Comparisons and Challenges Associated with Linear Interface

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IEEE 802.3dB Taskforce Meeting

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Overview

- Background on direct drive optics
- OIF ACO
- Eye opening from switch vs optics CDR
- Eye opening for CK channels
- Measured eye opening through mated MCB/HCB
- THD and linearity requirements for direct drive optics
- Power comparisons between retimed vs direct drive optics
- 100G MMF link results
- Summary.

Background on Direct Drive/Linear Optics

- **Direct drive optics is not a new concept**
  - Optical CATV is an example of direct drive optics with BW=1.2 GHz as defined by DOCSIS 3.1
  - But the more relevant standard is the OIF Analog Coherent Optics OIF-COM-ACO-1.0
- **Neither the SFI or the proposed ghiasi_02_1111_NG100GOPTX 25G nPPI were direct drive optics**
  - SFI TX/RX are limiting where the jitter passes through but the eye gets sharpened and opened by the limiting AMP
    - Only LRM and some 10G-ZR have used the more complex linear RX
  - Ghiasi proposed 25G nPPI was based on TX/RX limiting
- **What is OIF ACO**
  - OIF ACO defines a RF linear ”direct drive” TX and RX for 45 GBd and 64 GBd coherent DP-QPSK where the host DSP sits near CFP2 modules
  - CFP2 ACO had very short life due to system, SI, operational challenges, and the requirement that all host port carry costly DSP
  - With introduction of lower power DSP that can fit into CFP2 power envelop the ACO modules were replaced by the DCO modules.

OIF ACO TX RF Parameters

ID	Parameter	Conditions	Test Point	Min	Max	Units
TE.010	**Differential Voltage from Host**	Differential output voltage from Host measured at the TP1a compliance point and at 1.0GHz[3]. The voltage must include the effects of equalization required to compensate the Host and the module portion of the TE030 channel. Compensation is defined as the wave shaping required to obtain the desired system performance when carrying traffic. It is assumed the COM-ACO module will also support sufficient phase modulation to achieve the Host defined module performance (optical power, linearity, power dissipation, etc.).	TP1a	200	450	mVppd
TE.020	**Tx Modulator Driver Linearity**	Parameter is *not measurable at the module level.* It is evaluated in a test fixture representative of the application environment and at output voltage levels representative of in service operating conditions. Test frequencies are 2GHz, 5GHz, and 10GHz. THD = sqrt(V2^2 + V3^2 + … + Vinf^2)/V1.	NA		5	% THD
TE.030	**Tx EO S21 Magnitude Mask**	Normalized Tx EO MAG(S21) compliance mask measured from TP1 to Tx Out. Inner MZ modulator operating at quadrature and under small signal conditions (i.e. RF drive ≤ 0.3Vπ). MAG(S21) is normalized to 1GHz.	TP1	Normalized OE MAG(S21) Mask: in Figure 3 for 45Gbaud and Figure 4 for 64Gbaud		dBe
TE.040	**Tx EO Group Delay Variation**	Group Delay Variation Magnitude from 1GHz to 0.5*Baud Rate GHz with 1GHz span smoothing. TP1 to Tx Out.	TP1	0	20ps: 45Gbaud; 15ps: 64Gbaud	ps
TE.050	**Electrical Return Loss**	Electrical Return Loss at the TP1a and TP1 compliance points. This is a differential specification. 1MHz < f ≤ 0.5*Baud Rate GHz 0.5*Baud Rate GHz < f ≤ 0.75*Baud Rate GHz 0.75*Baud Rate GHz < f < Baud Rate GHz	TP1a TP1	10 8 6		dBe dBe dBe
TE.060	**Low corner cutoff frequency**	-3dBe low corner cutoff frequency. AC coupled. TP1 to Tx Out. S21 is normalized at 1GHz.	TP1		1000	kHz
TE.070	**IQ Timing Skew**	Time difference[4] up to 0.5*Baud Rate GHz of the Q channel relative to the I channel within a polarization. The time for a channel is defined as the mean of P and N. Includes TE090. TP1 to Tx Out.[5]	TP1	-5	+5	ps
TE.080	**XY Timing Skew**	Time difference[4] up to 0.5*Baud Rate GHz of the Y polarization relative to the X polarization, defined as (XI+XQ)/2 - (YI+YQ)/2, where the time for an individual I or Q channel is the mean of P and N. Includes TE090. TP1 to Tx Out.[5]	TP1	-8	+8	ps
TE.090	**Skew Variation**	Temporal variation up to 0.5*Baud Rate GHz among any two channels due to module temperature, wavelength, amplifier gain, and aging[4]. TP1 to Tx Out. Time for channel defined as mean of P and N.[6]	TP1	-1	1	ps
TE.100	**PN Intrapair Timing Skew**	Informative: Time difference[4] up to 0.5*Baud Rate GHz between any P and N pair over the module operating temperature and life. TP1 to RF driver input. Applies only to modules using RF drivers with a differential input stage.	TP1		1	ps

Host Switches Can't Deliver Such Large Signal Across 11 dB Channels!

Not required for PAM4

https://www.oiforum.com/wp-content/uploads/2019/01/OIF-CFP2-ACO-01.0.pdf

ACO Module TX OE Response

Implies MCB+Module+Optics has only 4 dB loss at Nyquist!

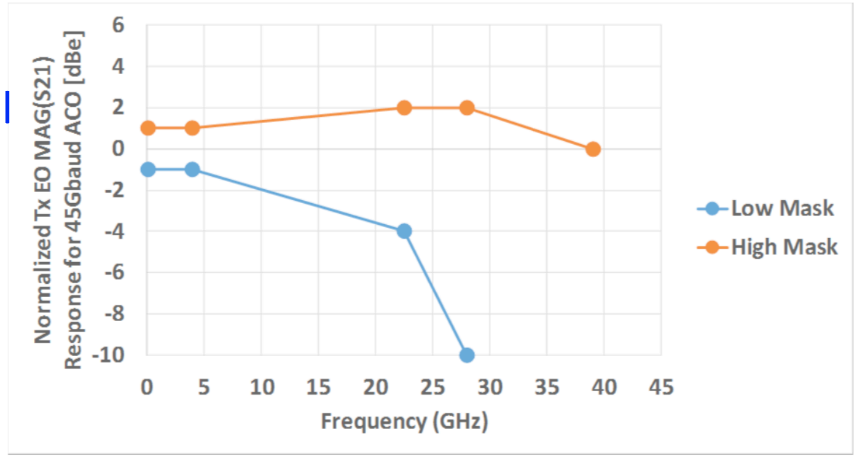


Figure 3: Normalized Tx OE CG MAG(S21) Compliance Mask for 45Gbaud ACO.

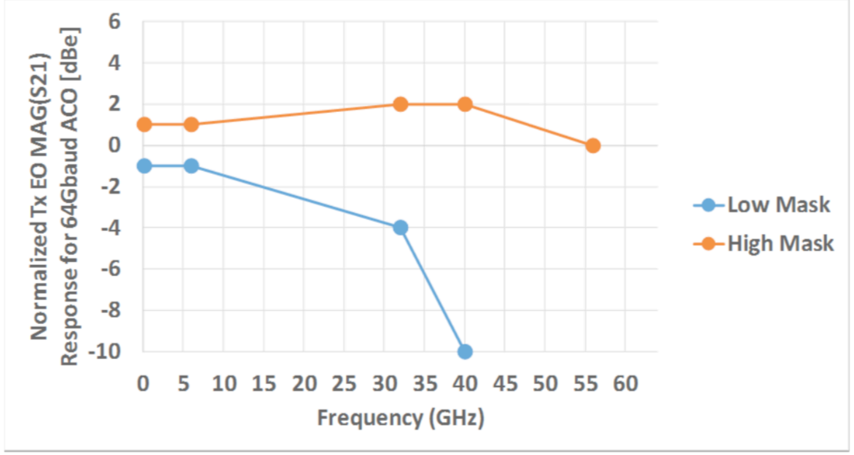


Figure 4: Normalized Tx OE CG MAG(S21) Compliance Mask for 64Gbaud ACO.

OIF ACO RX RF Parameters

ID	Parameter	Conditions	Test Point	Min	Max	Units
RE.010	**Differential Output Voltage Range (VOUT)**	Differential output voltage (VOUT) dynamic range at the TP4 compliance point and at 1GHz with the Rx electrical output not in shutdown. The necessary Rx In power will be provided for the agreed upon CGmin and CGmax. The dynamic range is controlled by the Host, which for CFP MIS is register BB8C (MGC) or register BBCC (AGC).	TP4	300	700	mVppd
RE.020	**Rx Channel Output Total Harmonic Distortion (THD)**	Rx channel output total harmonic distortion (THD) = sqrt(V2^2 + V3^2 + … + Vinf^2) / V1. Measured from Rx In to the TP4 compliance point and at 1GHz over the full range of differential output voltage VOUT in RE.010: VOUT ≤ 400 mVppd 400mVppd < VOUT ≤ 1000 mVppd	TP4		2.5 4	% %
RE.030	**Rx OE CG S21 Magnitude Mask**	Compliance mask for the normalized Rx OE Conversion Gain MAG(S21) response, measured from Rx In to TP4, over the CG range CGmin ≤ CG ≤ CGmax. CG MAG(S21) is normalized to 1GHz.	TP4	Normalized OE MAG(S21) Mask: in Figure 5Figure 3 for 45Gbaud and Figure 6 for 64Gbaud		dBe
RE.040	**Rx OE CG S21 Magnitude Response, Variation over CG**	Allowed variation in the CG MAG(S21) response determined in RE.030, relative to the midpoint CG response, over the CG range CGmin ≤ CG ≤ CGmax: f < 0.5*Baud Rate GHz 0.5*Baud Rate ≤ f ≤ 0.6*Baud Rate GHz	TP4	-1.5 -3.0	+1.5 +3.0	dBe dBe
RE.050	**OE S21 Deviation from Linear Phase**	Deviation from linear phase (DLP) is obtained by removing the electrical delay (ED) in seconds from the unwrapped phase ϕ: $ED = -AVG\left(\frac{1}{360}\frac{\partial\phi}{\partial f}\right)$ for 1GHz ≤ f ≤ 0.5*Baud Rate GHz, and then DLP is given by DLP = ϕ + 360 * f * ED. The DLP specification applies over the CG range CGmin ≤ CG ≤ CGmax, and for the frequency range from 0-20GHz. This parameter is acknowledged to be *difficult to measure at the*	TP4	-40	40	Degrees
RE.060	**Differential Electrical Return Loss**	Differential electrical return loss at the TP4 and TP4a compliance points: 100kHz < f ≤ 0.5*Baud Rate GHz 0.5*Baud Rate GHz < f ≤ 0.75*Baud Rate GHz 0.75*Baud Rate GHz < f ≤ Baud Rate GHz	TP4 TP4a	10 8 6		dBe dBe dBe
RE.070	**Low corner cutoff frequency**	3dB low corner cutoff frequency. AC coupled. Rx In to TP4. CG MAG(S21) is normalized to 1GHz.	TP4	10	1000	kHz
RE.080	**IQ Timing Skew**	Time difference of the Q channel relative to the I channel within a polarization⁷. Rx In to TP4. The time for a channel is defined as the mean of P and N. Applies for TIA GC_I = TIA GC_Q, over the TIA GC range, and at start of life and room temperature. The time difference could be extracted from the Beat Frequency skew measurement method⁸.	TP4	-3	+3	ps
RE.090	**XY Timing Skew**	Time difference of the Y polarization relative to the X polarization⁷. Rx In to TP4. The time for a polarization is defined as (XI+XQ)/2 – (YI+YQ)/2 where the time for an individual I or Q channel is the mean of P and N. Applies for TIA GC_XI = TIA GC_XQ = TIA GC_YI = TIA GC_YQ, over the TIA GC range, and at start of life and room temperature. Time difference could be extracted from the Beat Frequency Skew measurement method5⁸.	TP4	-8	+8	ps
RE.100	**Channel Timing Variation with GC**	Temporal variation of a channel over the TIA GC range. Rx In to TP4. Time for channel defined as mean of P and N.⁶	TP4	-1	+1	ps
RE.110	**IQ Skew Variation**	Deviation of IQ Timing Skew (RE.080) from the SOL room temperature value, over the module operating temperature range and life.⁶	TP4	-1	+1	ps
RE.120	**XY Skew Variation**	Deviation of XY Timing Skew (RE.090) from the SOL room temperature value, over the module operating temperature range and life.⁶	TP4	-1	+1	ps
RE.130	**P/N Intrapair Timing Skew**	Informative: Time difference between any P and N pair over the module operating temperature and life. Rx In to TP4. Applies over the CG range CGmin ≤ CG ≤ CGmax.	TP4		1	ps
RE.140	**Tx to Rx Crosstalk**	Rx electrical noise power is computed by integrating the 0.2-20GHz Rx RF output power spectrum on an ESA including the tones. Rx electrical noise power is measured with no light on the Rx In, for CG = CGmax, *with and without* PRBS-11 signals on the 4 Tx RF inputs [uncorrelated to each other.] The Tx to Rx Crosstalk is defined as 10·log₁₀(((Rx electrical noise power:Tx On) - (Rx electrical noise power:Tx Off)) / (Rx electrical noise power:Tx Off)).	TP4		20	dB

Require Power Hungary AGC

Not required for IMDD

Not required for IMDD

ACO Module RX OE Response

Implies MCB+Module+Optics has only 3 dB loss at Nyquist!

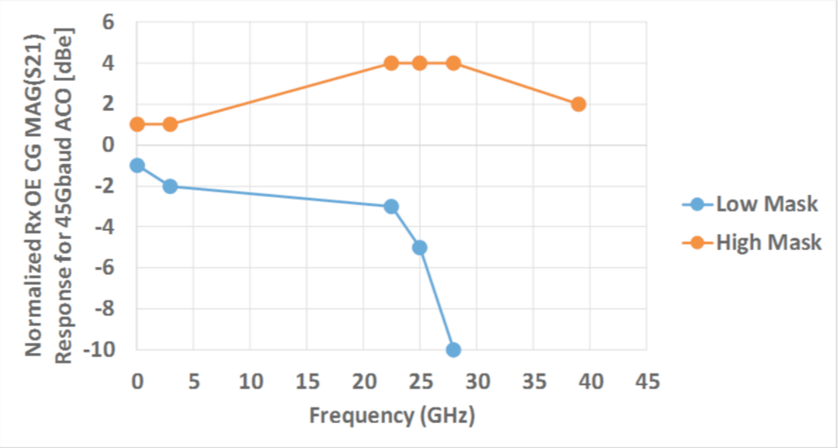


Figure 5: Normalized Rx OE CG MAG(S21) Compliance Mask for 45Gbaud ACO.

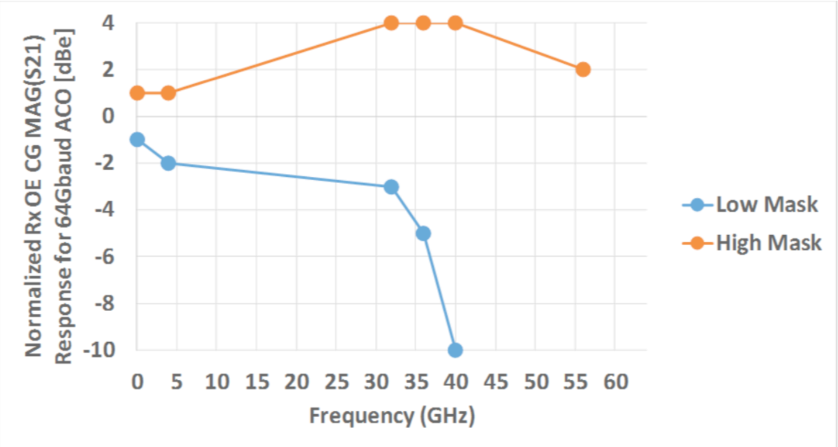


Figure 6: Normalized Rx OE CG MAG(S21) Compliance Mask for 64Gbaud ACO.

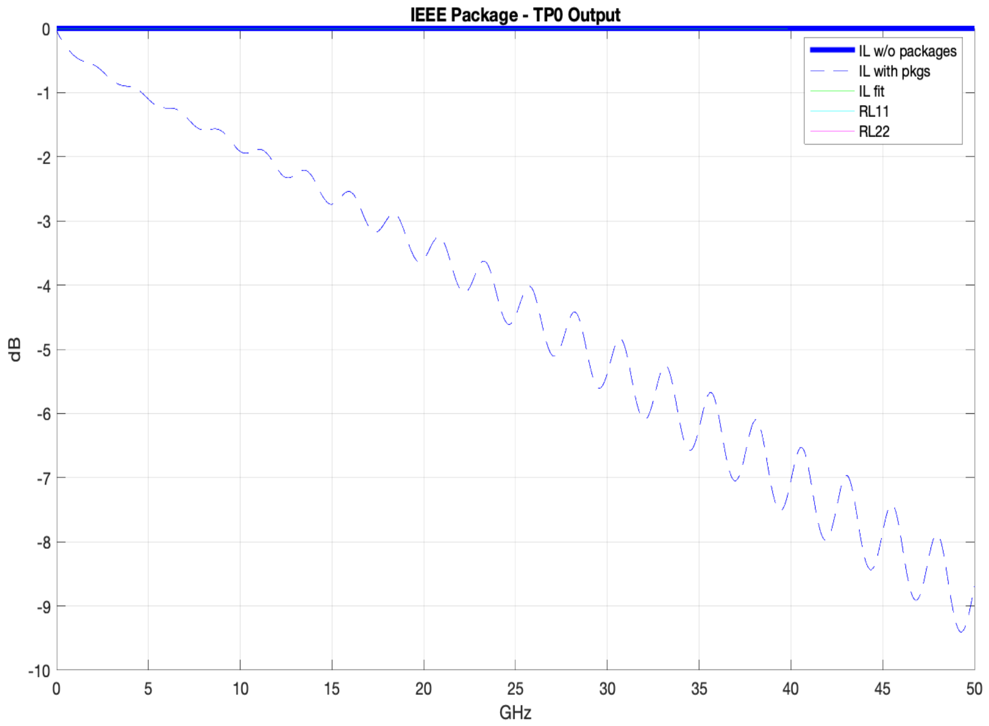
https://www.oiforum.com/wp-content/uploads/2019/01/OIF-CFP2-ACO-01.0.pdf

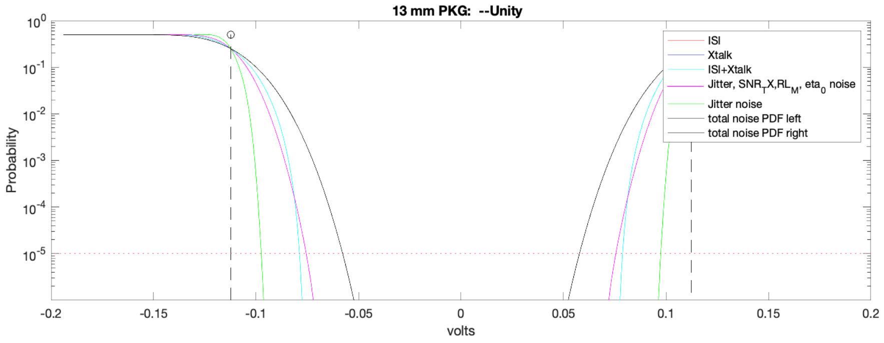
Retimed AUI Specifications Not Suitable as Bases for Analog RF Photonics Interface

- **Proposed latchman_3db_adhoc_01_101520 proposal is based on 802.3ck clause 120G**
  - Proposed Latchman "Baseline Physical Interface Proposal" starting with CK C2M specifications is not a relevant starting point instead should consider OIF ACO (Analog Coherent Optics) specifications
    - OIF ACO electrical signaling is based on PAM2 and some of the limits would have to be tightened for PAM4
    - Experience from OIF ACO is that it was a problematic interface in term of interoperability, link tuning, and link bring up
- **Some of the key specifications necessary for Analog RF Photonics are that are not considered by Latchman proposal are:**
  - Transmitter
    - THD
    - TP1-TP2 electrical to optical S21 magnitude and phase/group delay response
    - P & N Skew
    - Electrical VEC @TP1a needs to be <~3.5 dBe to avoided TDECQ being dominated by electrical impairments
    - TP1a ~20 mV eye opening needs to be amplified to ~ 2 V to drive optics require 40 dB power AMP
  - Receiver
    - 300 mV – 700 mV is necessary which implies power hungry AGC
    - THD
    - TP3-TP4 optical to electrical S21 magnitude and phase/group delay response
    - P & N Skew.

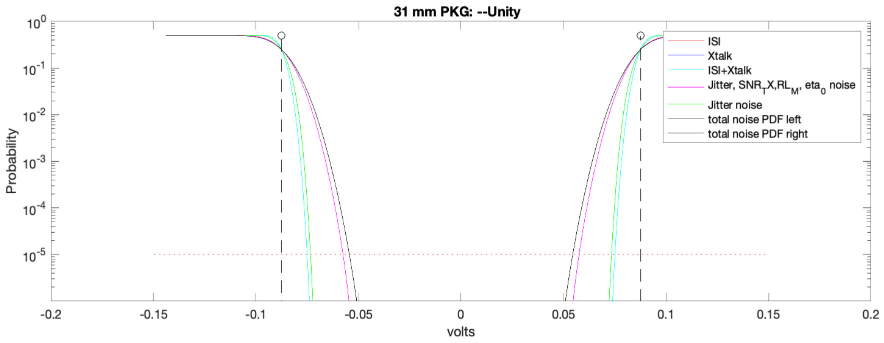
IEEE Package vs CDR Package

- **IEEE 802.3ck package represent large switch ASIC with up to 31 mm substrate trace and 1.8 mm core**
  - Typical module CDR traces are 4-7 mm and the substrate is core-less
  - Results are with 4T TX FIR, RX CTLE, with 820 mV amplitude and no crosstalk
  - An optics CDR chip VEC typically is ~ 3.5 dB with optimum TX FIR and without any RX equalization!





13 mm PKG
VEC=6.0 dB
VEO=112 mV
COM=6.0 dB



31 mm PKG
VEC=4.3 dB
VEO=107 mV
COM=8.2 dB

TP1a is not Suitable to Drive Optics Given the Impairments

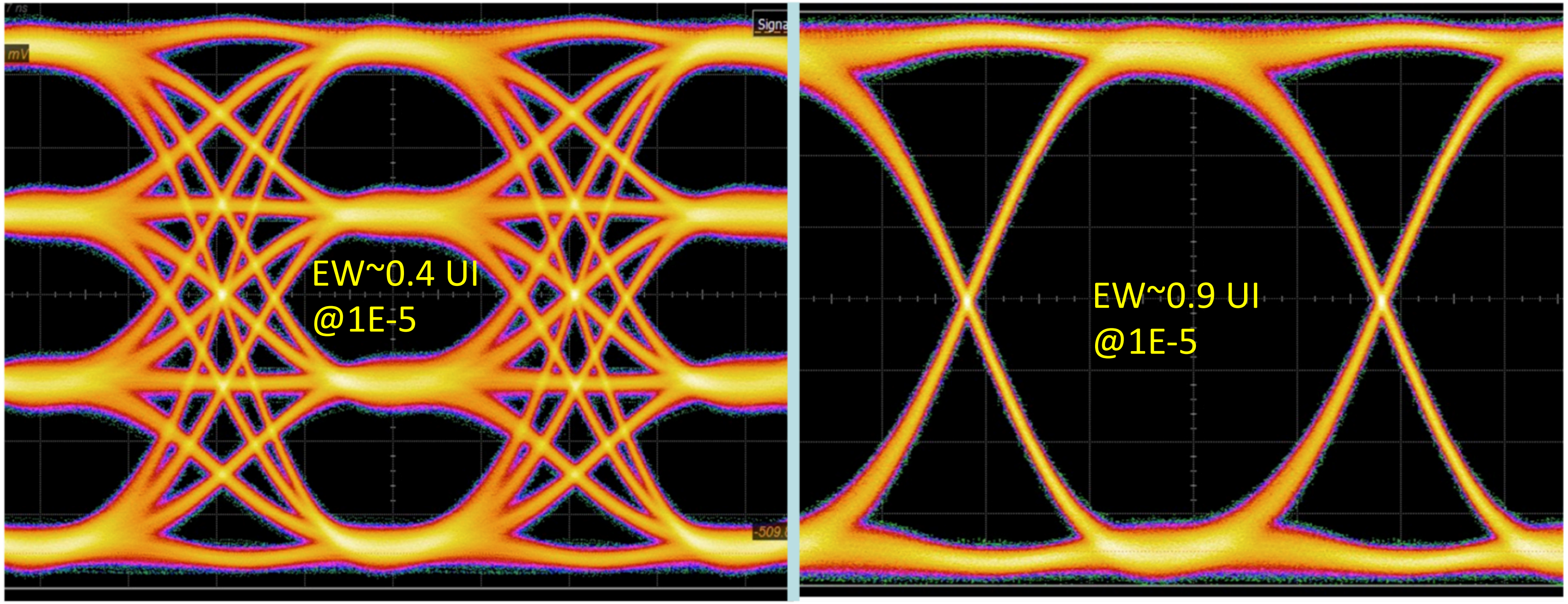
- **9 tap FFE was proposed by [latchman_3db_adhoc_01_101520] to test direct drive at TP2**
  - Results below for Lim 2” QSFP-dd channel at TP1a even with 12T FEE (excluding optics) the channel output VEC=5.8 dB and EW=0.219 UI (in line with Keysight reported VEC/EW for mated boards)
    - For configuration and additional results see https://www.ieee802.org/3/ck/public/20_03/ghiasi_3ck_01a_0320.pdf
    - VEC after device termination increases by ~2 dB
  - The end-end link consist of two C2M electrical segment plus the linear optics segment
  - A signal with VEC of 5.8 that already uses 12T FFE is not good enough to drive the optics and the far end M2C link!

Channel	Equalizer	Fitted IL@26.56 GHz	IL wPKG@26.55 GHz	VEO Case I/II	VEC Case I/II	EW Case I/II	COM Case I/II
Lim Channel 2” at TP1a FOM ILD = 0.16 ICN = 3.7 mV ERL11=12.3 dB ERL22=9.3 dB	5T FFE	5.9 dB	12.5 dB	21.4/31.3	11.5/6.0	0.156/0.219	2.7/6.0
	4T DFE	5.9 dB	12.5 dB	27.4/38.8	11.4/6.5	0.063/0.187	2.7/5.5
	2T+2T 12UI DFE	5.9 dB	12.5 dB	43.7/39.9	7.5/6.5	0.125/0.187	4.8/5.6
	12T FFE	5.9 dB	12.5 dB	48.4/32.3	5.4/5.8	0.219/0.219	6.6/6.3
Lim Channel 9” at TP1a FOM ILD = 0.13 ICN = 1.44 mV ERL11=16 dB ERL22=11.3 dB	5T FFE	14.8	21.4	11.3/13.9	10.8/6.5	0.125/0.187	3.0/5.5
	4T DFE	14.8	21.4	18.2/18.9	8.2/6.4	0.125/0.187	4.3/5.7
	2T+2T 12UI DFE	14.8	21.4	23.7/18.9	6.1/6.4	0.156/0.187	6.0/5.7
	12T FFE	14.8	21.4	19.1/13.2	5.3/6.2	0.219/0.187	6.8/5.8

Case I – 13 mm ASIC package
Case II – 31 mm ASIC package

Typical PAM4 CDR for Optics

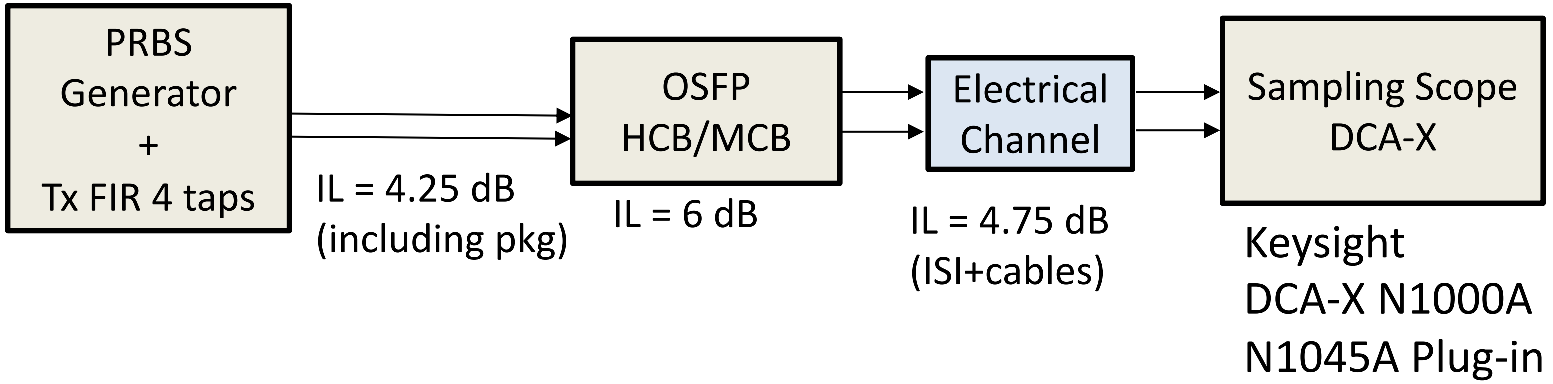
- **One of the 1st 50G PAM4 CDR chips in 28 nm CMOS , see K Gopalakrishnan ISSCC 2016**
  - Transmitter σj=0.24 ps, SNDR>33 dB, Tx swing =1400 mv p-p, $TR_{20\text{-}80\%}$~ 15 ps, VEC~ 3.0 dB, EW~0.4 UI
  - Performance significantly better than switch TP0a!



100G PAM4 CDR in 7nm have comparable relative performance!

Test Board Test Setup

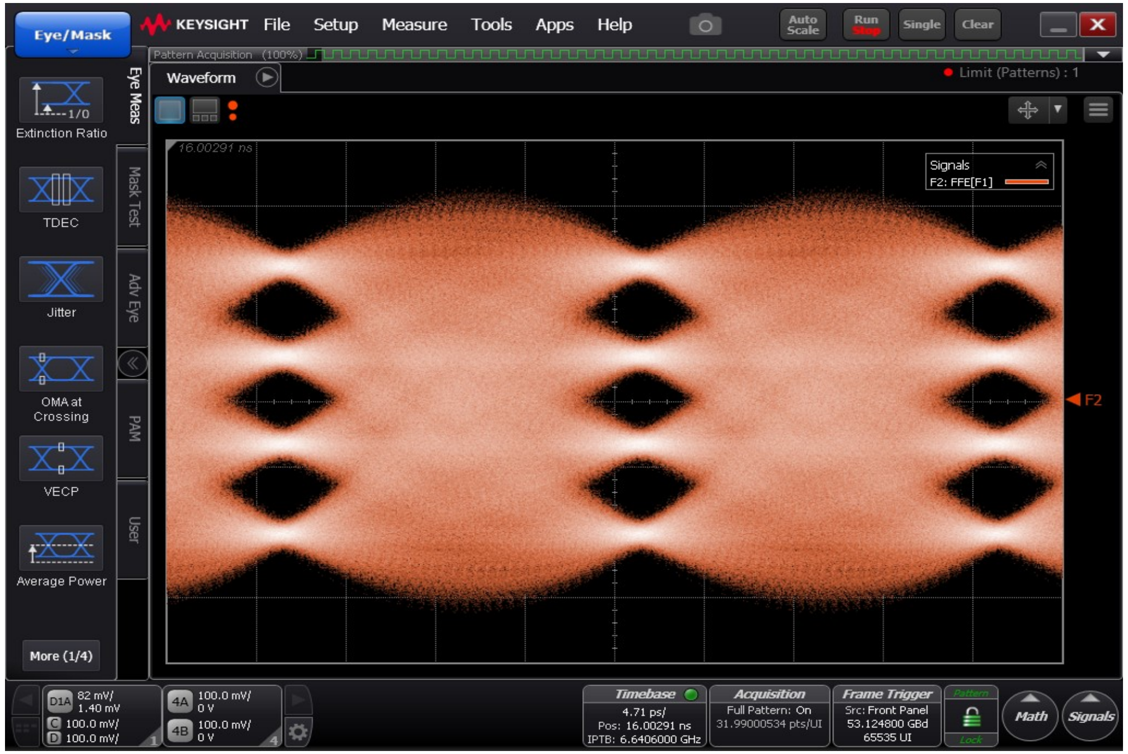
- Test board consist of 112G OSFP MCB/HCB plus high channel board with total loss of 10.75 dB
  - Generator PKG + test board had 4.25 dB of loss inline with assumed CK package loss
- IL Losses specified at 26.5G
- Scope BW set to 39.8 GHz.
- Pattern: SSPRQ
- Equalizer considered
  - CTLE+5T FFE
  - CTLE+12T FFE.



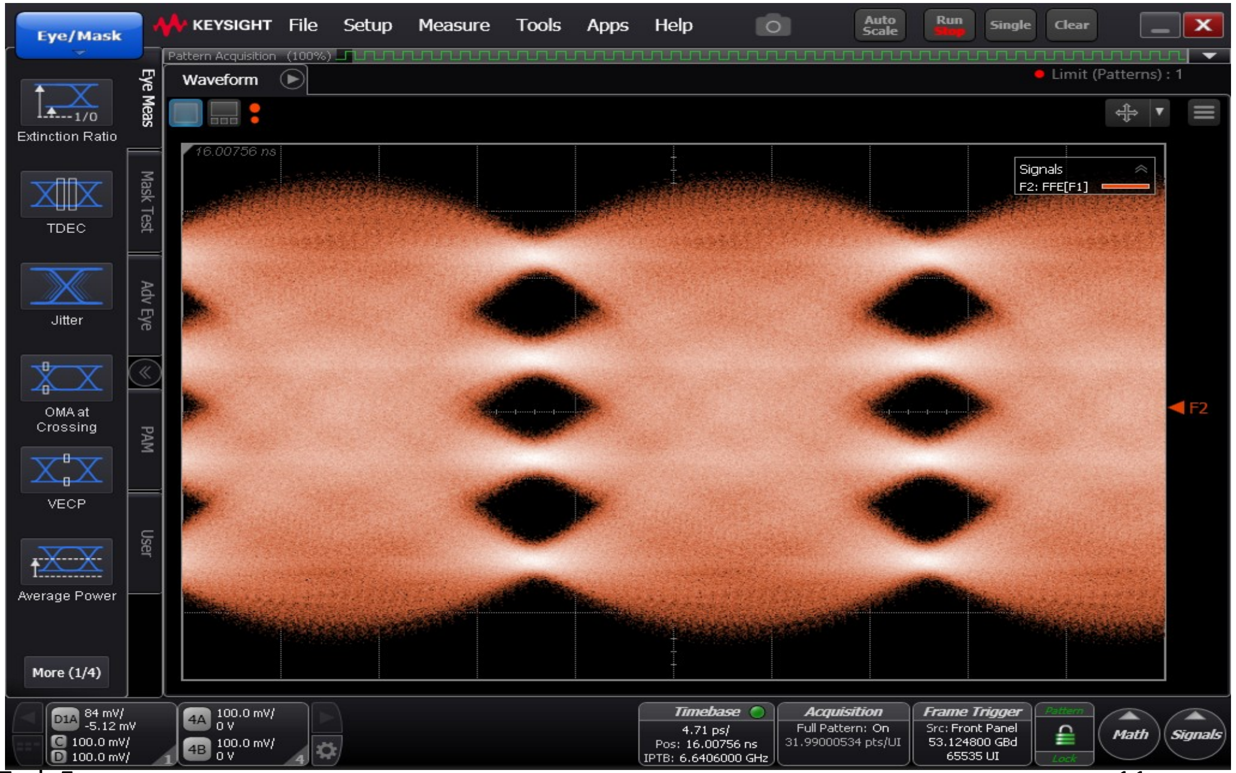
Measured TP1a Results with 5T and 12T FFE

- **TP1a eyes didn't sufficiently improve with 12T FFE by measurable amount without VCSEL**
  - Unlike the COM results from ghiasi_3ck_01a_0320 measured VEC with 5T FFE is lower but it doesn't improve with 12T
  - It has been suggested to use 11T FFE at TP2 to measure TDECQ where both electrical and optical channels are equalized
  - Unfortunately a VEC=9.03 dB and EW=160 mUI are unsittable to drive the VCSEL
  - Typical 100G optics CDR has VEC~ 3.5 dB and EW~0.35 UI.

VEC=9.1 dB, VEO=20.9 mV, EW=152 mUI



VEC=9.03 dB, VEO=21.1 mV, EW=160 mUI



Linear Driver/TIA Consume Substantial Power

- **M. Ahmed, et. al. report result for 34-GBd Linear Transimpedance Amplifier for Coherent 200G DP-QPSK/16QAM, in IEEE JOSSC 2018**
  - Cosine compression analyzed is for TIA/AGC
  - QAM16/PAM4 PP(dB)=$-10log\left(1-\frac{13}{9}\frac{4\times THD}{1+3\times THD}\right)$
    - A 4% THD as specified by ACO IA results in 1 dB optical penalty for PAM4
  - But other components in the link also have compression/non-linearities such as driver, driver, MZ modulators, and VCSEL/DMLs
- **Key results reported**
  - 0.13 µm SiGe BiCMOS process
  - Input referred noise 20 pA/√Hz
  - THD 1.5 % with output swing of 500 mV
  - Power per channel 313 mW
- **A TIA/AGC for 53 GBd with ~16 pA/√Hz which is the norm for single λ optics expected to consume 500 mW**
  - Typical single λ 53 GBd TIA siting in front of CDR only consumes ~175 mW!

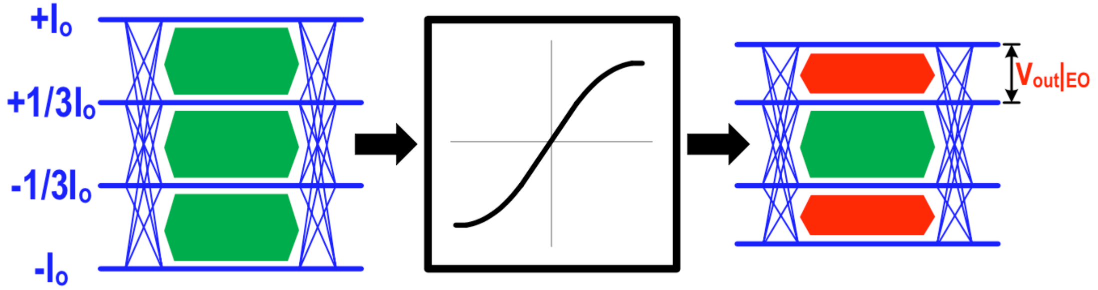


Fig. 3. Non-linearity impact on PAM4 signal.

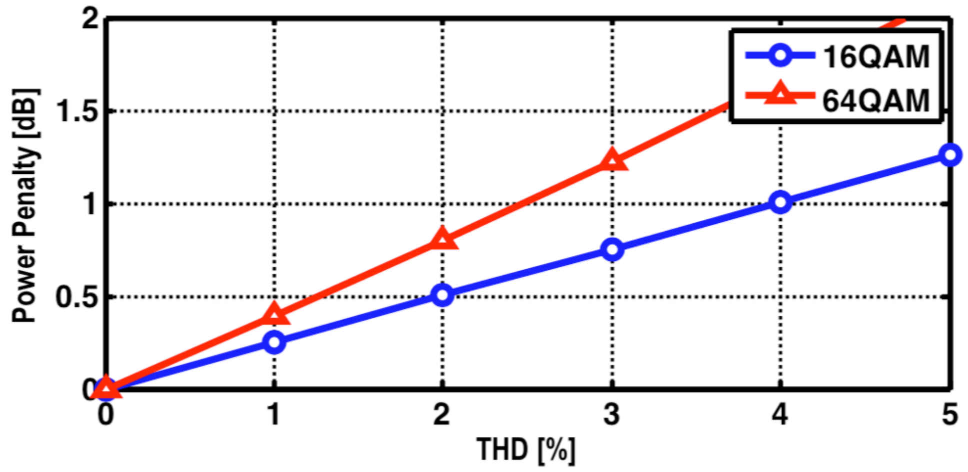
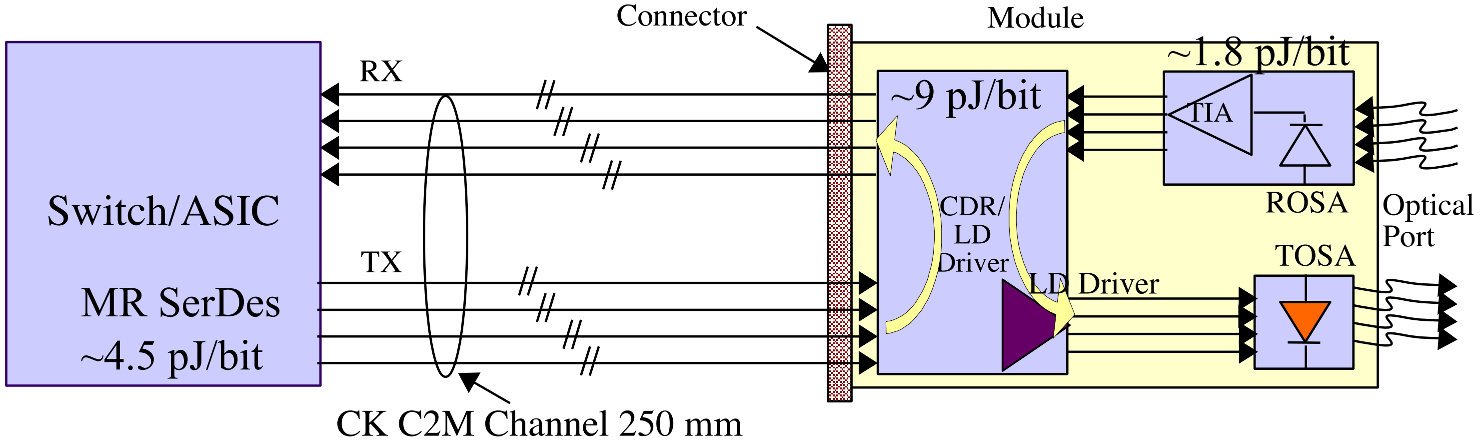


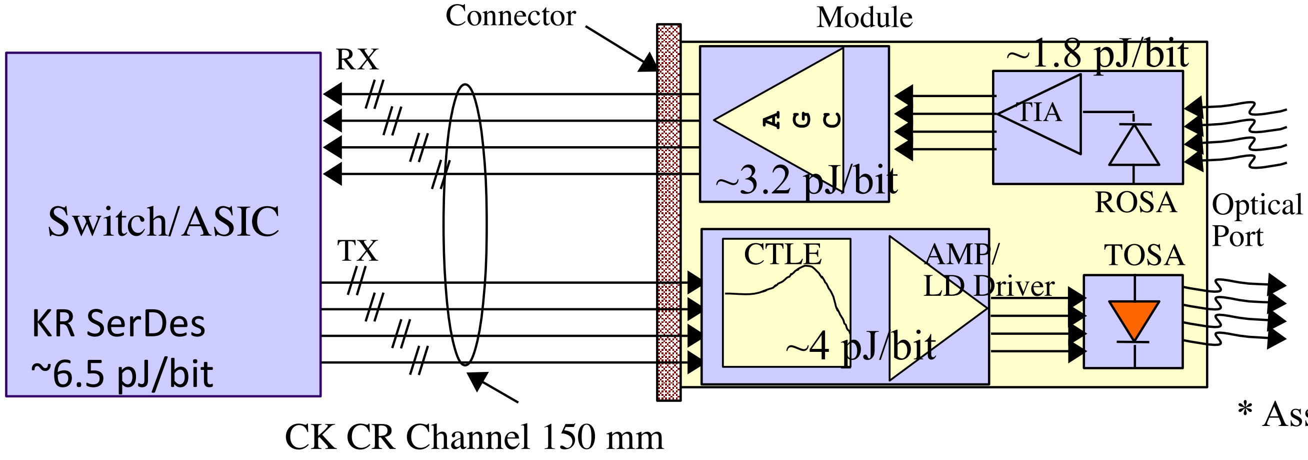
Fig. 4. Power penalty due to the receiver THD for 16QAM and 64QAM.

Retimed vs Linear Pluggable Key Block Diagrams and PD Estimates

- Plug and play C2M link excluding laser power consumes ~15.3 pJ/bit
- More complex linear optics excluding laser power assuming feasible consumes ~15.5 to 14.1 pJ/bit!



Excluding Laser
Estimated
Link PD ~15.3 pJ/bit

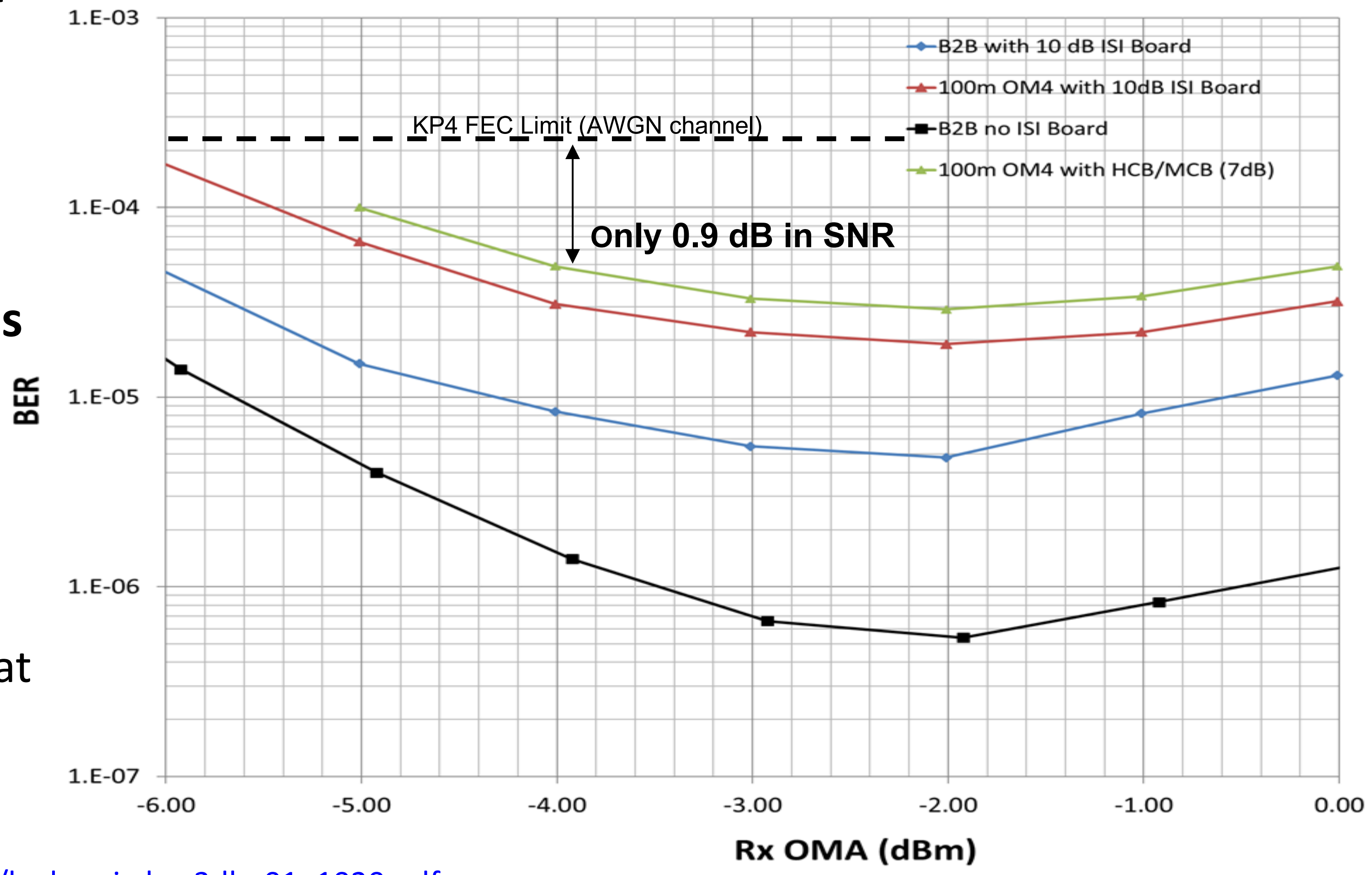


Excluding Laser
Estimated
Link PD ~15.5 pJ/bit
Link PD* ~14.1 pJ/bit

* Assumes an integrated TIA/AGC

Direct Drive Optics Pluggable Optics has Serious Error Flooring

- **The 100G VCSEL driven directly from the DSP but RX path include mated 112G OSFP MCB/HCB boards**
- **Sensitivity results indicate serious error flooring with just RX path MCB/HCB results flooring and results does not include:**
  - TX C2M connector and channel
  - Driver response and THD
  - Electrical Xtalk
  - PVT penalties (e.g. VCSEL measured at room temp.)
  - Component aging.



Also see https://www.ieee802.org/3/db/public/October20/lyubomirsky_3db_01_1020.pdf

Summary

- **Direct drive linear optics interface is not the same as SFI/nPPI**
  - SFI/nPPI were unretime limiting interfaces
  - Only LRM and some limited 80 km ZR links used linear receive interfaces
  - Limiting interface passes through the jitter but the limiter sharpens the eye and opens the eye vertically
  - Direct drive linear optics response is the cascade of {drive pulse, TX channel response, TX driver, laser/Modulator, PIN/TIA, AGC, RX channel, CTLE/ADC response} including non-linearities
- **Beside the fact that ~60% of switch ports will have channels with > 11 dB loss and/or may use MR SerDes, the switch SerDes does not have the same jitter and eye opening as typical optics CDR**
  - 2-3 dB higher VEC and ~0.15 UI lower EW is nonstarter to drive the optics
- **Direct drive linear optics require linear driver and AGC amplifier with low THD <2.0%**
  - These linear low THD amplifiers consume significant amount of power
  - Power dissipation of the robust retimed links is about the same as the more complex direct drive optics
- **Initial 100G MMF direct drive linear optics indicate even without TX channel and crosstalk the link is flooring therefore not technically feasible**
- **Given that timeline of the db task force to D1.0 no later than March-2021 the focus should be developing optical PMDs instead of dabbling in technically very challenging direct drive linear optics.**