDD
- Coherent does not reduce the cost and power of short reach optics
- There is no IMDD vs Coherent competition for Intra Datacenter links
  - Coherent is not even on the battleground

IMDD vs Coherent

Thank You

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- **Appendix 1**

Direct Detection (DD) Signal Path Variables

p_0 ≜ Input POP (Peak Optical Power) reference
$p_{IN\text{-}TX}$ ≜ TX input POP = AOP (Average OP) if CW
α_{AOP} ≜ TX POP to AOP modulation loss vs. er (extinction ratio)
α_{TX} ≜ TX path intrinsic loss at modulator bias point
p_{TX} ≜ TX total output AOP
α_{SMF} ≜ Link total power loss (connectors, SMF, other passives)
p_{RX} ≜ RX total input AOP
α_{RX} ≜ RX path intrinsic loss
p_{PD} ≜ RX PD input AOP
r_{PD} ≜ RX PD responsivity
α_{AVG} ≜ PD AOP to average electrical signal power loss vs. er

Direct Detection (DD) SNR

i_{SIG} ≜ RX PD signal current
$i_{SIG} = \alpha_{AVG}\, r_{PD}\, p_{PD} = \alpha_{AVG}\, \alpha_{RX}\, \alpha_{SMF}\, \alpha_{TX}\, \alpha_{AOP}\, r_{PD}\, p_0$

i_N ≜ RX input referred noise current; all sources
i_0 ≜ RX input noise current density reference
α_N ≜ RX input noise current loss vs. i_0
BW ≜ RX input noise bandwidth
$i_N = \alpha_N\, i_0 \sqrt{BW}$

$snr = (i_{SIG} / i_N)^2$
$\sqrt{snr} = \alpha_{AVG}\, \alpha_{RX}\, \alpha_{SMF}\, \alpha_{TX}\, \alpha_{AOP}\, r_{PD}\, p_0 / (\alpha_N\, i_0 \sqrt{BW})$

Coherent (CH) Signal Path Variables

p_0 ≜ Input POP (Peak Optical Power) reference
α_{TEC} ≜ Input POP loss due to laser TEC current
α_{LS} ≜ TX input POP loss due to (1- α_{LS}) LO (Local Oscillator) input split
$p_{IN\text{-}TX}$ ≜ TX input POP = AOP since CW
α_{AOP} ≜ TX POP to AOP modulation loss vs. MD (mod. drive)
α_{TX} ≜ TX path intrinsic loss at modulator bias point
α_G ≜ TX optical gain (α_G = 1 if no amplification)
p_{TX} ≜ TX total output AOP
α_{SMF} ≜ Link total power loss (connectors, SMF, other passives)

Coherent (CH) Signal Path Variables, cont.

p_{RX} ≜ RX total input AOP
p_{LO} ≜ RX LO input AOP
$\Phi(t)$ ≜ Phase angle between p_{RX} and p_{LO} electric fields
α_{RX} ≜ RX SIG path intrinsic loss
α_{LO} ≜ RX LO path intrinsic loss
p_{PD} ≜ RX PD input AOP
r_{PD} ≜ RX PD responsivity
α_{AVG} ≜ PD AOP to average electrical signal power loss vs. MD

Coherent Signal Addition

Optical signals, with same polarization state, add in the electric field domain

$E_{LO} / \sqrt{Z}$	$\triangleq \sqrt{p_{LO}}$
$E_{RX} / \sqrt{Z}$	$= \cos\Phi(t)\sqrt{p_{RX}} + j\sin\Phi(t)\sqrt{p_{RX}}$
$E_{PD} / \sqrt{Z}$	$= \sqrt{p_{LO}} + \cos\Phi(t)\sqrt{p_{RX}} + j\sin\Phi(t)\sqrt{p_{RX}}$
P_{PD}	$= (\sqrt{p_{LO}} + \cos\Phi(t)\sqrt{p_{RX}})^2 + (\sin\Phi(t)\sqrt{p_{RX}})^2$
	$= p_{LO} + 2\sqrt{p_{LO}}\sqrt{p_{RX}}\cos\Phi(t) + p_{RX}$
p_{RX}	$<< 2\sqrt{p_{LO}}\sqrt{p_{RX}}\cos\Phi(t)$
p_{LO} RIN	$<< 2\sqrt{p_{LO}}\sqrt{p_{RX}}\cos\Phi(t)$
p_{PD}	$= 2\sqrt{(p_{LO}\, p_{RX})}\cos\Phi(t)$

Coherent (CH) SNR

$i_{SIG} \triangleq$ RX balanced PD pair signal current

$i_{SIG} = \alpha_{AVG}\, r_{PD}\, 2 \sqrt{(p_{PD\text{-}RX}\, p_{PD\text{-}LO})} \cos \Phi(t)$

$\cos \Phi(t) \triangleq 1$ $\quad \alpha_{LS} \triangleq ½$ $\quad \alpha_{LO} \triangleq \alpha_{RX}$

$i_{SIG} = \alpha_{AVG}\, \alpha_{RX} \sqrt{(\alpha_{SMF}\, \alpha_G\, \alpha_{TX}\, \alpha_{AOP})}\, \alpha_{TEC}\, r_{PD}\, p_0$

$i_N \triangleq$ RX input referred noise current; all sources

$i_0 \triangleq$ RX input noise current density reference

$\alpha_N \triangleq$ RX input noise current loss vs. i_0

$BW \triangleq$ RX input noise bandwidth

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

$snr = (i_{SIG} / i_N)^2$

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

Ratio DD SNR to CH SNR: $\sqrt{(snr_{DD} / snr_{CH})}$

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

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

$r_{PD\text{-}DD} \triangleq r_{PD\text{-}CH}$

$BW_{DD} \triangleq BW_{CH}$

$$\sqrt{(snr_{DD} / snr_{CH})} = \alpha_{AVG\text{-}DD}\, \alpha_{RX\text{-}DD}\, \alpha_{SMF}\, \alpha_{TX\text{-}DD}\, \alpha_{AOP\text{-}DD}\, \alpha_{N\text{-}CH} / \alpha_{AVG\text{-}CH}\, \alpha_{RX\text{-}CH}\, \sqrt{(\alpha_{SMF}\, \alpha_G\, \alpha_{TX\text{-}CH}\, \alpha_{AOP\text{-}CH})}\, \alpha_{TEC}\, \alpha_{N\text{-}DD}$$

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

$A \triangleq$ loss in optical -dB

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

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

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

$A_{TX\text{-}T\text{-}DD} = A_{AOP\text{-}DD} + A_{TX\text{-}DD}$

$A_{TX\text{-}T\text{-}CH} = A_{AOP\text{-}CH} + A_{TX\text{-}CH} + A_G + 2A_{TEC}$

$A_{RX\text{-}T\text{-}DD} = A_{AVG\text{-}DD} + A_{RX\text{-}DD} - A_{N\text{-}DD}$

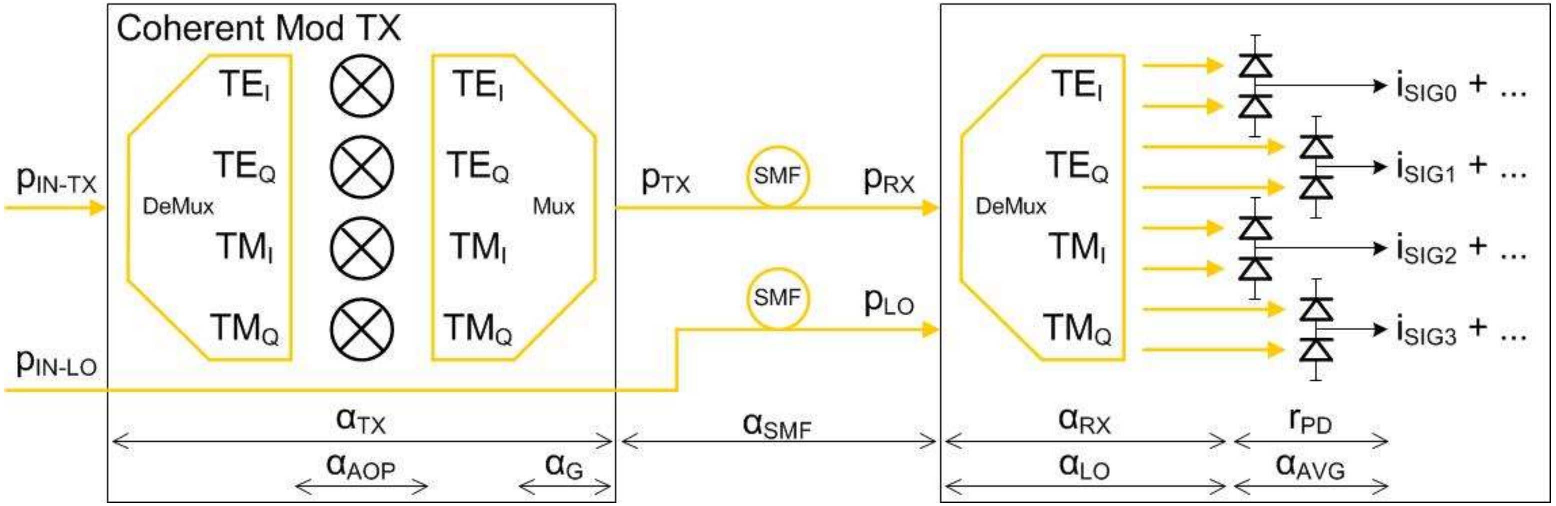
$A_{RX\text{-}T\text{-}CH} = A_{AVG\text{-}CH} + A_{RX\text{-}CH} - A_{N\text{-}CH}$

$$\Delta SNR_{DD\text{-}CH} = (A_{TX\text{-}T\text{-}CH} + A_{SMF} + 2A_{RX\text{-}T\text{-}CH}) - 2(A_{TX\text{-}T\text{-}DD} + A_{SMF} - A_{RX\text{-}T\text{-}DD})$$

Outline

- NRZ vs HOM
- Serial vs WDM
- Coherent in Telecom
- Coherent in Datacom
- IMDD vs Coherent SNR
- Intra Datacenter Optics
- **Appendix 2**

Coherent (CH) w/ same TX Signal & LO Path



$p_{IN\text{-}TX} = 4\ \alpha_{LS}\ \alpha_{TEC}\ p_0$

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

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

$i_{SIG} = \alpha_{AVG}\ r_{PD}\ 2\ \sqrt{(p_{PD\text{-}RX}\ p_{PD\text{-}LO})}$

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

$p_{PD\text{-}RX} = \alpha_{RX}\ p_{RX} / 4$

$p_{PD\text{-}LO} = \alpha_{LO}\ \alpha_{SMF}\ \alpha_G\ \alpha_{TX}\ \alpha_{AOP}\ p_{IN\text{-}LO} / 4$

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

Coherent (CH) RX Signal w/ same TX Signal & LO Path

$i_{SIG} \triangleq$ RX balanced PD pair signal current

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

$$\alpha_{LS} \triangleq ½ \qquad \alpha_{LO} \triangleq \alpha_{RX}$$

$$i_{SIG} = \alpha_{AVG}\, \alpha_{RX}\, \alpha_{SMF}\, \alpha_{G}\, \alpha_{TX}\, \alpha_{AOP}\, \alpha_{TEC}\, r_{PD}\, p_0$$

Equal DD and CH total input AOP condition:

$$p_{IN\text{-}DD\text{-}TX} \triangleq p_{IN\text{-}CH\text{-}TX} + p_{IN\text{-}CH\text{-}LO}$$

$$i_{DD\text{-}SIG} = i_{CH\text{-}SIG}$$

When the LO is remote, i.e. it’s a RO, there is no Coherent signal gain!

Same TX Signal and LO Path analysis approach proposed by Mike Frankel, Ciena, 18 Jan 2018.

Outline

- NRZ vs HOM
- Serial vs WDM
- Coherent in Telecom
- Coherent in Datacom
- IMDD vs Coherent SNR
- Intra Datacenter Optics
- **Appendix 3**

$\Delta SNR_{DD\text{-}CH} = SNR_{DD} - SNR_{CH}$ Examples

$\Delta SNR_{DD\text{-}CH} / 2 =$

$- A_{AOP\text{-}DD}$	$+ A_{AOP\text{-}CH} / 2$	// TX
$- A_{TX\text{-}DD}$	$+ A_{TX\text{-}CH} / 2$	// TX
$- (- A_{G} / 2)$	$+ A_{TEC}$	// TX Scenario
$- A_{SMF}$	$+ A_{SMF} / 2$	// Link
$- A_{RX\text{-}DD}$	$+ A_{RX\text{-}CH}$	// RX
$- A_{AVG\text{-}DD}$	$+ A_{AVG\text{-}CH}$	// RX
$- (- A_{N\text{-}DD})$	$+ (- A_{N\text{-}CH})$	// RX

TX Modulation Loss

- α_{AOP}, A_{AOP} ≜ TX input POP to AOP modulation loss; linear, -dB
- $\alpha_{AOP\text{-}NRZ}$ [er] = (er + 1) / (2 er) // Mod. TX
  $\alpha_{AOP\text{-}NRZ}$ [er] = 1 // DML TX
  $\alpha_{AOP\text{-}PAM4}$ [er] = (er + 1) / (2 er) // Mod. TX
  $\alpha_{AOP\text{-}PAM4}$ [er] = 1 // DML TX
- $\alpha_{AOP\text{-}QPSK}$ [$2V_\pi$] = 1
  $\alpha_{AOP\text{-}QPSK}$ [V_π] = 1/2
  $\alpha_{AOP\text{-}QAM16}$ [$2V_\pi$] = 5/9
  $\alpha_{AOP\text{-}QAM16}$ [V_π] = 5/18
- Equal DD & CH TX modulation drive
  $MD_{DD\text{-}Max}$ ≜ ½ $MD_{CH\text{-}Max}$
  MD_{CH} = V_π

TX Modulation Loss Values

- $A_{AOP} \triangleq$ TX input POP to AOP modulation loss, -dB

mod. loss variable	ER dB	DD mod. loss value -dB		DD DM loss value -dB	
		NRZ	PAM4	NRZ	PAM4
$A_{AOP\text{-}DD}$	∞	3.0	3.0	*0.0*	*0.0*
	7	2.2	2.2	*0.0*	*0.0*
	4.8	*1.8*	*1.8*	0.0	0.0

mod. loss variable	MD	CH loss value -dB		CH loss value -dB / 2	
		QPSK	QAM16	QPSK	QAM16
$A_{AOP\text{-}CH}$	$2V_{\pi}$	*0.0*	*2.6*	*0.0*	*1.3*
	V_{π}	*3.0*	*5.6*	1.5	2.8

TX Signal Path Intrinsic Loss Values

- A_{TX} ≜ TX path intrinsic loss, -dB

Ex. #	Implementation	DD loss value -dB	CH loss value -dB
		$A_{TX\text{-}DD}$	$A_{TX\text{-}CH}$
1	Ideal TX & RX, no loss	0	0
2	DD CWDM4 TFF DML TX, RX CH SiP	4	14
3	DD CWDM4 TFF EML TX, RX CH SiP (ECOC'18 WS Example)	5	14
4	DD PSM4 SiP TX & RX CH SiP	6	14
5	DD CWDM4 SiP TX & RX, CH SiP	8	14

TX Scenarios

- α_{TEC}, A_{TEC} ≜ TX_{CH} input POP loss, laser TEC current; linear, -dB
- α_G, A_G ≜ TX_{CH} optical gain

  A_G TX_{CH} optical gain = - A_G TX_{DD} optical loss in $\Delta SNR_{DD\text{-}CH}$ table
- Scenario 1: equal laser DC power (40% efficient CH TEC)

  $i_{Laser\text{-}bias\text{-}DD} \triangleq i_{Laser\text{-}bias\text{-}CH} + i_{Laser\text{-}TEC\text{-}CH}$

  $\alpha_{TEC} \triangleq 0.4$

  $\alpha_G \triangleq 1$
- Scenario 2: equal TX & LO total input POP (no CH TEC)

  $p_{IN\text{-}TX\text{-}DD} \triangleq p_{IN\text{-}TX\text{-}CH} + p_{IN\text{-}LO\text{-}CH}$

  $\alpha_{TEC} \triangleq 1$

  $\alpha_G \triangleq 1$

TX Scenarios, cont.

- Scenario 3: equal TX total output AOP (no DC power limit)

$$p_{TX\text{-}DD} \triangleq p_{TX\text{-}CH}$$

$$A_{TX\text{-}DD} + A_{AOP\text{-}DD} = A_G + A_{TX\text{-}CH} + A_{AOP\text{-}CH} + A_{LS} + A_{TEC}$$

$$\alpha_{TEC} \triangleq 1$$

$$A_{TEC} = 0$$

$$\alpha_{LS} \triangleq 1/2$$

$$A_{LS} = 3$$

$$- A_G / 2 = ((A_{TX\text{-}CH} + A_{AOP\text{-}CH} + 3) - (A_{TX\text{-}DD} + A_{AOP\text{-}DD})) / 2$$

TX Scenarios Loss Values

- A_{TEC} ≜ TX_{CH} input POP loss due to laser TEC current, -dB
- A_G ≜ A_G TX_{CH} optical gain = $-A_G$ TX_{DD} optical loss

$\Delta SNR_{DD\text{-}CH} / 2$ TX Scenario		DD loss variable	DD loss value -dB	CH loss variable	CH loss value -dB
1	Equal laser DC power	$-A_G / 2$	0	A_{TEC}	4
2	Equal total input AOP	$-A_G / 2$	0	A_{TEC}	0
3	Equal TX total output AOP	$-A_G / 2$	formula	A_{TEC}	0

Link Loss Values

- $A_{SMF} \triangleq$ Link total power loss (connectors, SMF, other passives), -dB
- Standard datacenter link loss budget
  $A_{SMF} \triangleq 4$

DD loss value -dB	CH loss value -dB
A_{SMF}	$A_{SMF} / 2$
4.0	2.0

RX Signal Path Intrinsic Loss Values

- $A_{RX} \triangleq$ RX path intrinsic loss, -dB
- $A_{LO} \triangleq$ RX LO path intrinsic loss, -dB: $A_{LO\text{-}CH} \triangleq A_{RX\text{-}CH}$

Ex. #	Implementation	DD loss value -dB	CH loss value -dB
		$A_{RX\text{-}DD}$	$A_{RX\text{-}CH}$
1	Ideal TX & RX, no loss	0	0
2	DD CWDM4 TFF DML TX, RX CH SiP	2	4
3	DD CWDM4 TFF EML TX, RX CH SiP (ECOC'18 WS Example)	2	4
4	DD PSM4 SiP TX & RX CH SiP	2	4
5	DD CWDM4 SiP TX & RX, CH SiP	4	4

RX Modulation Loss

- α_{AVG}, A_{AVG} ≜ RX PD AOP to average electrical signal power loss; linear, -dB
- α_{LS} ≜ TX input POP loss due to (1- α_{LS}) split with LO input
- $\alpha_{AVG\text{-}NRZ}$ [er] $= (er - 1) / (er + 1)$
  $\alpha_{AVG\text{-}PAM4}$ [er] $= \sqrt{(5/9)}\,(er - 1) / (er + 1)$
- $\alpha_{AVG\text{-}QPSK}$ $[2V_\pi]$ $= 1$
  $\alpha_{AVG\text{-}QPSK}$ $[V_\pi]$ $= 1$
  $\alpha_{AVG\text{-}QAM16}$ $[2V_\pi]$ $= 1$
  $\alpha_{AVG\text{-}QAM16}$ $[V_\pi]$ $= 1$
- Equal DD & CH TX modulation drive
  $MD_{DD\text{-}Max}$ ≜ ½ $MD_{CH\text{-}Max}$
  $MD_{CH} = V_\pi$

RX Modulation Loss Values

- $A_{AVG} \triangleq$ RX PD AOP to average electrical signal power loss, -dB

Mod. loss variable	ER dB	DD Mod. loss value -dB		DD DM loss value -dB	
		NRZ	PAM4	NRZ	PAM4
$A_{AVG\text{-}DD}$	∞	0.0	1.3	*0.0*	*1.3*
	7	1.8	3.0	*1.8*	*3.0*
	4.8	*3.0*	*4.3*	3.0	4.3

Mod. loss variable	MD	CH loss value -dB	
		QPSK	QAM16
$A_{AVG\text{-}CH}$	$2V_{\pi}$	*0.0*	*0.0*
	V_{π}	0.0	0.0

Coherent Unequal SIG/LO Split Loss

- α_{ALS}, A_{ALS} ≜ Unequal SIG/LO split $\alpha_{LS} \neq ½$ loss; linear, -dB
  $\alpha_{ALS} = 2 \sqrt{(\alpha_{LS} (1 - \alpha_{LS}))}$
  α_{LS} ≜ 1/2
  $A_{ALS} = 0$
  α_{LS} ≜ 2/3
  $A_{ALS} = 0.3$
- $A'_{AVG\text{-}CH} = A_{AVG\text{-}CH} + A_{ALS}$

mod. loss variable	MD	CH loss value -dB			
		$\alpha_{LS} = 1/2$		$\alpha_{LS} = 2/3$	
		QPSK	QAM16	QPSK	QAM16
$A'_{AVG\text{-}CH}$	$2V_{\pi}$	*0.0*	*0.0*	*0.3*	*0.3*
	V_{π}	0.0	0.0	*0.3*	*0.3*

RX Input Referred Noise Current Loss Values

- A_N ≜ RX input noise current density loss vs. reference, -dB
- $\alpha_N \, i_0$ ≜ RX input noise current density
- RX input noise current density values

$\alpha_{N\text{-}DD} \, i_0 = 12 pA/\sqrt{Hz}$

$\alpha_{N\text{-}DD} \triangleq 1$

$i_0 = 12 pA/\sqrt{Hz}$

$\alpha_{N\text{-}CH} \, i_0 = 20 pA/\sqrt{Hz}$

$\alpha_{N\text{-}CH} = 5/3$

DD loss value -dB	CH loss value -dB
$A_{N\text{-}DD}$	$A_{N\text{-}CH}$
0.0	-2.2

Ex.1: $\Delta SNR_{DD\text{-}CH} / 2$ Ideal TX & RX no loss

Ex. 1 $\Delta SNR_{DD\text{-}CH} / 2$ dB		DD loss var.	DD Ideal TX ER = ∞ loss value -dB		CH loss var.	CH Ideal TX MD = V_π loss value -dB	
Loss Type		A_{DD}	NRZ	PAM4	A_{CH}	QPSK	QAM16
TX		A_{AOP}	3.0	3.0	$A_{AOP} / 2$	1.5	2.8
		A_{TX}	0		$A_{TX} / 2$	0	
1	Equal laser DC power	$- A_G / 2$	0.0		A_{TEC}	4.0	
2	Equal total input AOP		0.0			0.0	
3	Equal TX output AOP		1.5	2.8		0.0	
Link		A_{SMF}	4		$A_{SMF} / 2$	2	
RX		A_{RX}	0		A_{RX}	0	
		A_{AVG}	0.0	1.3	A'_{AVG}	0.0	0.0
		$- A_N$	0.0		$- A_N$	2.2	

1. Equal laser DC power		2. Equal total input AOP		3. Equal TX output AOP	
NRZ - QPSK	PAM4 - QAM16	NRZ - QPSK	PAM4 - QAM16	NRZ - QPSK	PAM4 - QAM16
2.7	**2.7**	**-1.3**	**-1.3**	**-2.8**	**-4.1**

Ex.2: $\Delta SNR_{DD\text{-}CH} / 2$ DD CWDM TFF, DML TX

Ex. 2 $\Delta SNR_{DD\text{-}CH} / 2$ dB		DD loss var.	DD CWDM4 TFF, DML TX ER = 4.8 loss value -dB		CH loss var.	CH SiP TX MD = V_π loss value -dB	
Loss Type		A_{DD}	NRZ	PAM4	A_{CH}	QPSK	QAM16
TX		A_{AOP}	0.0	0.0	$A_{AOP} / 2$	1.5	2.8
		A_{TX}	4		$A_{TX} / 2$	7	
1	Equal laser DC power	$- A_G / 2$	0.0		A_{TEC}	4.0	
2	Equal total input AOP		0.0			0.0	
3	Equal TX output AOP		8.0	9.3		0.0	
Link		A_{SMF}	4		$A_{SMF} / 2$	2	
RX		A_{RX}	2		A_{RX}	4	
		A_{AVG}	3.0	4.3	A'_{AVG}	0.0	0.0
		$- A_N$	0.0		$- A_N$	2.2	

1. Equal laser DC power		2. Equal total input AOP		3. Equal TX output AOP	
NRZ - QPSK	PAM4 - QAM16	NRZ - QPSK	PAM4 - QAM16	NRZ - QPSK	PAM4 - QAM16
7.7	7.7	3.7	3.7	-4.3	-5.5

Ex.3: $\Delta SNR_{DD\text{-}CH} / 2$ DD CWDM TFF, EML TX

Ex. 3 (ECOC'18 WS Ex.) $\Delta SNR_{DD\text{-}CH} / 2$ dB		DD loss var.	DD CWDM4 TFF, EML TX ER = 7 loss value -dB		CH loss var.	CH SiP TX MD = V_π loss value -dB	
Loss Type		A_{DD}	NRZ	PAM4	A_{CH}	QPSK	QAM16
TX		A_{AOP}	2.2	2.2	$A_{AOP} / 2$	1.5	2.8
		A_{TX}	5		$A_{TX} / 2$	7	
1	Equal laser DC power	$- A_G / 2$	0.0		A_{TEC}	4.0	
2	Equal total input AOP		0.0			0.0	
3	Equal TX output AOP		6.4	7.7		0.0	
Link		A_{SMF}	4		$A_{SMF} / 2$	2	
RX		A_{RX}	2		A_{RX}	4	
		A_{AVG}	1.8	3.0	A'_{AVG}	0.0	0.0
		$- A_N$	0.0		$- A_N$	2.2	

1. Equal laser DC power		2. Equal total input AOP		3. Equal TX output AOP	
NRZ - QPSK	PAM4 - QAM16	NRZ - QPSK	PAM4 - QAM16	NRZ - QPSK	PAM4 - QAM16
5.7	**5.7**	**1.7**	**1.7**	**-4.6**	**-5.9**

Ex.4: $\Delta SNR_{DD\text{-}CH}$ / 2 DD PSM4 SiP

Ex. 4 $\Delta SNR_{DD\text{-}CH}$ / 2 dB		DD loss var.	DD PSM4 SiP TX ER = 7 loss value -dB		CH loss var.	CH SiP TX MD = V_π loss value -dB	
Loss Type		A_{DD}	NRZ	PAM4	A_{CH}	QPSK	QAM16
TX		A_{AOP}	2.2	2.2	A_{AOP} / 2	1.5	2.8
		A_{TX}	6		A_{TX} / 2	7	
1	Equal laser DC power	- A_G / 2	0.0		A_{TEC}	4.0	
2	Equal total input AOP		0.0			0.0	
3	Equal TX output AOP		5.9	7.2		0.0	
Link		A_{SMF}	4		A_{SMF} / 2	2	
RX		A_{RX}	2		A_{RX}	4	
		A_{AVG}	1.8	3.0	A'_{AVG}	0.0	0.0
		- A_N	0.0		- A_N	2.2	

1. Equal laser DC power		2. Equal total input AOP		3. Equal TX output AOP	
NRZ - QPSK	PAM4 - QAM16	NRZ - QPSK	PAM4 - QAM16	NRZ - QPSK	PAM4 - QAM16
4.7	**4.7**	**0.7**	**0.7**	**-5.1**	**-6.4**

Ex.5: $\Delta SNR_{DD\text{-}CH} / 2$ DD CWDM4 SiP

Ex. 5 $\Delta SNR_{DD\text{-}CH} / 2$ dB		DD loss var.	DD CWDM4 SiP TX ER = 7 loss value -dB		CH loss var.	CH SiP TX MD = V_{π} loss value -dB	
Loss Type		A_{DD}	NRZ	PAM4	A_{CH}	QPSK	QAM16
TX		A_{AOP}	2.2	2.2	$A_{AOP} / 2$	1.5	2.8
		A_{TX}	8		$A_{TX} / 2$	7	
1	Equal laser DC power	$- A_G / 2$	0.0		A_{TEC}	4.0	
2	Equal total input AOP		0.0			0.0	
3	Equal TX output AOP		4.9	6.2		0.0	
Link		A_{SMF}	4		$A_{SMF} / 2$	2	
RX		A_{RX}	4		A_{RX}	4	
		A_{AVG}	1.8	3.0	A'_{AVG}	0.0	0.0
		$- A_N$	0.0		$- A_N$	2.2	

1. Equal laser DC power		2. Equal total input AOP		3. Equal TX output AOP	
NRZ - QPSK	PAM4 - QAM16	NRZ - QPSK	PAM4 - QAM16	NRZ - QPSK	PAM4 - QAM16
0.7	0.7	-3.3	-3.3	-8.1	-9.4

$\Delta SNR_{DD\text{-}CH}$ dB Examples, 4dB SMF Link

$\Delta SNR_{DD\text{-}CH}$ dB	Scenario	1. Equal laser DC power		2. Equal total input AOP		3. Equal TX output AOP	
Ex. #	TX & RX Implementation	NRZ - QPSK	PAM4 - QAM16	NRZ - QPSK	PAM4 - QAM16	NRZ - QPSK	PAM4 - QAM16
1	Ideal TX & RX no loss DD ER = ∞, CH MD = V_π	5.4		-2.6		-5.6	-8.1
2	DD CWDM4 TFF DML TX ER = 4.8, SiP CH MD = V_π	15.4		7.4		-8.6	-11.1
3	DD CWDM4 TFF EML TX ER = 7, SiP CH MD = V_π	11.5		3.5		-9.3	-11.8
4	DD PSM4 SiP TX ER = 7, SiP CH MD = V_π	9.5		1.5		-10.3	-12.8
5	DD CWDM4 SiP TX ER = 7, SiP CH MD = V_π	1.5		-6.5		-16.3	-18.8

Coherent vs. IMDD SNR Examples Conclusion

Application	Direct Detection NRZ / PAM4 SNR		SNR Relation	Coherent QPSK / QAM16 SNR	
	TX	RX		TX	RX
Laser DC Power Constrained	EML, DML single λ or TFF, PLC WDM	PIN single λ or TFF, PLC WDM	>>	SiP	SiP
	single λ SiP (PSM)	single λ SiP (PSM)	>>	SiP	SiP
4dB Link Loss	WDM SiP	WDM SiP	≈	SiP	SiP
TX Out Power Constrained	Any	PIN	<<	SiP	SiP

For most intra datacenter links, IMDD has better SNR than Coherent, contrary to conventional wisdom.

IMDD vs Coherent Appendices

Thank You

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