Measurement and Estimation of the Mode Partition Coefficient *k*

Rick Pimpinella and Jose Castro

IEEE P802.3bm 40 Gb/s and 100 Gb/s Fiber Optic Task Force

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Background & Objective

- ***Background:***
  - *Mode Partition Noise in MMF channel links is caused by pulse-to-pulse power fluctuations among VCSEL modes and differential delay due to dispersion in the fiber (Power independent penalty)*
  - *"k" is an index used to describe the degree of mode fluctuations and takes on a value between 0 and 1, called the mode partition coefficient [1,2]*
  - *Currently the IEEE link model assumes k = 0.3*
  - *It has been discussed that a new link model requires validation of k*
  - *The measurement & estimation of k is challenging due to several conditions:*
    - *Low sensitivity of detectors at 850nm*
    - *The presence of additional noise components in VCSEL-MMF channels (RIN, MN, Jitter – intensity fluctuations, reflection noise, thermal noise, …)*
    - *Differences in VCSEL designs*
- ***Objective:***
  - *Provide an experimental estimate of the value of k for VCSELs*
  - *Additional work in progress*

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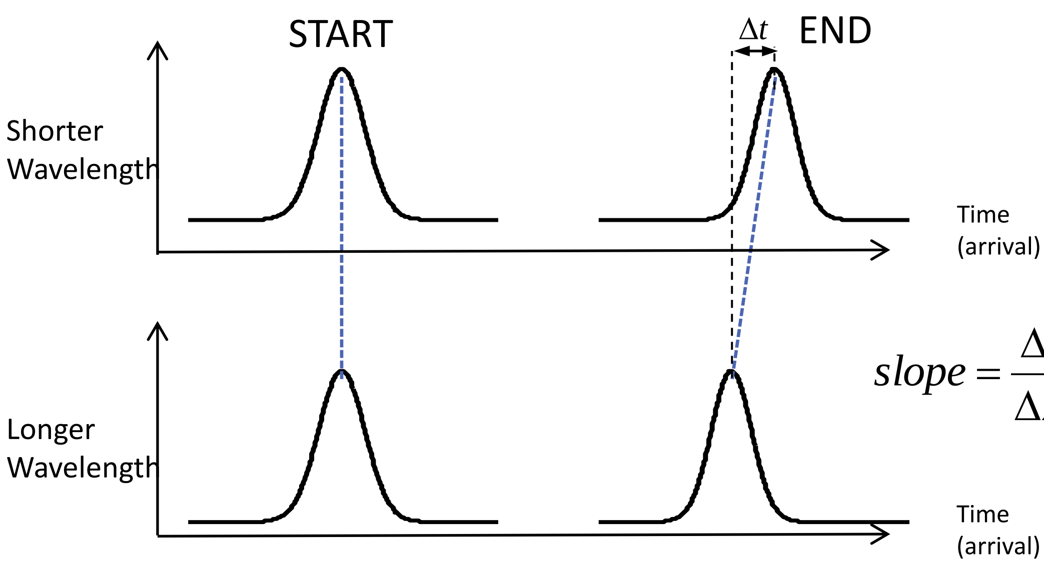
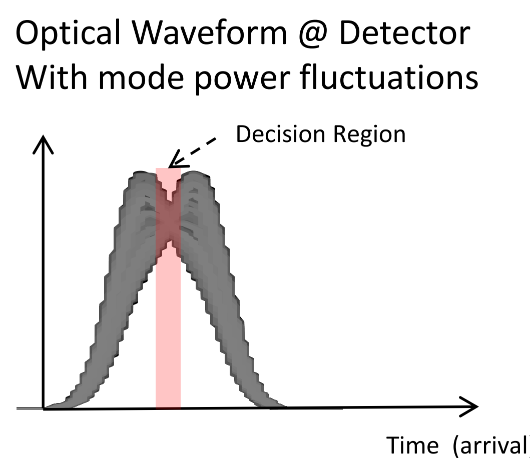
MPN Theory

Originally derived for Fabry-Perot lasers and SMF [3]

- ***Assumptions:***
  - *Total power of all modes carried by each pulse is constant*
  - *Power fluctuations among modes are anti-correlated*
- ***Mechanism:***
  - *When modes (different wavelengths) travel at the same speed their fluctuations remain anti-correlated and the resultant pulse-to-pulse noise is zero.*
  - *When modes travel in a dispersive medium the modes undergo different delays resulting in pulse distortions and a noise penalty.*
- ***Example:*** *Two VCSEL modes transmitted in a SMF undergoing chromatic dispersion:*

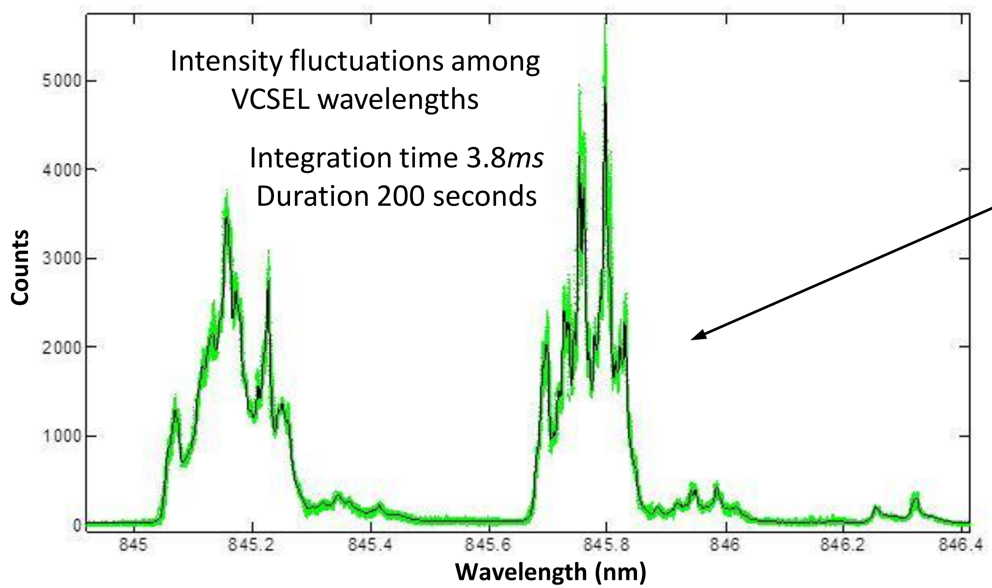


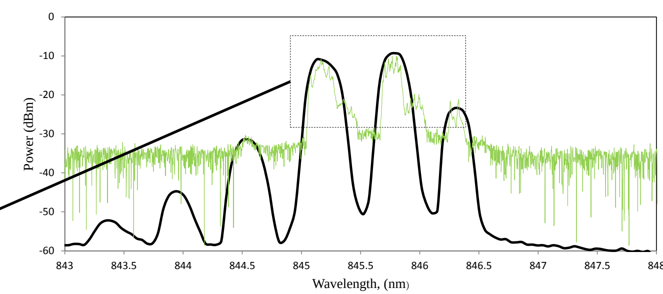
$$slope = \frac{\Delta t}{\Delta \lambda} = DL$$



Example of Intensity Fluctuation among VCSEL modes

- *MPN can be observed using an Optical Spectrum Analyzer (OSA).*
- *Measurements require a detector with high sensitivity and high bandwidth, and a means of isolating other noise components.*
- *The Figure below shows the optical spectrum of a 16GFC transceiver*
  - *Green traces are 100 VCSEL spectral measurements at ~2 second intervals*
  - *Black trace is the average spectrum*
  - *Noise can be observed but a slow detector does not provide a means of estimating the magnitude*





- High Resolution OSA (0.005nm)
- Low Sensitivity
- Linear amplitude
- 3.8*ms* integration time (min)
- Two VCSEL “*Mode Sets*”

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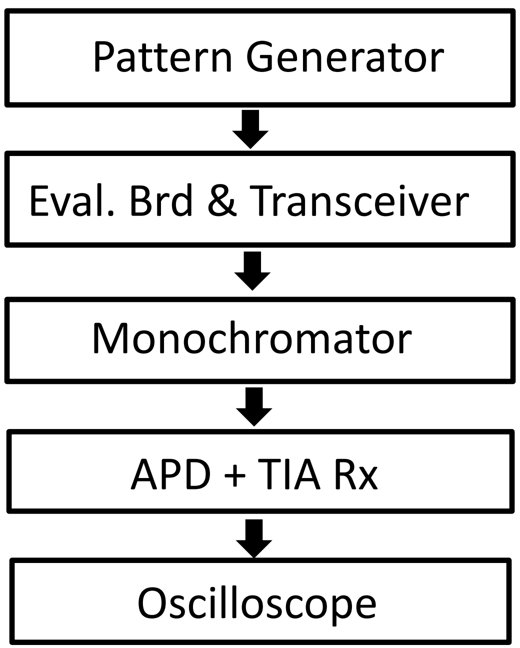
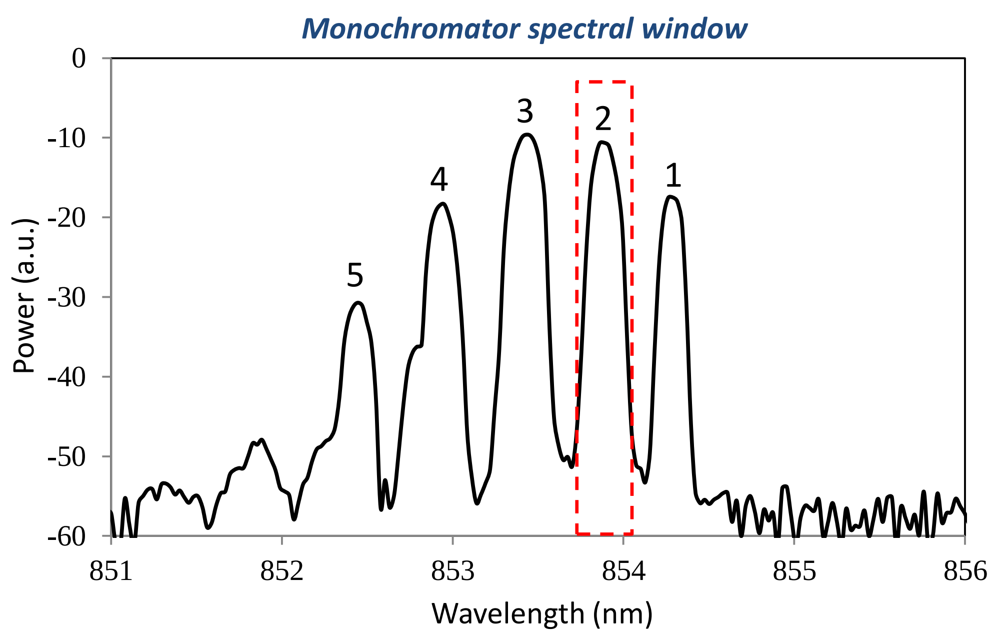
Measurement Methods

- ***Two methods used to measure k:***
  1. *Monochromator and APD measurements (equivalent to OSA)*
     - *High sensitivity*
     - *Bandwidth limited by APD*
     - *Fast transceivers were modulated at lower rates*
     - *Could not measure MPN for response rates >2.5Gbps*
     - *Short length used (5m) to avoid dispersion effects*
  2. *Temporal measurements in the spectral domain – specific data patterns measured at 16G data rates*
     - *Useful for evaluating noise dependence on transmitted pattern [4,5]*
     - *Fast detector – enables measurements at high bit rates (i.e. 14.025Gbps for 16GFC)*
     - *Short lengths used (5m) to avoid dispersion effects*
     - *Lower sensitivity must be compensated by increasing measurement time i.e., sample size*
     - *Need to estimate the noise introduced by other noise components*

Method 1: Monochromator–APD measurement

- *Signal measured using an APD (M > 40).*
- *Modulation rate limited to <2.5Gbps due to APD bandwidth (180ps rise time).*
- *VCSEL spectra separated into VCSEL Mode Sets (MS's). In practice only 4 MS's could be measured due to low power levels*
- *Light from the transceiver was filtered using a tunable monochromator with a spectral resolution between 0.2nm–0.5nm*
- *Oscilloscope used to obtain the signal histogram for specific bits in the sequence*





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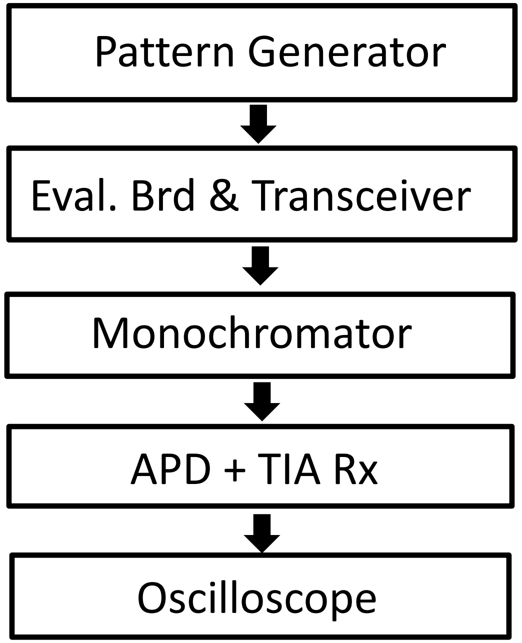
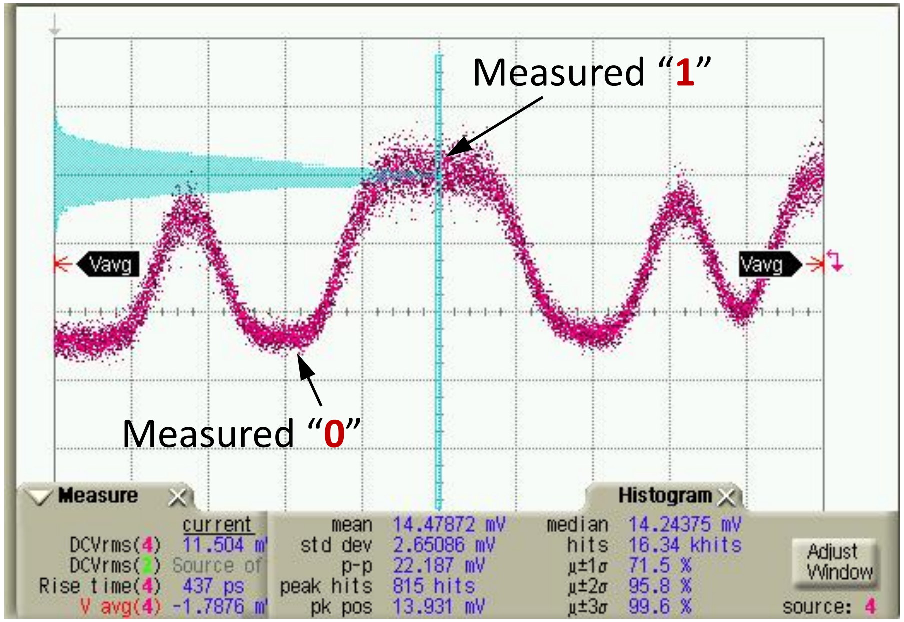
Method 1: Monochromator–APD measurement

- *Used PRBS 2^7-1 bit pattern*
- *For consistency only the zero and one bits shown in red in the following sequence were measured. "…10**0**1**1**1001… "*

Measured signal level histogram away from pulse edges





Time scale: 500*ps*/div

Y-axis in *mV*

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Method 1: Monochromator–APD Calculation

- *Computation using [2]:*

$$k = \sqrt{\frac{\overline{a_i^{\,2}} - \left(\overline{a_i}\right)^2}{\overline{a_i} - \left(\overline{a_i}\right)^2}}$$

for any mode set i

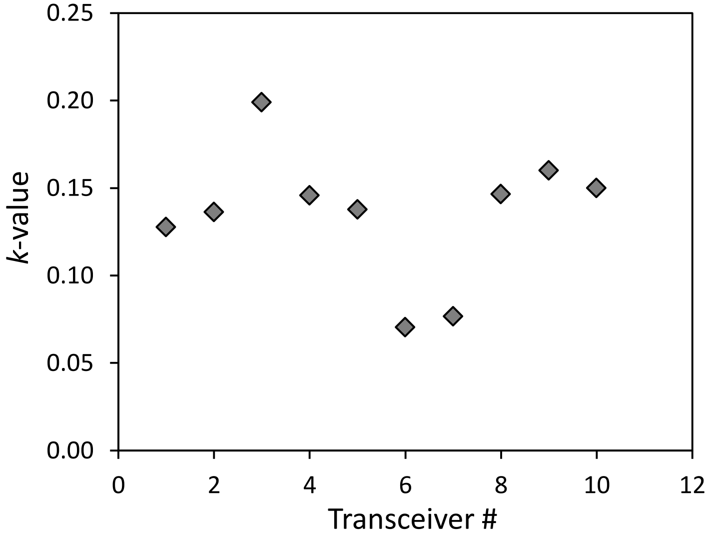
- *Where a_i and $\overline{a_i^{\,2}}$ are the normalized mean powers of each peak (measured as rms voltage) and the rms variation respectively, after subtracting the background noise SD (0.89mV).*
- *All OMA measurements limited to <2.5Gbps due to APD bandwidth limitations*

Computation Example

MS	MEAN (m*V*)	SD (m*V*)	a_i	SD a_i	*k*
1	~0.000	0.850	~0.000	~0.000	---
2	26.017	2.500	0.419	0.038	0.077
3	26.910	3.200	0.433	0.050	0.100
4	9.214	1.570	0.148	0.021	0.060

Total Power (*Vrms*) = 62.14*mV* **Max. *k* = 0.1**

Maximum k for each transceiver



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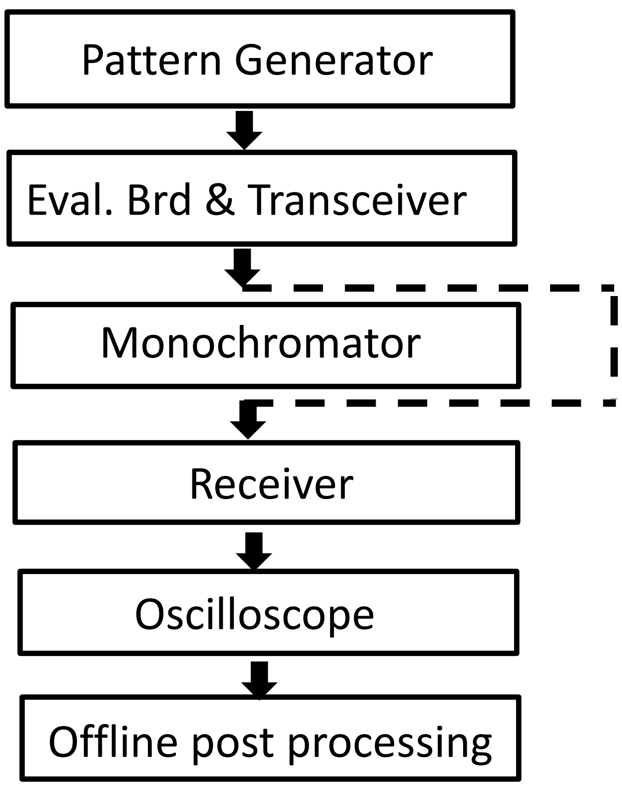
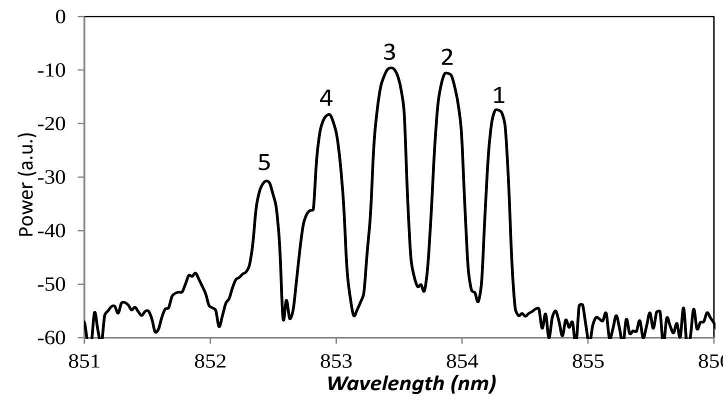
Method 1: Measurement Issues

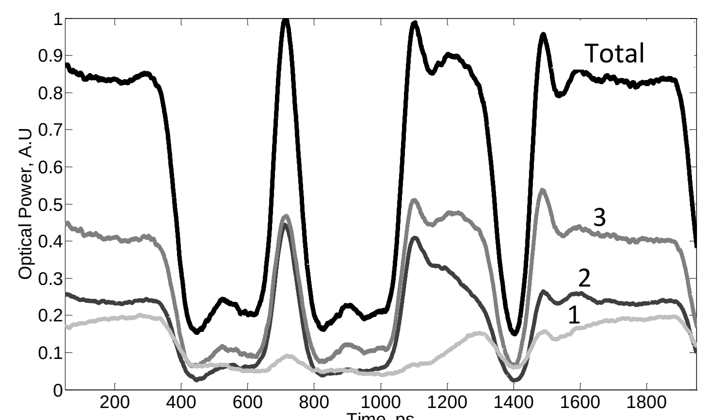
- *Limited APD bandwidth (2.5Gbps) might result in a lower value for k (filters high frequency noise).*
- *Are the 16G transceivers operating properly at 2.5Gbps, or are we introducing additional noise?*
- *Is a correction required to extrapolate to 14Gbps?*
  - *Based on theory [2] the noise variance should be scaled.*
    - *However, in order to apply scaling, we must assume how the MPN spectrum behaves above the cutoff frequency.*
  - *It is challenging to use the laser rate equations to predict the noise spectrum above cutoff for the individual transceivers measured.*
- *All these questions indicate an alternative method in which the transceivers operate at the specified line rate is required.*

Method 2: Temporal-Spectral characterization using a fast detector and post processing

- ***Procedure***
  - *The transceiver is modulated with a specific bit pattern*
  - *Resultant waveforms measured for 5m to 1km lengths with and without monochromator*
  - *The measurements reported here are for 5m*
  - *Sampling Oscilloscope with high bandwidth optical plug-in*
  - *The oscilloscope acquired the waveforms and sent them to a computer for processing*



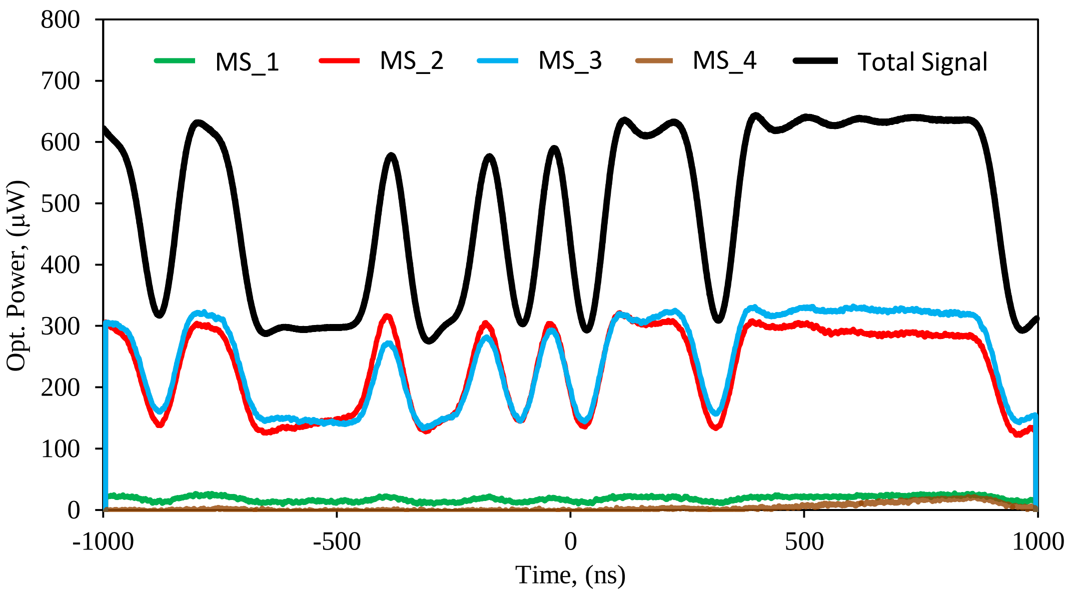




Example for a 10G signal

Method 2: Signal acquisition

- ***Test Equipment Characteristics***
  - *Sources: 16GFC Transceivers (clock 14.025GHz)*
  - *Linear Receiver: DCA plug-in,12GHz BW*
  - *Sampling Oscilloscope DCA 861000, temporal resolution = 0.5ps*
- ***Acquisition Procedure***
  - *The chromatic unfiltered signal (black trace) was measured*
  - *The signals for 4 VCSEL mode sets were acquired using the monochromator (colored traces)*
  - *Signals were compensated for measurement noise and monochromator loss*



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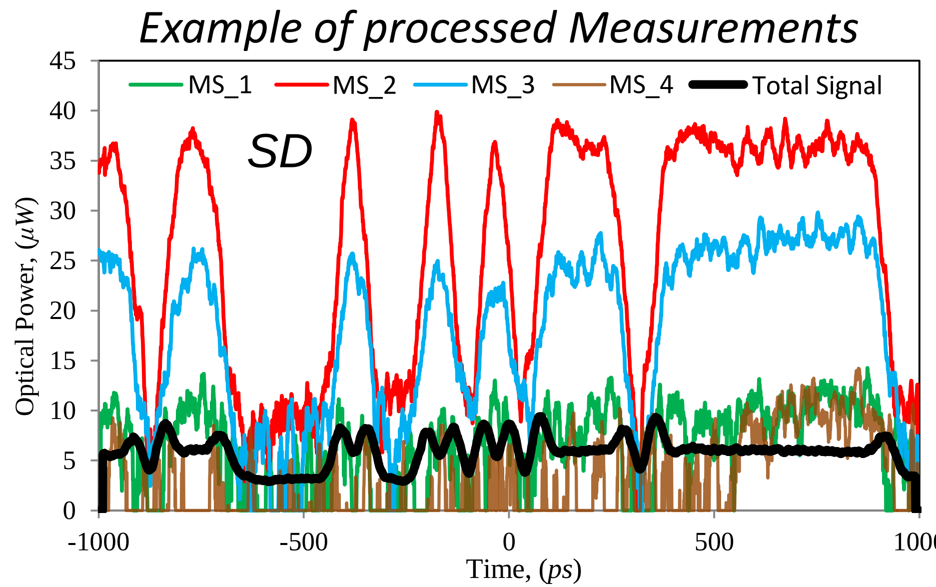
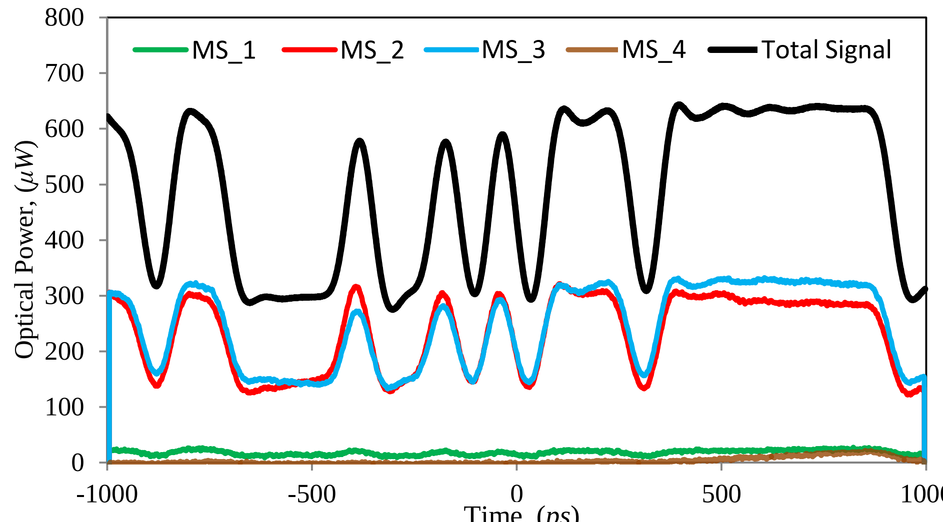
Method 2: Procedure

- ***Noise Computation Procedure***
  - *>500 signal waveforms were captured for each MS*
  - *The standard deviation (SD) for each MS signal was computed every 0.5ps*
  - *The SD of the total signal (black trace in Top Fig.) is less than the noise in any one VCSEL MS signal*
  - *This is attributed to the high degree of anti-correlation among VCSEL modes [2]*
  - *There are other noise components in the total noise including thermal, jitter-intensity fluctuations, RIN, …*
  - *Using this measurement method the maximum k is ~0.22*

$$k = \sqrt{\frac{\overline{a_i^{\,2}} - \left(\overline{a_i}\right)^2}{\overline{a_i} - \left(\overline{a_i}\right)^2}}$$





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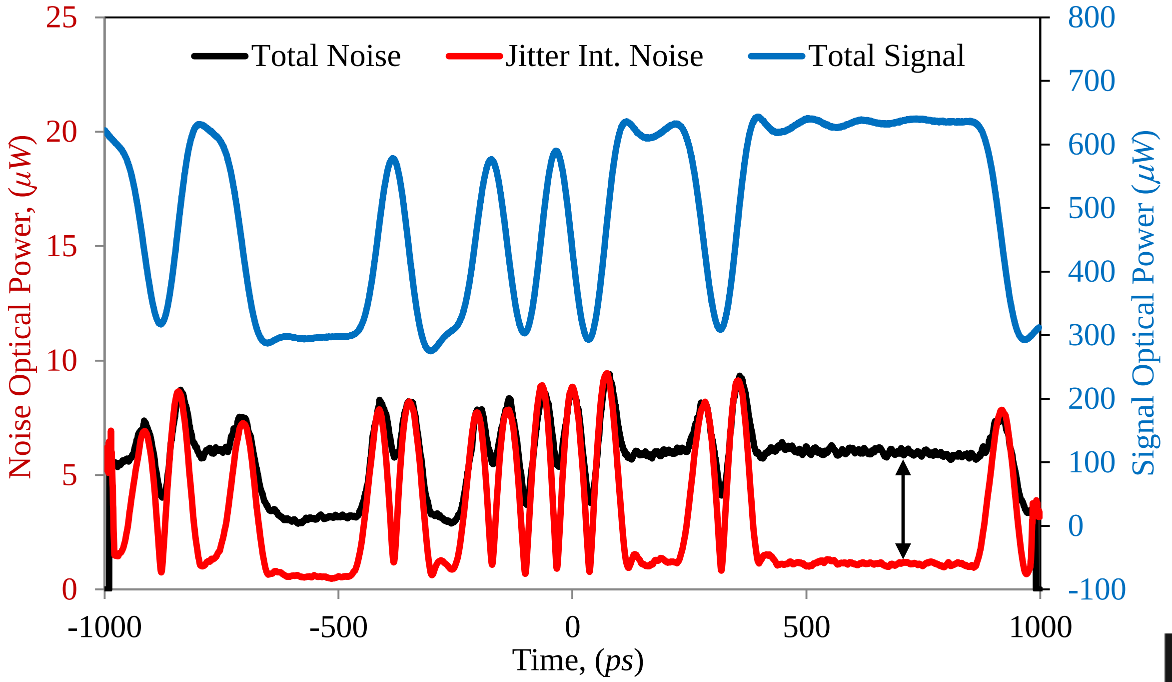
Method 2: Noise considerations

- *The Random and Deterministic Jitter was measured, used RJ for noise calculations.*
- *The signal waveform and measured jitter was used to calculate the jitter-intensity noise (red trace). Method to be published.*
- *It can be observed that the jitter-intensity noise matches the total noise at the pulse edges.*
- *The magnitude of the noise contributions due to RIN and other noise components can be obtained by subtracting the jitter-intensity noise (red trace) from the total noise (black trace). The difference is indicated by the double arrow.*
- *Close inspection of the jitter-intensity noise and the total noise suggests the remainder of noise is proportional to signal intensity.*



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Conclusions

- ***Two methods where used to measure k:***
  - *Measurements made at 2.5Gbps and 14Gbps*
  - *Both methods yield similar values for k*
  - *Method 1, monochromator and APD:*
    - *The maximum value for k was measured to be 0.20*
  - *Method 2, Temporal-Spectral characterization:*
    - *The maximum value for k was measured to be 0.22*
- ***The current value for k (0.3) is reasonable, but might be conservative***
  - *A value 0.25 could be more accurate*
  - *Additional work underway*
    - *Larger transceiver sample set*
    - *MPN over long lengths*
    - *Effect of modal-chromatic dispersion and spectral mode coupling [6]*

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References

[1] K. Ogawa, “Analysis of Mode Partition Noise in Laser Transmission Systems, *IEEE J. Quantum Electron*., vol. QE-18, no. 5, May 1982.

[2] K. Ogawa and R.S. Vodhanel, “Measurements of Mode Partition Noise of Laser Diodes,” *IEEE J. Quantum Electron*., vol. QE-18, No. 7, July 1982.

[3] G. Agrawal, P. Anthony, and T. Shen, “Dispersion Penalty for 1.3-mm Lightwave Systems with Multimode Semiconductor Lasers,” J. Lightwave Technol., vol. 6, no. 5, May 1988.

[4] P. Pepeljugoski, “Dynamic Behavior of Mode Partition Noise in Multimode Fiber Links,” *IEEE J. Lightwave Technol.*, vol. 30, no. 15, August 2012.

[5] J. Castro, R. Pimpinella, B. Kose, and B. Lane, “The Interaction of Modal and Chromatic Dispersion in VCSEL based Multimode Fiber Channel Links and its Effect on Mode Partition Noise,” *Proceedings of the 61 IWCS 2012*.

[6] J. Castro, R. Pimpinella, B. Kose, and B. Lane, “Investigation of the Interaction of Modal and Chromatic Dispersion in VCSEL-MMF Channels,” *J. Lightwave Technol*., vol. 30, no. 15, August 2012

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