Modal Noise Measurements with 25G VCSELs

Re: Comment IDs 4 and 10 against D1.1

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IEEE P802.3cm 400 Gb/s over Multimode Fiber Task Force
Long Beach, CA, January 2019

Introduction

- Recent discussions in 802.3cm suggest that a better estimation of modal noise (MN) is necessary
- Experimental data shown in castro_3cm_01_1118 provided a rough estimation
  - However, in those experiments, which used lateral offsets between fibers with air gaps, it was difficult to isolate modal noise from noise produced by reflections
  - Also, the range of noises were high due to the large number of connections
- Three approaches to improve the MN estimation were discussed in previous ad hoc meetings including:
  - (1) index matching filling air gap, (2) angle cleaved fiber, (3) spliced offsets
  - Approach (1) was impractical due to mechanical alignment issues
  - Approach (2) increased separation of the fibers due to the cleaved angle, and therefore increased losses.
- New experiments using a set of spliced fiber patch cords with specific losses are presented here
- A comparison with previous work and the evaluation of MN penalties are given

Experimental Setup

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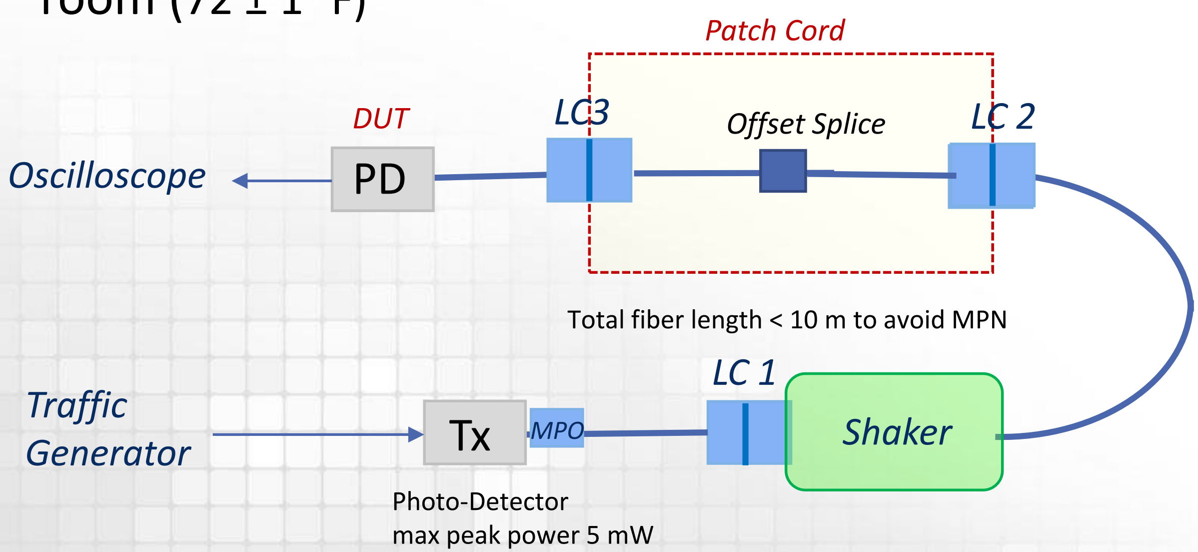
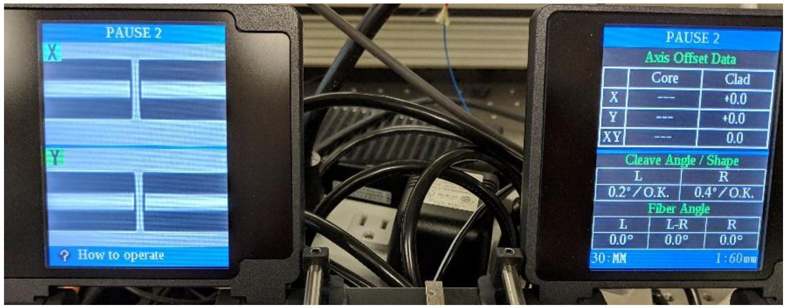
- A set of three patch cords to simulate channels with specific ranges of losses
  - BIMMF patch cord with offset splices: 0, 7 and 11 µm
  - The losses using and EF compliant LED source for the patch cords (LC2+Offset Splice) and the total channel loss (LC1+LC2+Offset_Splice +LC3) is shown in table below.
- Reference grade fibers used in all other connections
- 100GBASE-SR4 transceivers from FIT, Finisar, and Lumentum
  - Randomly labeled manufacturer A, B and C.
  - At least 2 transmitters per manufacturer shown in this presentation.
- Experimental data collected with the shaker on and off in a temperature controlled room (72 ± 1 ^{0}F)

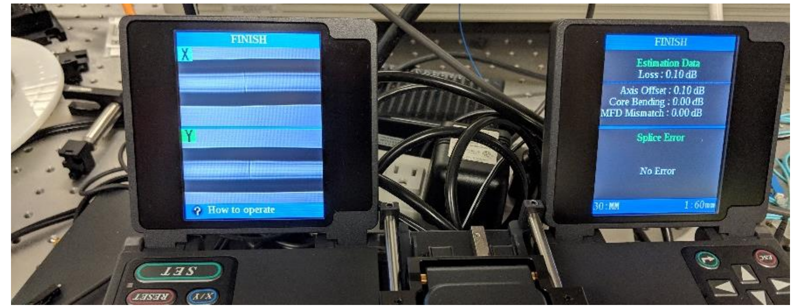


Channel	Patch cord used	Losses (EF LED source)	
	Offset (µm)	Patch Cord *Loss (dB)*	Channel *Loss (dB)*
1	0	0.087	0.424
2	7	1.11	1.363
3	11	1.452	1.773

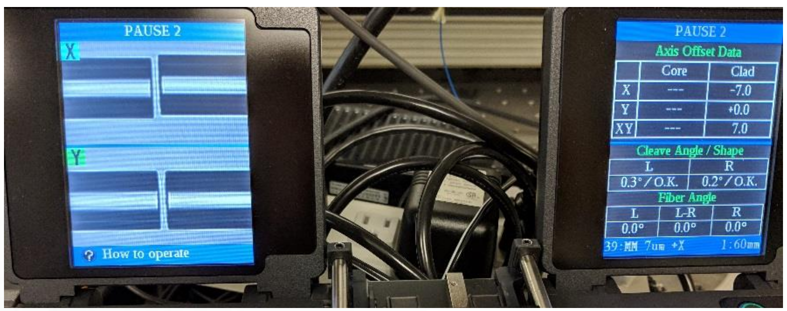
Spliced Patch Cords

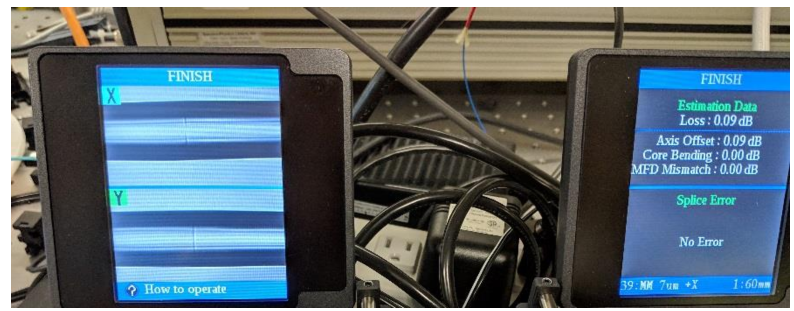
0 µm



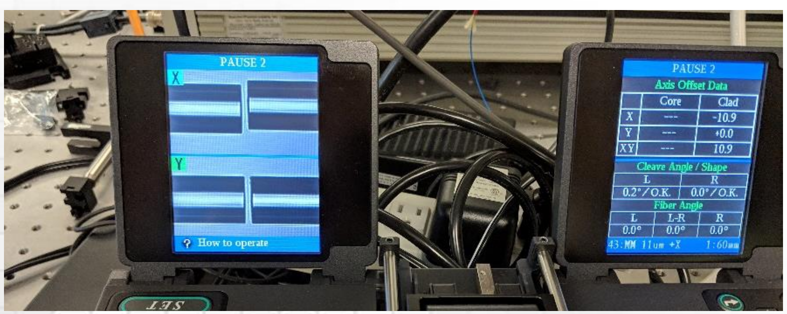


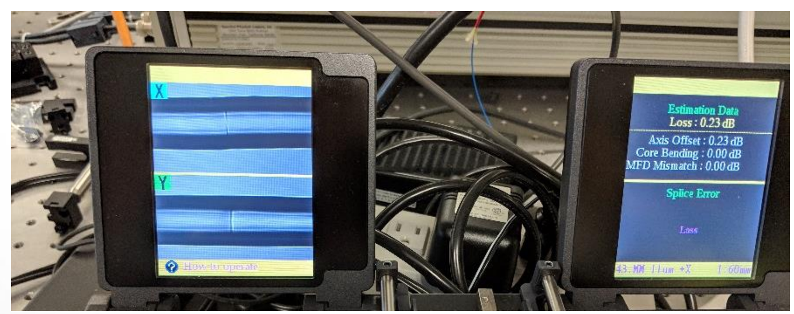
7 µm





11 µm

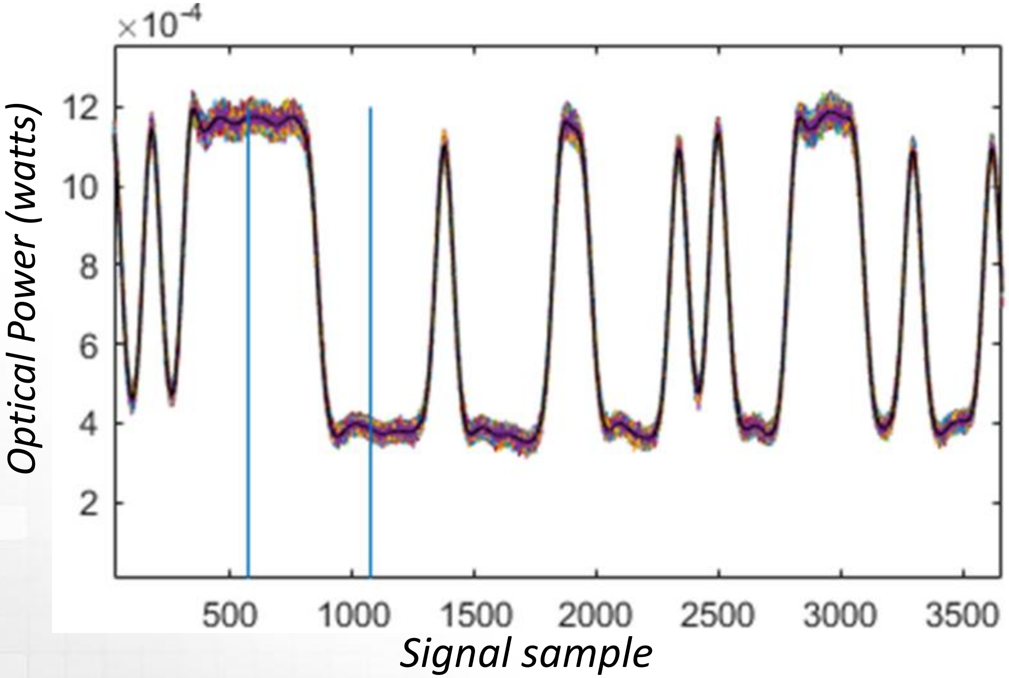




Data Acquisition Method

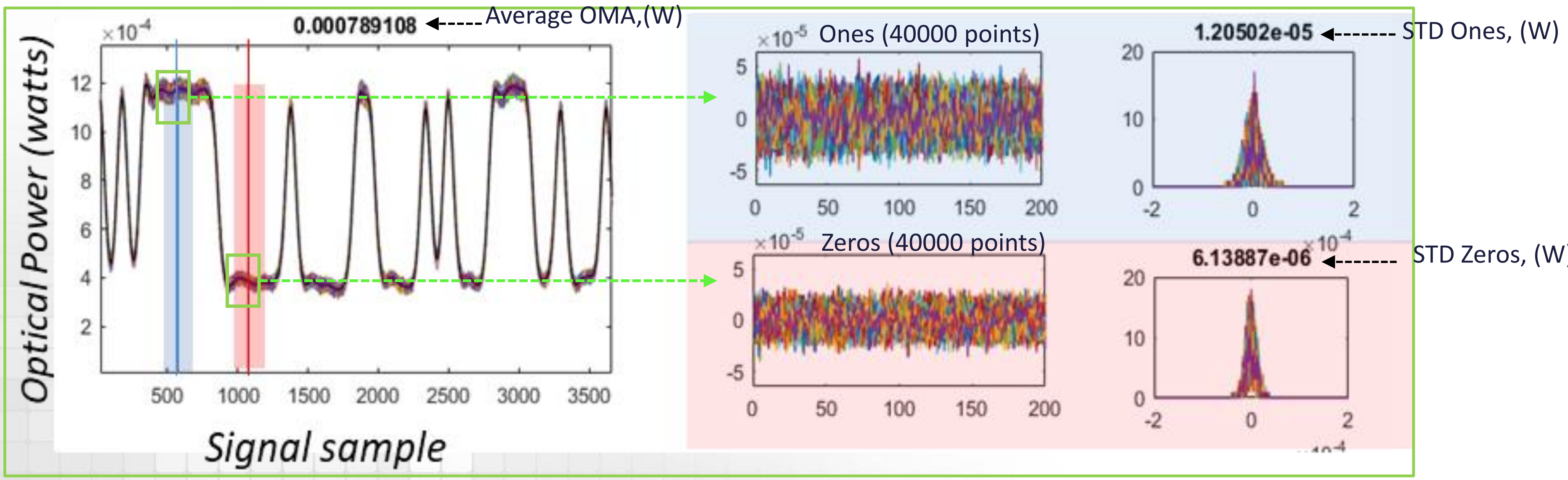
- Signal rate, waveform, and sampling acquisition parameter rates shown in table below
  - The acquisition duration per waveform (200 PRBS patterns) was ~8.128 seconds
- Before measurements, the oscilloscope background noise (BN) was characterized
  - The BN values, ~7 µW, were removed (quadratically subtracted) from subsequent measurements
- Signals as shown in the figure below were stored in 10,160 x 200 arrays
  - Black trace shows the mean signal of 200 patterns

Signal Rate	25.78	Gbps
Pattern (length)	PRBS 2^7-1=127	symbols
Sampling Rate	250	KSa/s
Symbol	80	points
Waveform	200x127x80	points



Data Acquisition Method cont…

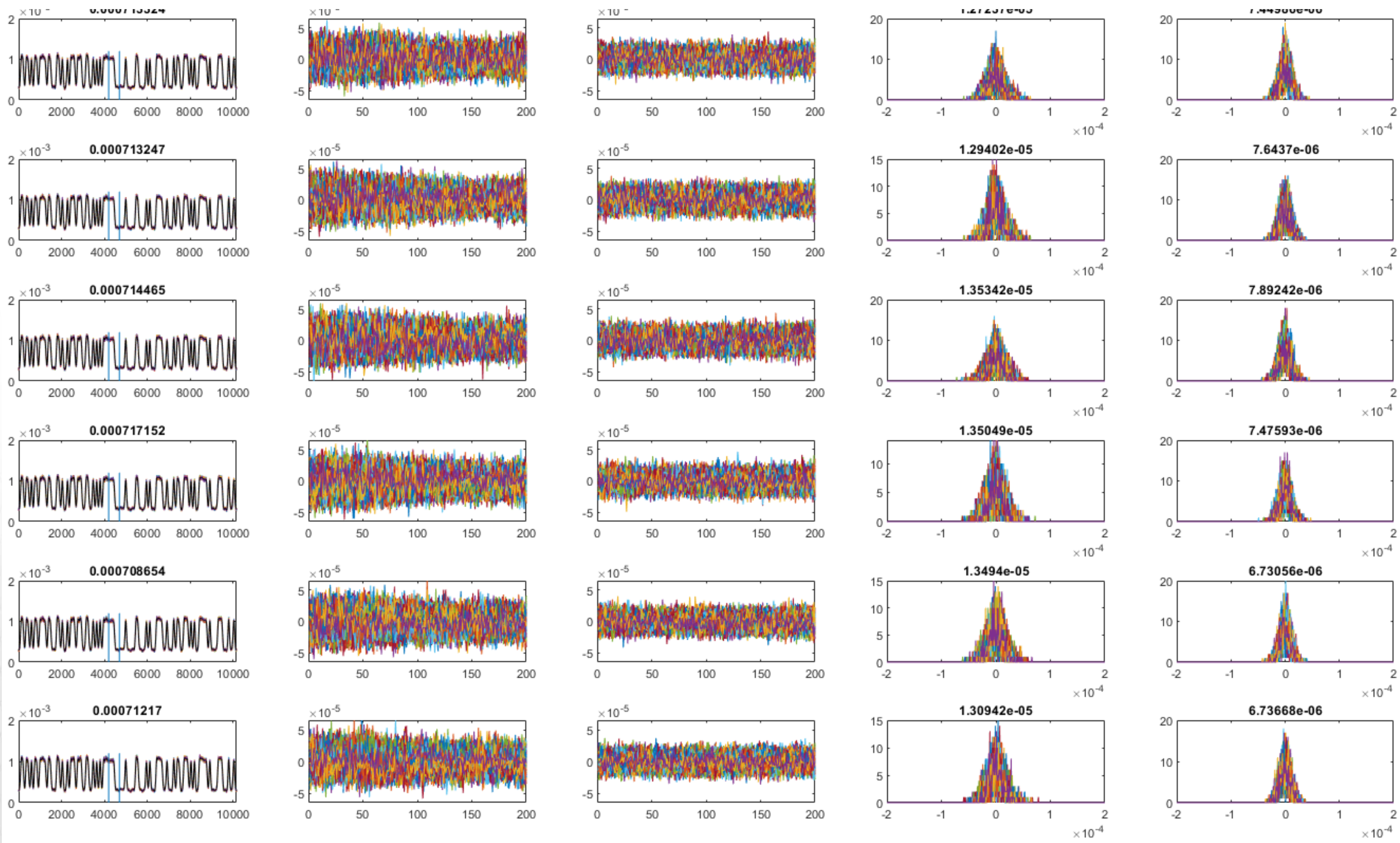
- The samples were acquired at the center of the longest periods of zeros and ones as shown in the figure below to minimize effect of jitter
  - 200 points around the center of the symbols one and zero we used
  - The STD of the 40,000 points (200 points x 200 waveforms) was computed for the zero and one symbol (BN subtracted), and the mean value per sample was subtracted
- For each patch cord and VCSEL combination, the previous steps were repeated eight times
  - Each 200 waveforms acquisition took approximately 30 seconds



Example

- Figure shows six of eight acquisitions for one transmitter and one patch cord

200 PRBS 2^7-1	Ones	Zeros	Ones	Zeros



Results

- In the next slides the colored circles represent:
  - Blue: direct connection to the PD bypassing patch cords and shaker.
  - Orange: channel 1, uses patch cord with 0 micron offset, IL =0.424 dB
  - Yellow: channel 2, uses patch cord with 7 micron offset, IL= 1.363 dB
  - Purple: channel 3, uses patch cord with 11 micron offset, IL =1.773 dB
- At least 8 repetitions for each channel and VCSEL
- The horizonal axis of each figure represents the link IL computed from the average power in the scope using each VCSEL. It is different than the channel loss that was measured EF compliant sourc.e

Manufacturer A

In all the figures the vertical axis represents $(\sigma_1 + \sigma_0)$ /OMA

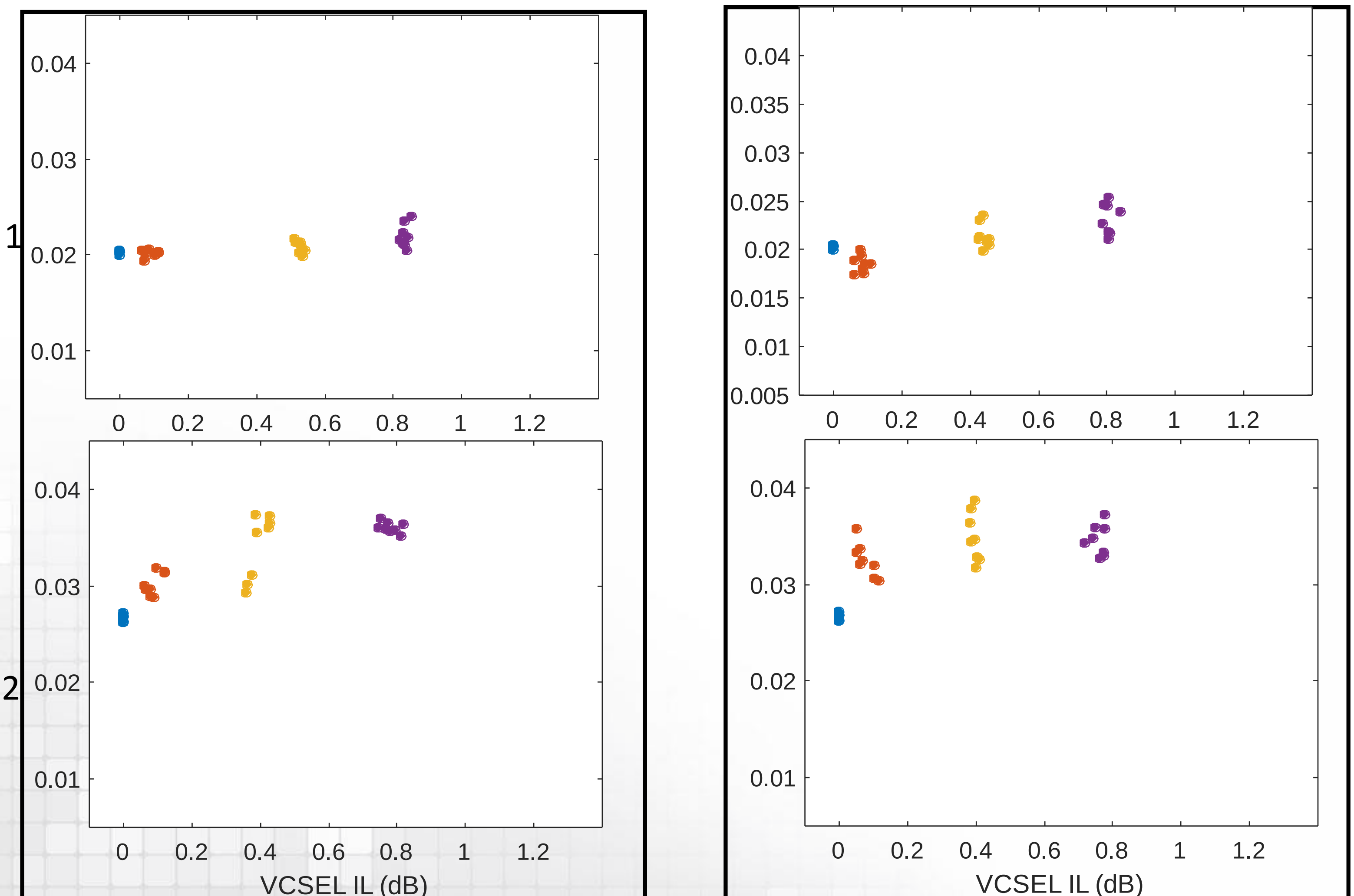
Horizontal channel loss is the loss as measured by each VCSEL using the scope

- Direct connection
- Channel 1, IL (LED)= 0.424 dB
- Channel 2, IL (LED)= 1.363 dB
- Channel 3, IL (LED) = 1.773 dB

Shaker Off | Shaker On

VCSEL 1

VCSEL 2



Manufacturer B

In all the figures the vertical axis represents $(\sigma_1 + \sigma_0)$ /OMA

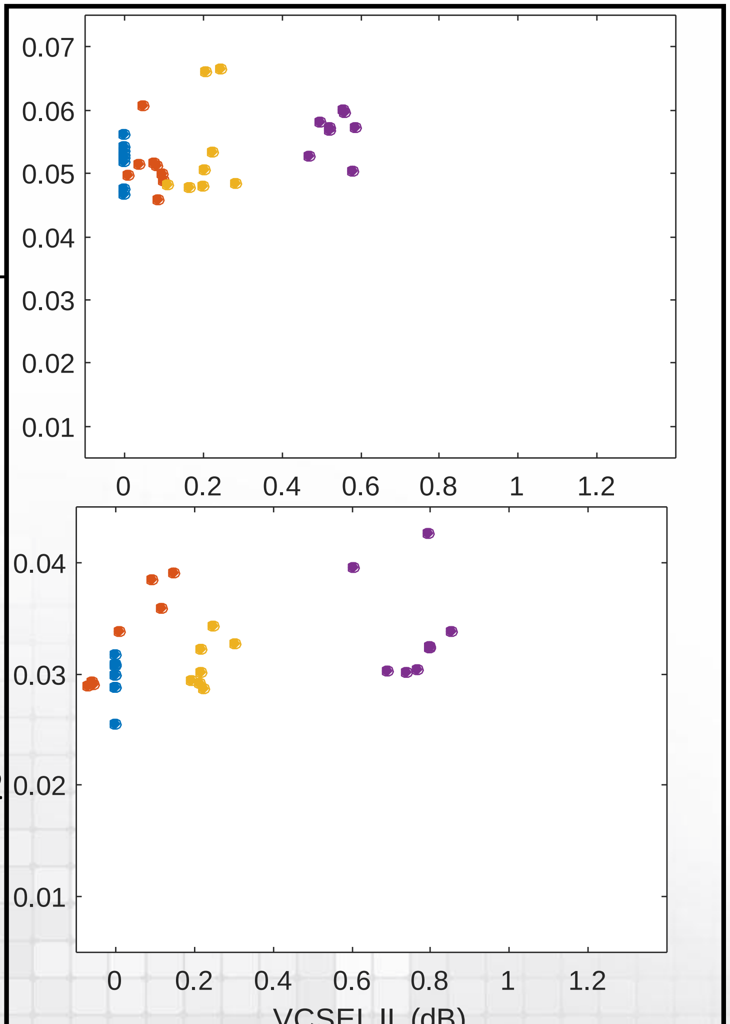
Horizontal channel loss is the loss as measured by each VCSEL using the scope

- Direct connection
- Channel 1, IL (LED)= 0.424 dB
- Channel 2, IL (LED)= 1.363 dB
- Channel 3, IL (LED) = 1.773 dB

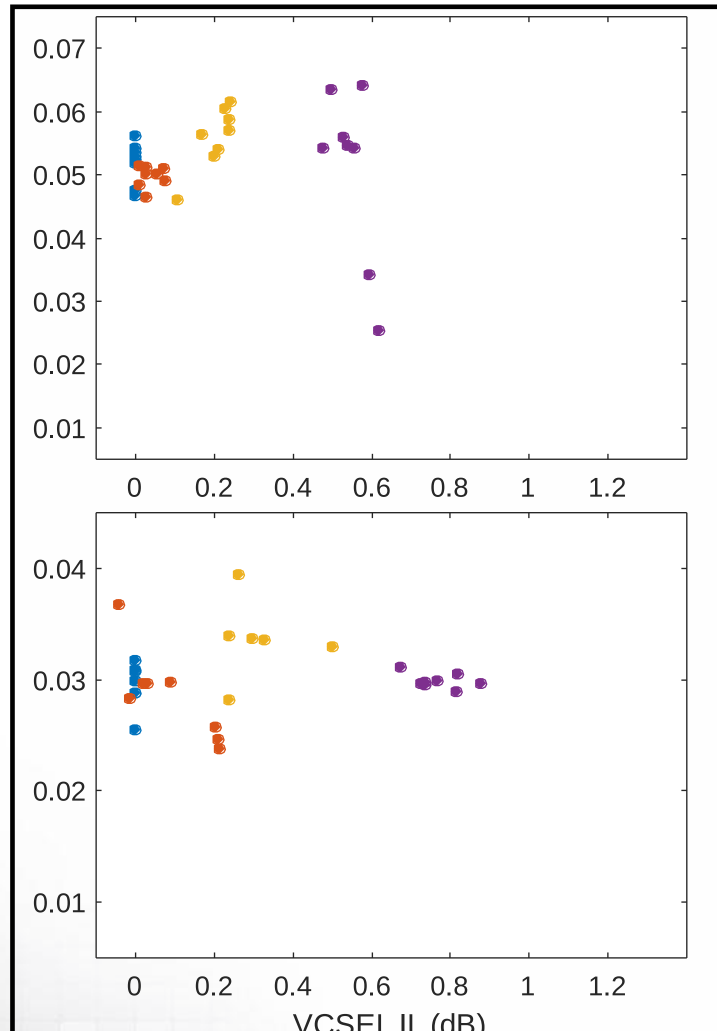
Shaker Off

VCSEL 1

VCSEL 2



Shaker On



Manufacturer B

In all the figures the vertical axis represents $(\sigma_1 + \sigma_0)$ /OMA
Horizontal channel loss is the loss as measured by each VCSEL using the scope

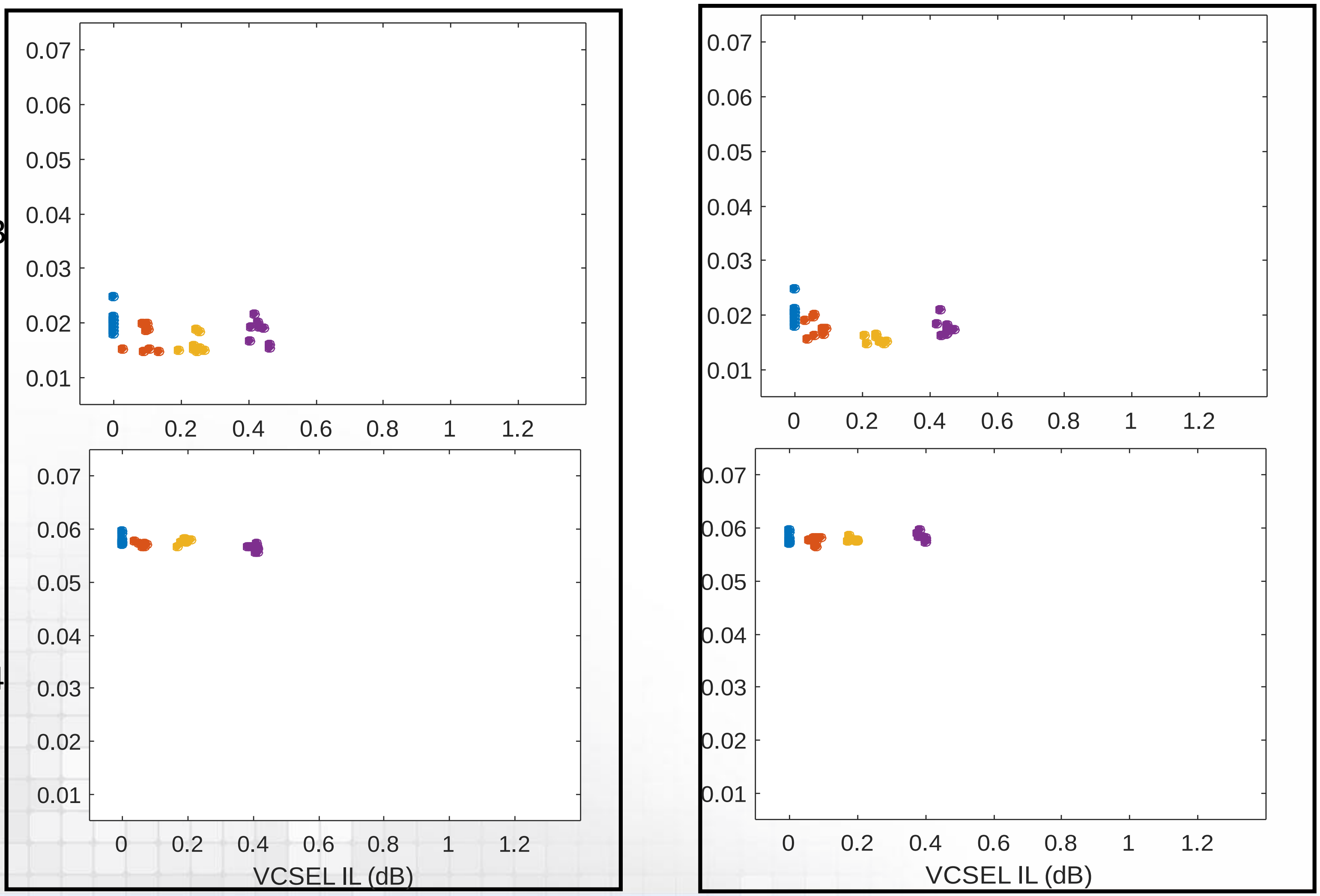
Direct connection
Channel 1, IL (LED)= 0.424 dB
Channel 2, IL (LED)= 1.363 dB
Channel 3, IL (LED) = 1.773 dB

Shaker Off

Shaker On

VCSEL 3

VCSEL 4



Manufacturer B

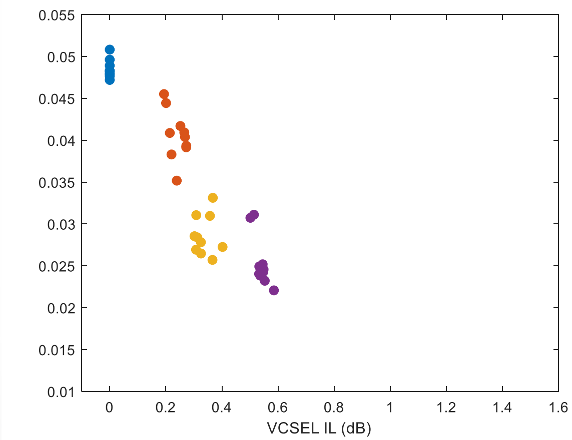
In all the figures the vertical axis represents $(\sigma_1 + \sigma_0)$ /OMA
Horizontal channel loss is the loss as measured by each VCSEL using the scope

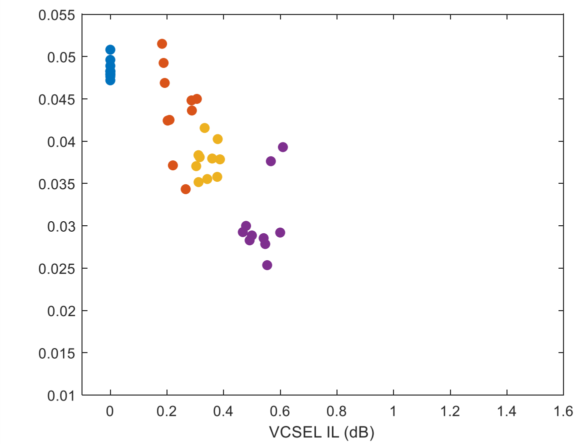
- Direct connection
- Channel 1, IL (LED)= 0.424 dB
- Channel 2, IL (LED)= 1.363 dB
- Channel 3, IL (LED) = 1.773 dB

Shaker Off

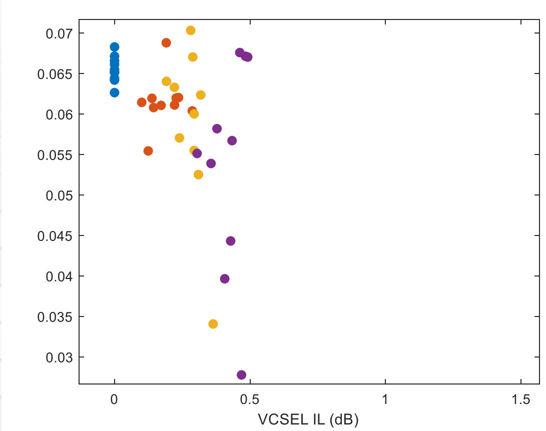
Shaker On

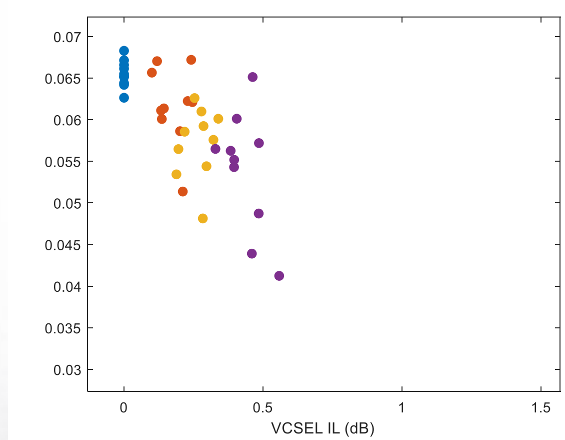
VCSEL 5





VCSEL 6





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Manufacturer B

In all the figures the vertical axis represents $(\sigma_1 + \sigma_0)$ /OMA
Horizontal channel loss is the loss as measured by each VCSEL using the scope

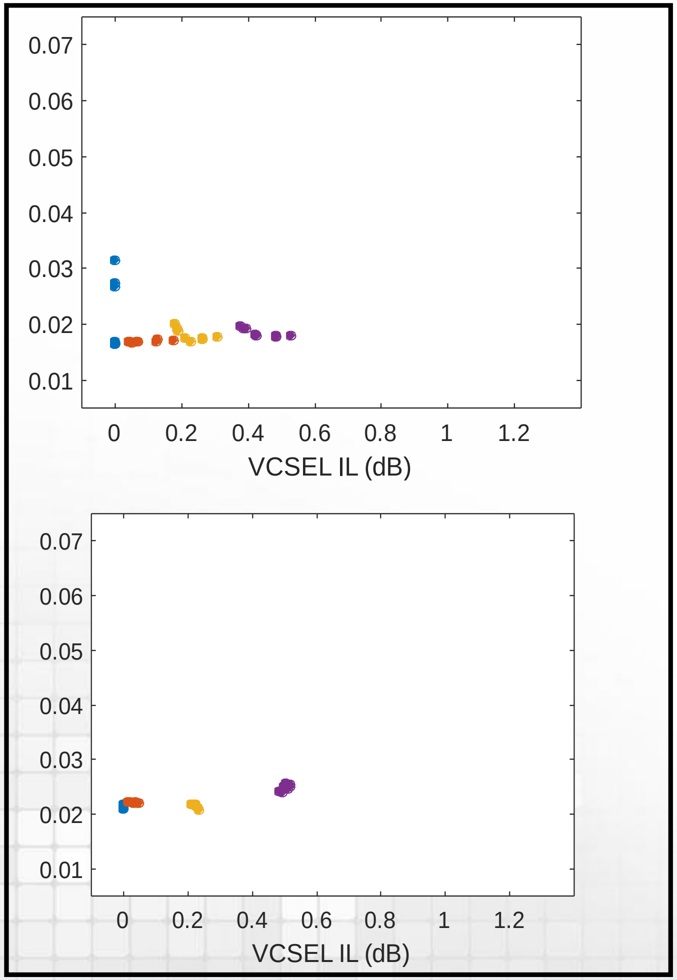
- Direct connection
- Channel 1, IL (LED)= 0.424 dB
- Channel 2, IL (LED)= 1.363 dB
- Channel 3, IL (LED) = 1.773 dB

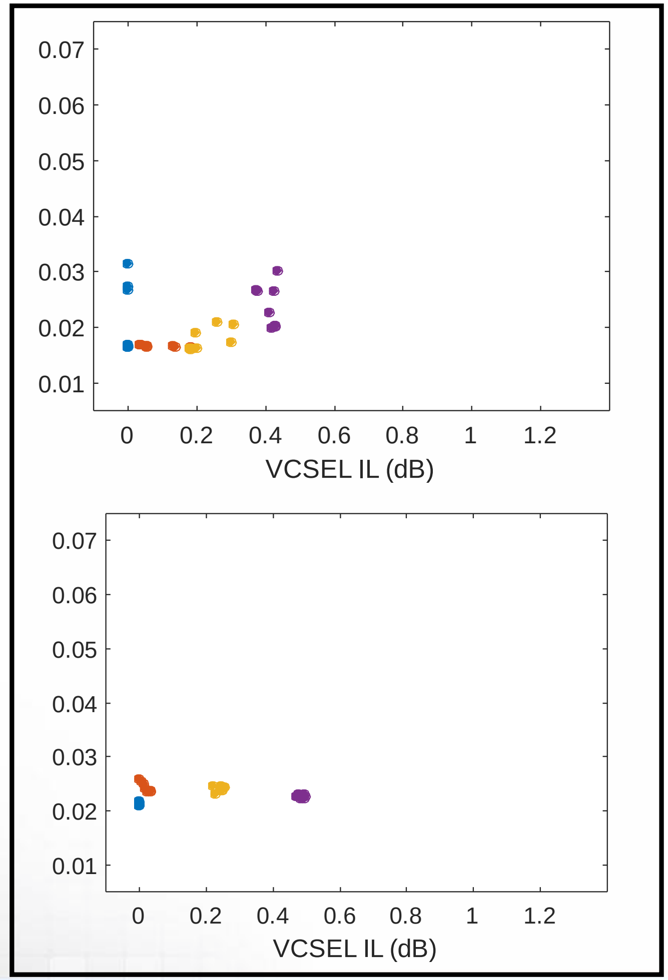
Shaker Off

Shaker On

VCSEL 7

VCSEL 8





Manufacturer C

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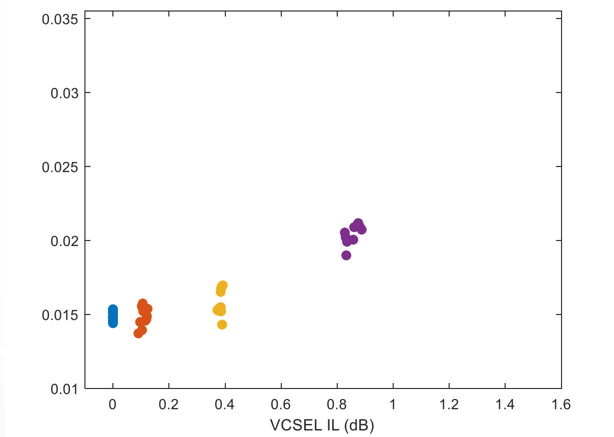
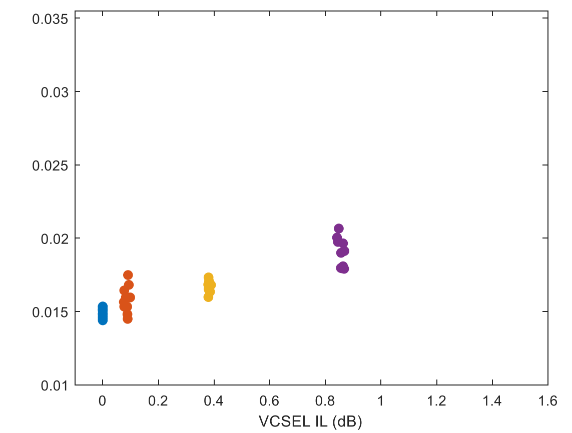
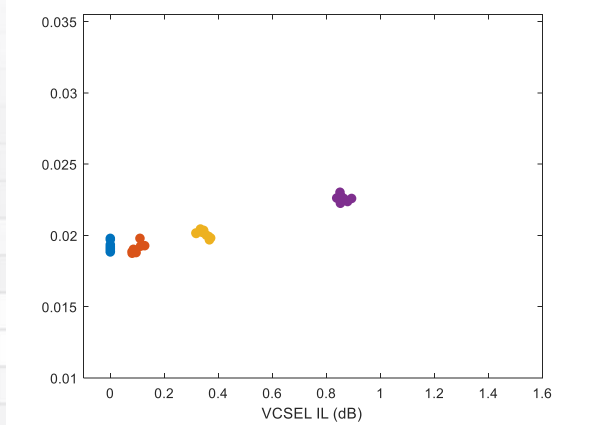
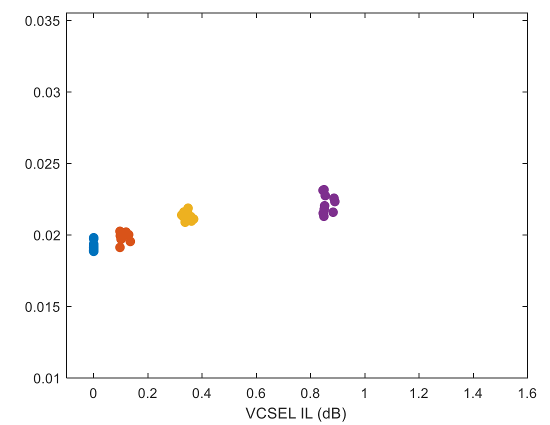
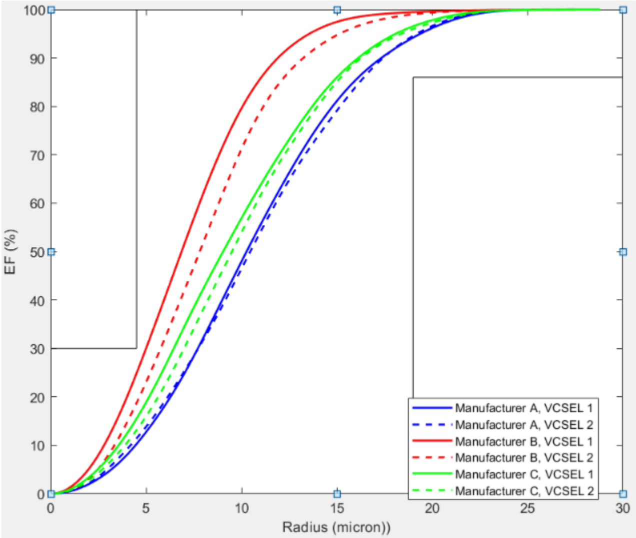
- Direct connection
- Channel 1, IL (LED)= 0.424 dB
- Channel 2, IL (LED)= 1.363 dB
- Channel 3, IL (LED) = 1.773 dB

In all the figures the vertical axis represents $(\sigma_1 + \sigma_0)$ /OMA
Horizontal channel loss is the loss as measured by each VCSEL using the scope

	Shaker Off	Shaker On
VCSEL 1		
VCSEL 2		

Discussion

- Manufacturers have difference launch conditions as confirmed by the encircle flux measurements shown below



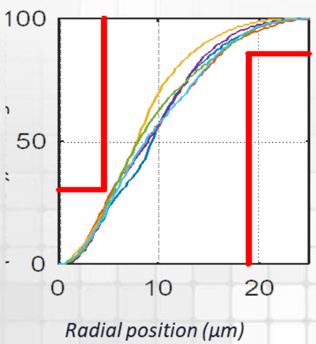
- Due to the differences in launch condition the connector impairments produce different signal losses for each manufacturer
  - Significant differences between the channels losses measured using an EF compliant source and the ones using the tested transmitters (VCSEL losses).
  - Underfilled sources tend to be less affected by connector lateral offsets and therefore show lower VCSEL losses.

Discussion cont…

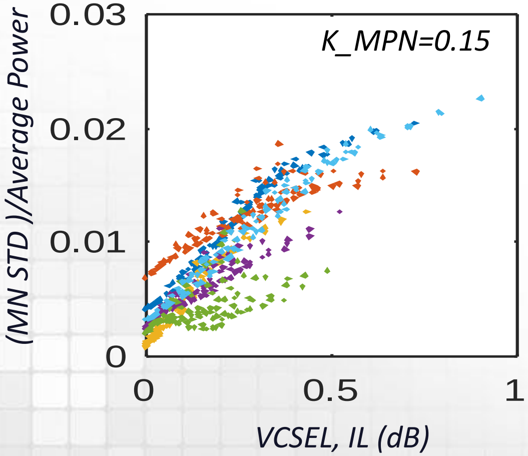
- For the evaluated samples it can be observed that noise dependence on connector IL is different for each manufacturer
  - Maximum normalized noise averaged STD for manufacturer A < 0.04
  - Maximum normalized noise averaged STD for manufacturer B < 0.07
  - Maximum normalized noise averaged STD for manufacturer C < 0.025
- Some transmitters from manufacturer B produced significant higher noise, with direct connection than other manufacturers
  - In some cases, the noises seems independent of IL.
  - High mode selective losses (MSL) caused during the VCSEL-fiber coupling could produce this type of behavior as shown in next slides.

Numerical Modeling of MN

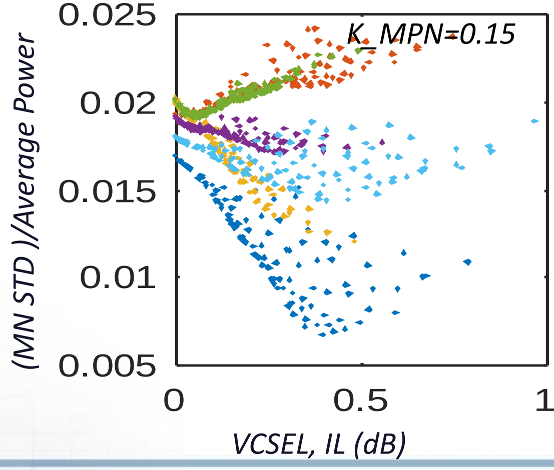
- Our MN numerical model uses parameters that meet statistical conditions described in Ogawa papers and account for the power fluctuation of VCSEL modes.
- The IL and MN of thousands of VCSELs with different spectrum and launch conditions were modeled in a channel with two connectors.
  - A detailed description of the MN model is beyond the scope of this presentation.
- The modeling results indicates that MN become less dependent on connector losses when MSL caused by VCSEL-MMF is high.
- For illustration purposes only 6 VCSELs with EFs shown below are used in this analysis



Very low MSL produced at the VCSEL-MMF interface MN scale with IL



High MSL produced at the VCSEL-MMF interface (1.2 dB loss for VCSEL mode 2) MN does not increase with IL in many cases



Experimental estimation of MN

- Removal of noise several components:
  - Spliced offsets eliminated the reflection effects
  - MPN was eliminated by using short fiber length
  - Sampling method and DSP also minimize jitter
  - Background noise removed
- RIN removal depends on the type of VCSEL.
- For manufacturers where noise tend to increase with connector losses (such as A and C), the RIN was assumed to be the noise measured during direct connection.
- This RIN was removed from the noise measured at ~1.5 dB

  - *A worst case: MN STD at 1.5 dB≈ $\mathrm{sqrt}(0.04^2-0.025^2)=0.031$*
  - *C worst case : MN STD at 1.5 dB ≈ $\mathrm{sqrt}(0.018^2-0.014^2)=0.012$*

- Assuming a worst case extinction ratio (ER =2) and Q=3.4917 for PAM-4 and Q=3.89 for NRZ, the MN penalties are obtained using (See appendix I for calculation details):

  - *NRZ Penalty ≈ $-5x\log10(1-(Qx0.031)^2)=0.032$ dB*
  - *PAM-4 Penalty ≈ $-5x\log10(1-(Qx0.031x1.22x3)^2)=0.37$ dB*

Estimation of MN cont..

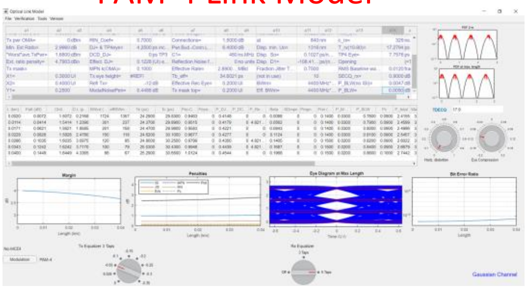
- For the VCSELs where the noise does not scale with IL we could assume that the VCSELs have a better OMA RIN than -128 dB/Hz.
  - Value used in link model spreadsheet for 802.3bm (Petrilla's spreadsheet).
- At 1.5 dB the worst-case average STD measured was 0.065 (VCSEL 6 manufacturer B)
  - *sqrt*$(0.065^2-0.052^2)=0.039$,
  - which produces MN Penalties of 0.62 dB for PAM-4
- This MN penalty is high. The fact that this transmitter also have very low IL (~1.1 dB less IL than the LED source) should let us re-evaluate what is acceptable for worst case penalty.
- Also the penalty was estimated for the top eye (worst case eye) of a PAM-4 signal (appendix I). A more realistic estimation of MN penalties is shown in next slide.

Estimation of MN penalties for PAM-4

- Previously penalties were computed for the worst-case eye (top eye)
  - Therefore, results are very pessimistic, since, the performance of the channel will depend on the transitions between other eye levels (bottom and middle)
- Here we use the link model disclosed in castro_3cm_02a_1118.pdf to estimate a more realistic MN penalty.
- Results indicate that the overall MN penalties are ≈67% of the value shown for the worst-case eye as shown in the table.

$(\sigma_1 + \sigma_0)$ /OMA	PAM-4 MN Penalty worst eye* (dB)	PAM-4 Link Model MN penalty (dB)
0.03	0.34	0.23
0.04	0.66	0.45

PAM-4 Link Model



- We propose to use 0.04 as maximum OMA normalized MN STD and 0.45 dB as maximum penalty for 1.5 dB loss.
- An expression to set a limit for MN at other losses is given by:

$$MN\_Penalties\_PAM4 = -0.67x5\log_{10}[1-(0.02x(EF\_Connector\_Loss-2)+0.05)^2]$$

Summary and conclusions

- Experimental results and modeling for modal noise produced by patch cords with mid-span lateral offset splices were presented
- A method for sample acquisition and a procedure for estimating MN from those measurements was described
- An initial estimation of MN was shown based on a small sample of VCSELs
- Results were compared with previous study, castro_3cm_01_1118 that show that estimation the MN parameter for a connector with 1.5 dB is

$$\frac{\sigma_1 + \sigma_0}{OMA} = 0.02(IL(=1.5\,dB) - 2) + 0.05 = 0.04$$

- Those experiment were subject to noises difficult to remove such as reflections. However, the worst case estimation of noise is not far from values obtained then

Summary and conclusions cont…

- The experiments shown in this presentation indicate values for $(\sigma_1+\sigma_0)/OMA$ around 0.03 to 0.04 producing a MN penalty range between of 0.23 dB to 0.45 dB for PAM-4 when all three eyes are including in the analysis
- The MN penalties can increase up to 0.66 dB if only the third eye (top eye) is evaluated. However, this will over penalize the link.

Appendices

Appendix I: Estimation of Penalties

- MN Penalties were obtained $Penalties\_MN = -5\log_{10}(1-(Q_T\sigma_S)^2)$
- For NRZ we assume $\sigma_1 = ER\sigma_0 = 2\sigma_0$

$$\sigma_S = \sigma_{S\_NRZ} = \left(\frac{V_1 - th}{\sigma_1}\right)^{-1} = \left(\frac{th - V_0}{\sigma_0}\right)^{-1} = \left(\frac{V_1 - (V_1\sigma_0 + V_0\sigma_1)/(\sigma_1+\sigma_0)}{\sigma_1}\right)^{-1} = \left(\frac{\sigma_1 V_1 - V_0\sigma_1}{\sigma_1(\sigma_1+\sigma_0)}\right)^{-1} = \frac{\sigma_1+\sigma_0}{OMA}$$

- For ER=2, $\sigma_{S\_NRZ} = 3\frac{\sigma_0}{OMA}$
- And for PAM-4, third eye (worst case) we assume $\sigma_3 = ER\sigma_0$ $, \sigma_2 = 2\frac{(ER-1)}{3}\sigma_0 + \sigma_0 = \frac{5}{3}\sigma_0$

$$\sigma_{S\_PAM4\_3\_eye} = \frac{\sigma_3+\sigma_2}{(OMA/3)} = \frac{11}{3}\frac{\sigma_0}{(OMA/3)} = 11\frac{\sigma_0}{(OMA)} = \frac{11}{3}\sigma_{S\_NRZ} \approx 3.66\sigma_{S\_NRZ}$$

- Note that all this estimation are pessimistic for PAM-4. The 3 eyes should be considered in the penalty estimation.

Appendix II: RIN_{OMA} approximation for transceivers B

- The RIN_{OMA} a square wave pattern (i.e., 8 zeros and 8 threes as indicated in 802.3bs Table 139-9).
- For NRZ model used by Petrilla spreadsheet (802.3 bm) the normalized RIN variance is given by,

$$\sigma_{RIN-OMA}{}^2 = \frac{\sigma_0{}^2 + \sigma_1{}^2}{2(OMA/2)^2} = \frac{K_{RIN} 10^{-RIN/10} 10^6}{\sqrt{0.477/BW_{RX}{}^2)}} \approx 0.055$$

  - Assumed not ISI penalties due to short fiber and extinction ratio of 2 we can use

$$(\sigma_0 / OMA)\sqrt{2(ER^2+1)} = (\sigma_0 / OMA)\sqrt{10} = 0.055$$

  - And obtain

$$(\sigma_0 / OMA) \approx 0.0174$$

$$(\sigma_1 / OMA) \approx 0.0348$$

  - Therefore the sum of STD due to RIN can be approximately estimated using,

$$(\sigma_0 + \sigma_1)/OMA \approx 0.052$$