Direct Detection vs. Coherent SNR Inside the Datacenter

Will Coherent Optics Become a Reality
for Intra-data Center Applications?
OFC 2019 Workshop
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FINISAR®

Background: CH vs. DD Signal, ECOC'18 WS

$$P_{PD\text{-}S\text{-}CH} - P_{PD\text{-}S\text{-}DD} = A_{TX\text{-}DD} - A_{TX\text{-}CH}/2 + A_{RX\text{-}DD} - A_{RX\text{-}CH} + A_{SMF}/2 - A_{TEC}$$

Ex. Client Optics

- EML TX w/ TFF WDM Mux intrinsic loss: 5dB
- PIN RX w/ TFF WDM DeMux intrinsic loss: 1dB
- SMF FR loss budget (4dB) /2: 2dB

- Coherent SiP TX intrinsic loss /2: 7dB
- Coherent SiP RX intrinsic loss: 3dB
- TEC loss 4dB

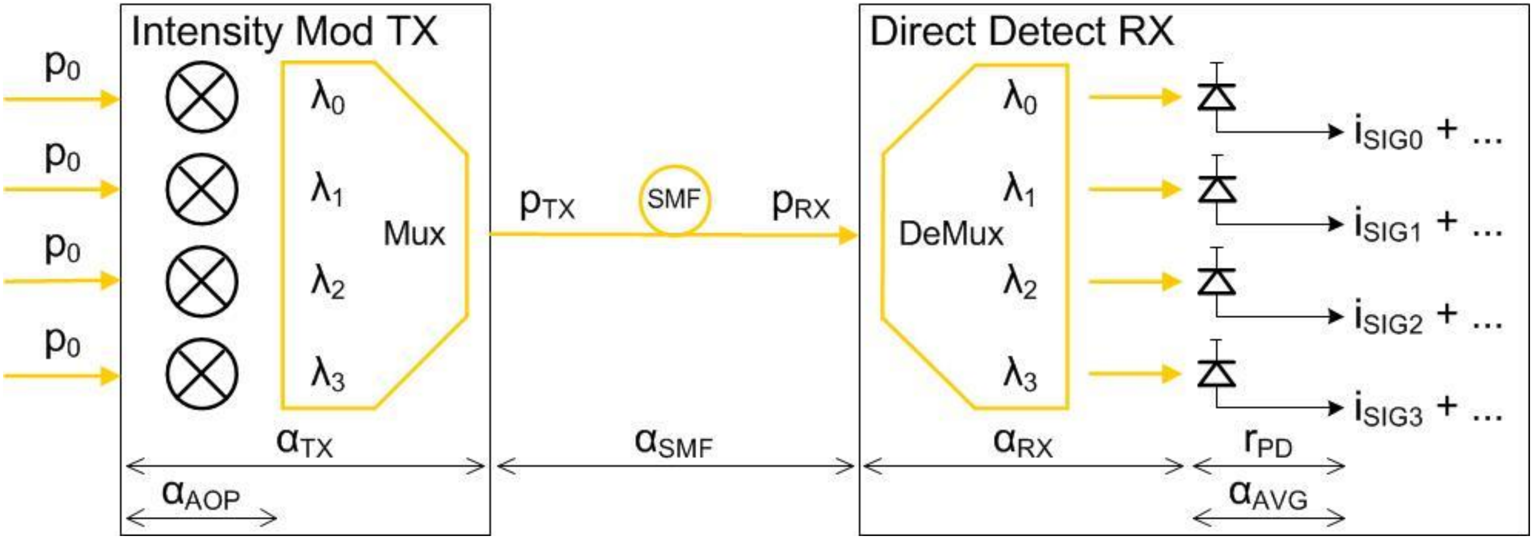
Direct Detection has 6dB higher signal for client optics

Introduction: Critical Datacenter Spec is SNR

CWDM4 λs 1km SMF Spec Limits

- L0 λ: 1271nm (1264.5 to 1277.5nm span)
  λ_{min} = 1264.5nm and $\lambda_{zero\_dispersion\_max}$ = 1324nm:
  - Dispersion = -6 ps/nm
  - PMD = 0.5 ps
  - Loss = 0.47dB
- L3 λ: 1331nm (1324.5 to 1337.5nm span)
  λ_{max} = 1337.5nm and $\lambda_{zero\_dispersion\_min}$ = 1304nm:
  - Dispersion = 3 ps/nm
  - PMD = 0.5 ps
  - Loss = 0.43dB
- Inside the Datacenter, link impairments are minor
- TX/RX signal path loss and Link total loss (connectors, SMF, other passives) drives SNR, and TX/RX architecture

Direct Detection (DD) Signal Path



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

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

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

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

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

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Direct Detection (DD) Signal Path Variables

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

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Direct Detection (DD) SNR

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

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

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

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

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

i_{ND}, $i_0 \triangleq$ RX input noise current density, reference

BW $\triangleq$ RX input noise current bandwidth

$i_N = i_{ND} \sqrt{BW}$

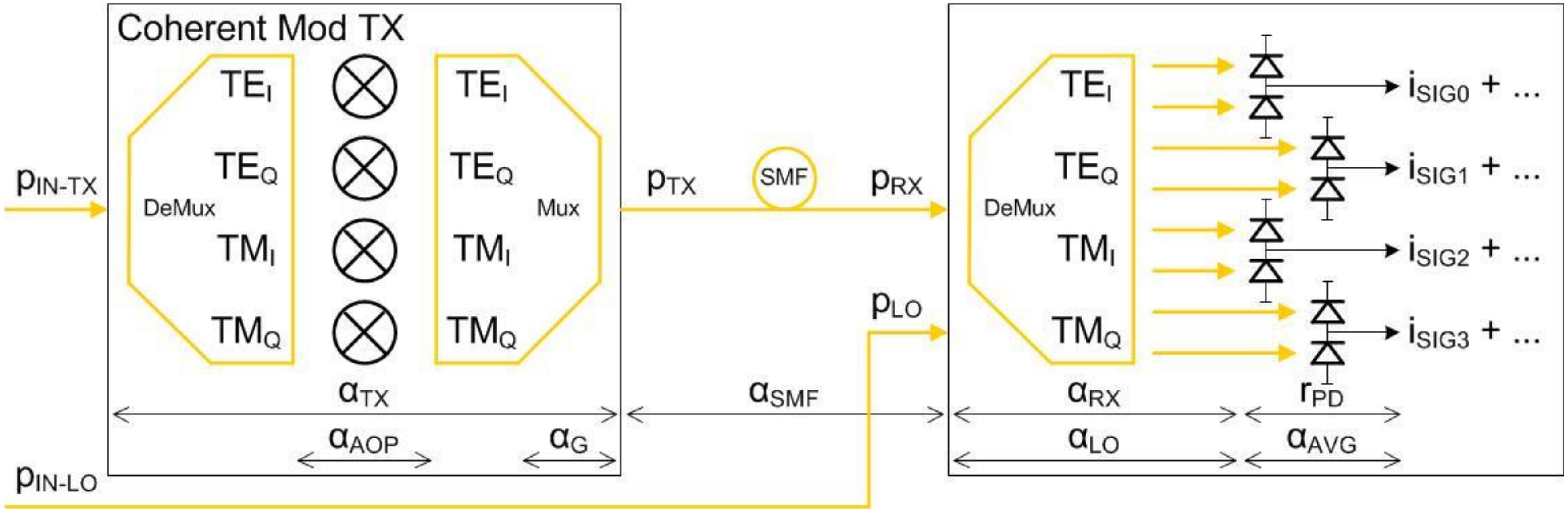
$i_{ND} = \alpha_N\, i_0$

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

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

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

Coherent (CH) Signal Path



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

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

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

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

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

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

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

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

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Coherent (CH) Signal Path Variables

$p_0 \triangleq$ Input POP (Peak Optical Power) reference
$\alpha_{TEC} \triangleq$ Input POP loss due to laser TEC current
$\alpha_{LS} \triangleq$ TX input POP loss due to (1- α_{LS}) split with LO input
$p_{IN\text{-}TX} \triangleq$ TX input POP = AOP since CW
$\alpha_{AOP} \triangleq$ TX POP to AOP modulation loss vs. MD (mod. drive)
$\alpha_{TX} \triangleq$ TX path intrinsic loss at modulator bias point
$\alpha_G \triangleq$ TX optical gain ($\alpha_G = 1$ if no amplification)
$p_{TX} \triangleq$ TX total output AOP
$\alpha_{SMF} \triangleq$ Link total power loss (connectors, SMF, other passives)
$p_{RX} \triangleq$ RX total input AOP
$p_{LO} \triangleq$ RX LO input AOP
α_{RX}, $\alpha_{LO} \triangleq$ RX, RX LO path intrinsic loss
$p_{PD,}$ $r_{PD} \triangleq$ RX balanced PD pair input AOP, responsivity
$\alpha_{AVG} \triangleq$ PD AOP to average electrical signal power loss vs. MD

Coherent (CH) SNR

$i_{SIG} \triangleq$ RX balanced PD pair signal current
$i_{SIG} = \alpha_{AVG}\, r_{PD}\, 2\, \sqrt{(p_{PD\text{-}RX}\, p_{PD\text{-}LO})}\, \cos(\Phi)$
$\cos(\Phi) \triangleq 1$
$\alpha_{LS} \triangleq 1/2,\ \alpha_{LO} \triangleq \alpha_{RX}$
$i_{SIG} = \alpha_{AVG}\, \alpha_{RX}\, \sqrt{(\alpha_{SMF}\, \alpha_{G}\, \alpha_{TX}\, \alpha_{AOP})}\, \alpha_{TEC}\, r_{PD}\, p_0$

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

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

DD vs. CH: $\Delta SNR_{DD\text{-}CH} = SNR_{DD} - SNR_{CH}$ dB

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

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

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

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

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

$A \triangleq$ loss in optical -dB

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

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

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

Summary DD vs. CH: ΔSNR_{DD-CH} dB

ΔSNR_{DD-CH} dB		Scenario #	1		2		3	
4dB SMF Link		Scenario	Equal laser DC power		Equal total input AOP		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**		**7.5**		**-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**

Conclusions DD vs. CH: Relative SNR

Application	Direct Detection SNR NRZ / PAM4		SNR Relation	Coherent SNR QPSK / QAM16	
	Implementation			Implementation	
	TX	RX		TX	RX
Intra Datacenter 4dB SMF Link DC Power constrained	EML, DML single λ or TFF, PLC WDM	PIN single λ or TFF, PLC WDM	>>	SiP	SiP
	single λ SiP	single λ SiP	>>	SiP	SiP
	WDM SiP	WDM SiP	≈	SiP	SiP
Inter Datacenter DC Power Unconstrained	Any	PIN	<<	SiP	SiP

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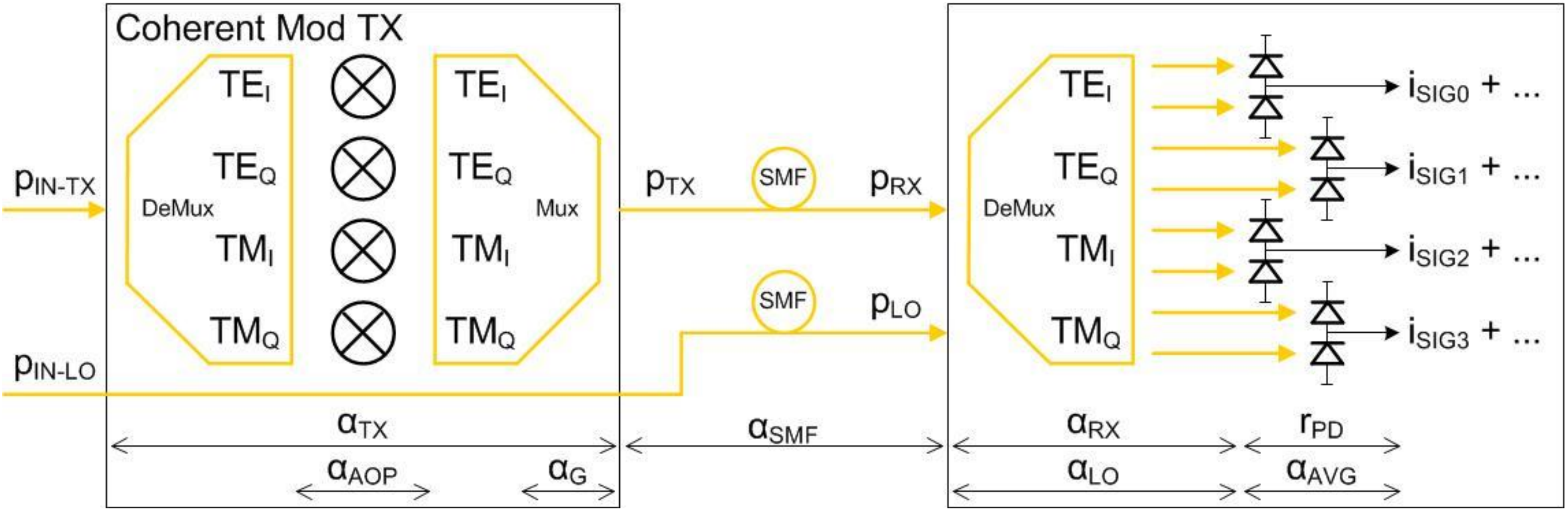
Direct Detection vs. Coherent in the Datacenter

The author would like to thank Thang Pham, Facebook, for detailed review and comments, and for SNR insight, and Mike Frankel, Ciena, for detailed review and comments, and for Signal & LO Same Path insight in Appendix 1

Thank You

Appx. 1: Coherent Signal & LO Same Path



$$p_{IN-TX} = 4\, \alpha_{LS}\, \alpha_{TEC}\, p_0$$
$$p_{TX} = \alpha_G\, \alpha_{TX}\, \alpha_{AOP}\, p_{IN-TX}$$
$$p_{IN-LO} = 4\,(1 - \alpha_{LS})\, \alpha_{TEC}\, p_0$$

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

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

Coherent Signal & LO Same Path i_{SIG}

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

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

$\cos(\Phi) \triangleq 1$

$\alpha_{LS} \triangleq 1/2,\ \alpha_{LO} \triangleq \alpha_{RX}$

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

Equal DD and CH Signal & LO Same Path input AOP

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

results in equal DD and CH Signal & LO Same Path i_{SIG}

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

The Coherent Signal & LO Same Path is for insight only.
It is not used in DD vs. CH ΔSNR comparisons.

Appx 2: $\Delta SNR_{DD-CH} = SNR_{DD} - SNR_{CH}$ Calc.

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

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

- α_{AOP}, A_{AOP} ≜ TX input POP to AOP modulation loss; linear, -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

- α_{TX}, $A_{TX} \triangleq$ TX path intrinsic loss; linear, -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 Scenario

- α_{TEC}, A_{TEC} $\triangleq$ TX_{CH} input POP loss due to laser TEC current; linear, -dB
- α_G, A_G $\triangleq$ TX_{CH} optical gain
  In $\Delta SNR_{DD\text{-}CH}$
  A_G TX_{CH} optical gain = - A_G TX_{DD} optical loss
- 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 Scenario, 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 Scenario Loss Values

- α_{TEC}, A_{TEC} ≜ TX_{CH} input POP loss due to laser TEC current; linear, -dB
- α_G, 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

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Link Loss Values

- α_{SMF}, $A_{SMF} \triangleq$ Link total power loss (connectors, SMF, other passives); linear, -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

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RX Signal Path Intrinsic Loss Values

- α_{RX}, $A_{RX} \triangleq$ RX path intrinsic loss; linear, -dB
  α_{LO}, $A_{LO} \triangleq$ RX LO path intrinsic loss; $\alpha_{LO\text{-}CH} \triangleq \alpha_{RX\text{-}CH}$

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}, $A_{AVG} \triangleq$ RX PD AOP to average electrical signal power loss; linear, -dB
- $\alpha_{LS} \triangleq$ 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
  $MD_{DD\text{-}Max} \triangleq ½\, MD_{CH\text{-}Max}$
  $MD_{CH} = V_{\pi}$

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RX Modulation Loss Values

- α_{AVG}, A_{AVG} ≜ RX PD AOP to average electrical signal power loss; linear, -dB

Mod. loss variable	ER dB	DD Mod. loss value -dB		DD DM loss value -dB	
		NRZ	PAM4	NRZ	PAM4
A_{AVG-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-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
  $\alpha_{ALS} = 2\sqrt{(\alpha_{LS}(1 - \alpha_{LS}))}$
  $\alpha_{LS} \triangleq 1/2$
  $A_{ALS} = 0$
  $\alpha_{LS} \triangleq 2/3$
  $A_{ALS} = 0.3$
- $A'_{AVG\text{-}CH} = A_{AVG\text{-}CH} + A_{ALS}$

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

- α_N, A_N $\triangleq$ RX input noise current loss vs. ref.; linear, -dB
- i_{ND}, i_0 $\triangleq$ RX input noise current density, reference
  $i_{ND} = \alpha_N \, i_0$
- RX noise current density values
  $i_{ND\text{-}DD} = 12\text{pA} / \sqrt{\text{Hz}}$
  $\alpha_{N\text{-}DD} \triangleq 1$
  $i_0 = 12\text{pA} / \sqrt{\text{Hz}}$
  $i_{ND\text{-}CH} = 20\text{pA} / \sqrt{\text{Hz}}$
  $\alpha_{N\text{-}CH} = 5/3$

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

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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**

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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**

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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**