Time-dependence of FWM Outage Probability in 800G-LR4 PMD

John Johnson, Broadcom

IEEE P802.3dj Task Force
January 2023 Sessions

BROADCOM®

Supporters

- Xiang Liu, Huawei
- Frank Chang, Source Photonics
- Nobuhiko Kikuchi, Hitachi
- Chris Cole, Coherent
- Jeffery Maki, Juniper Networks
- Ernest Muhigana, Lumentum
- Roberto Rodes, Coherent
- Rangchen Yu, SiFotonics

Motivation

- Previous contributions [1-4], including by this author, have interpreted the FWM outage probabilities derived from Monte Carlo calculations and fiber transmission simulations with PMD as interchangeable and cumulative
- This contribution explains why this view is incorrect, and what the distinctions are between the two types of FWM outage probability
  - Static probability, based on the configurations of transmitter and fiber parameters
  - Time-dependent probability, based on the random evolution of polarizations in the fiber
- The conclusions of this exercise are
  - Any links with outages in time above an application-specific maximum level must be considered to be unusable
  - Polarization interleaving isn't sufficient to fix configurations with strong static FWM generation potential if fiber PMD isn't restricted to low values, << 0.1 ps/√km.
- The focus must therefore be on defining the wavelength grid, power budget and fiber specs necessary to ensure a commercially viable, static outage probability
  - This will by necessity require the use of statistical fiber survey data for ZDW and possibly PMD

Interpretation of FWM outage probabilities

- Multiple contributions have studied the probability of FWM outage for 800G-LR4 (and future 1.6T-LR8) PMDs using Monte-Carlo techniques [1-4]
  - The calculations use analytical formulae for FWM generation for co-polarized (XXXX), CW signals, resulting in a ratio of FWM noise to signal power on the upper rail
  - The results depend critically on the assumed distributions of laser wavelengths, fiber ZDW and optical launch powers. Assumptions about fiber segment length also apply.
  - Since these parameters are relatively constant, the FWM outage probabilities predicted by Monte-Carlo can be considered to be **static**
- Other contributions have studied the effects of polarization interleaving to further reduce FWM outage probabilities [2,4]
  - XYYX polarization interleaved launch is effective to reduce FWM in the absence of PMD, but becomes significantly less effective as PMD increases and scrambles the polarizations
  - Since DGD is a stochastic process which varies in time on a given fiber, the reduction of FWM by XYYX polarization launch is not a constant **but varies in time**
  - If the outage probability in time isn't low enough, the link will not meet in-service criteria for the application and is considered unusable

Static and time-varying FWM

Time-independent parameter distributions

Monte Carlo using CW, co-polarized approximation

Transmission simulation with equal launch power, perfect phase matching, polarization interleaving and fiber with PMD

Fiber ZDW
Laser WL
TX OMA

→

CW Monte Carlo (XXXX)

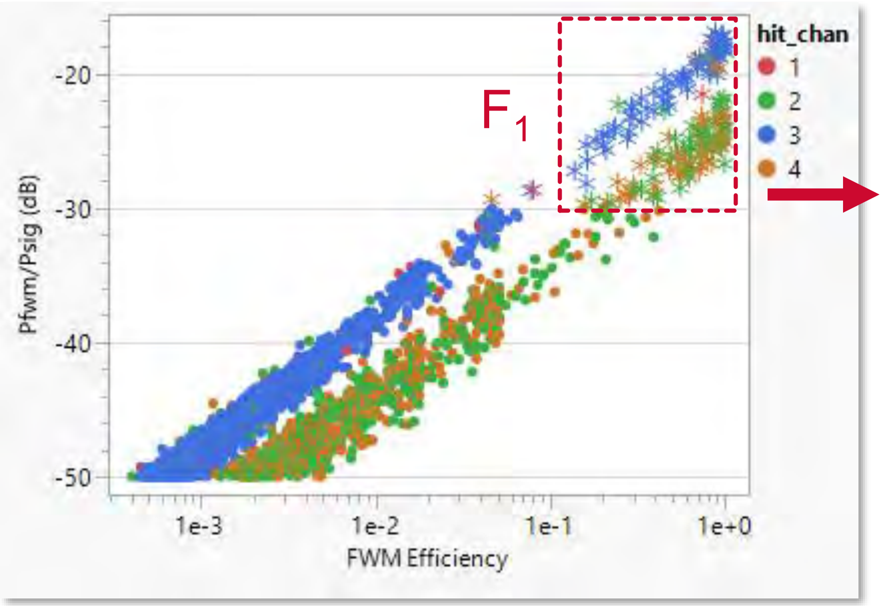
→

Static probability of links having high FWM efficiency (phase match) and launch power

Transmission Simulation (XYYX Launch with PMD)

→

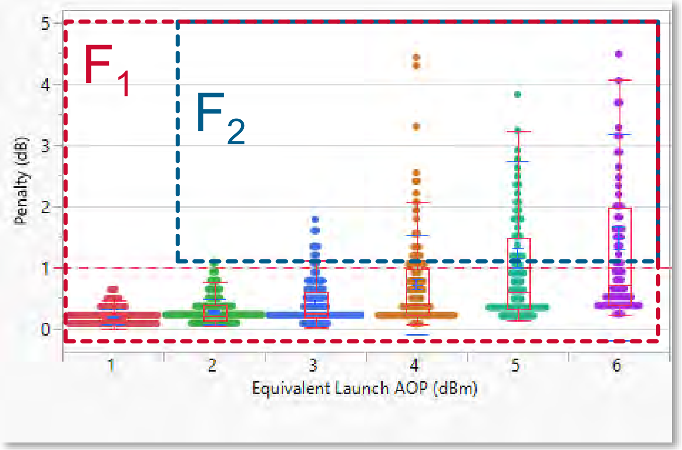
Fraction of time that a link with given launch power has more than X dB FWM penalty



→

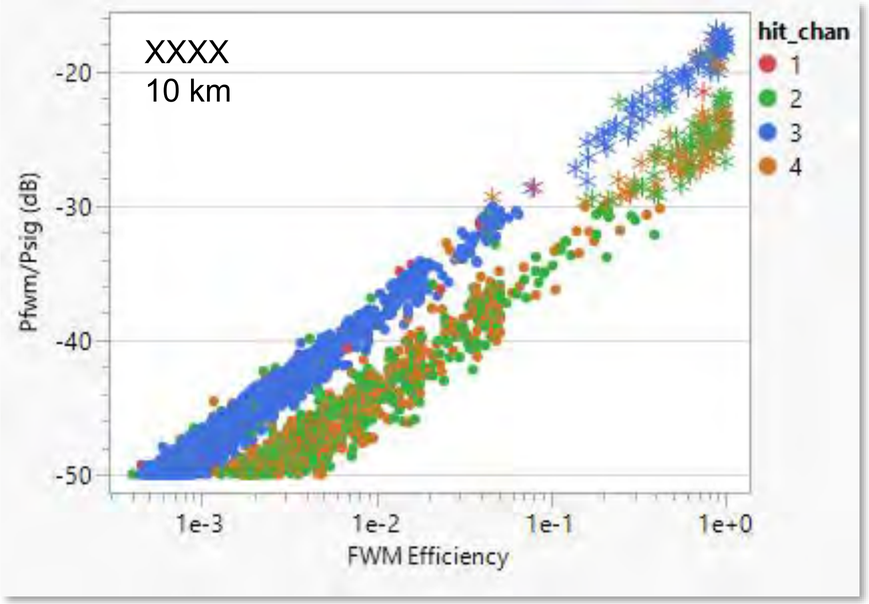
F_1 of channels have FWM efficiency and launch power high enough to cause an outage

→



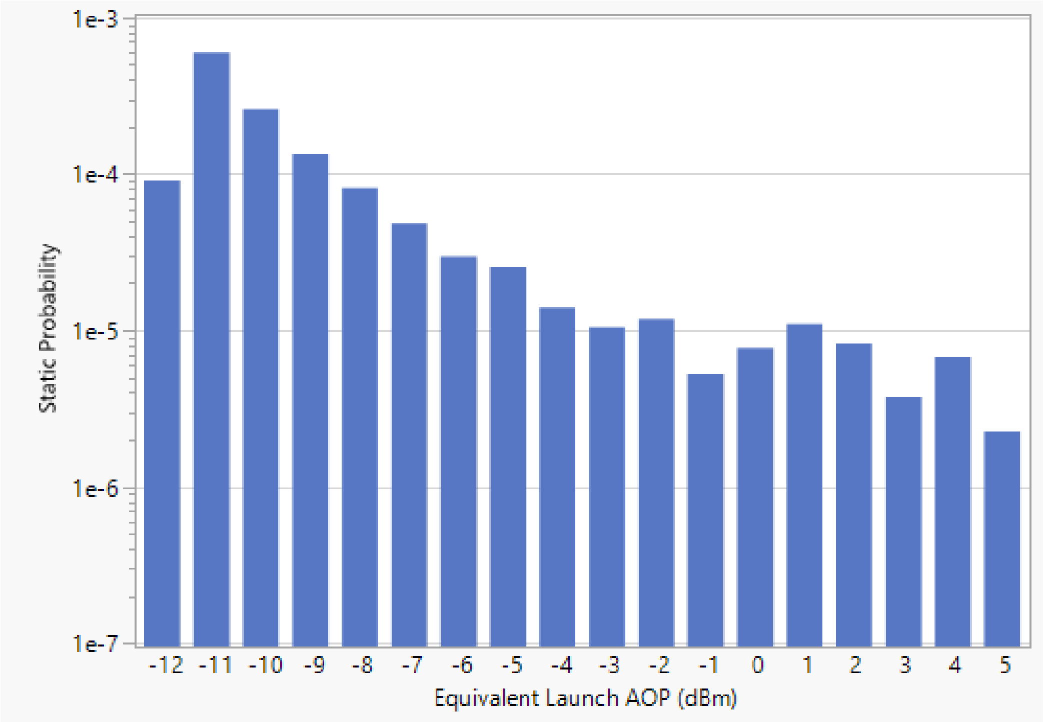
The fraction F_1 of links that have high FWM efficiency and power will experience high FWM penalties fraction F_2 of the time when using XYYX interleaving and fiber with PMD

800GBASE-LR4 Example: Static Monte Carlo



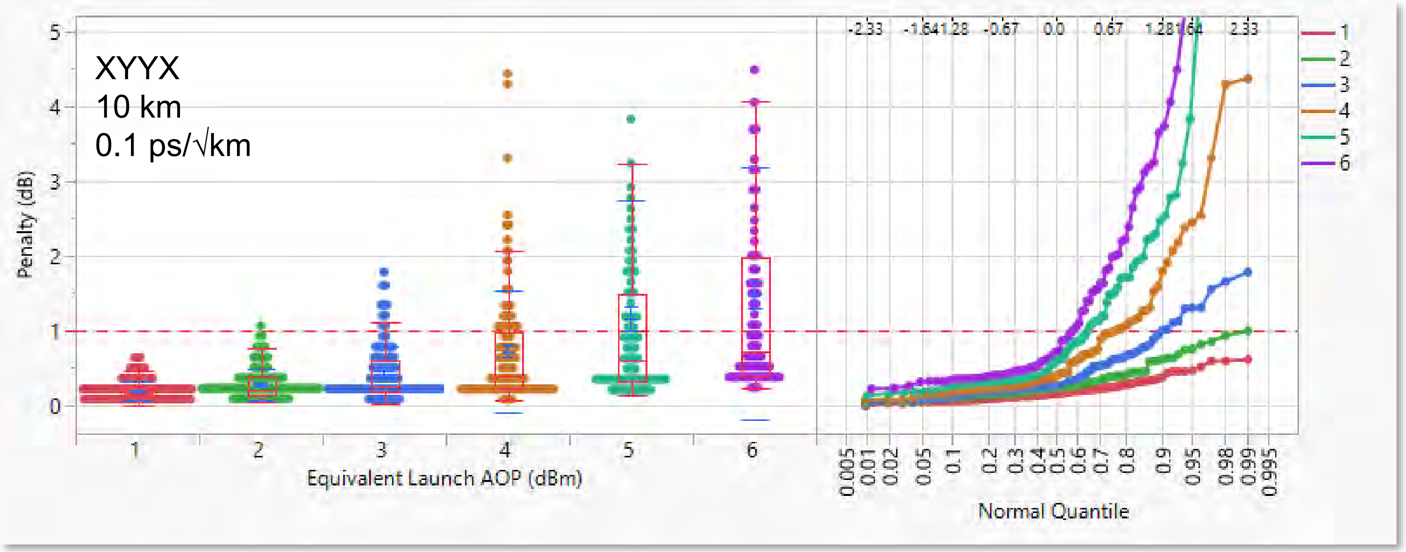
Using the equation $P_{ijk}/P_s = \left(\frac{D_{ijk}}{3}\gamma L e\right)^2 \frac{P_i P_j P_k}{P_s} e^{-\alpha L}\eta$, simplify the multi-variable Monte Carlo distribution to an equivalent single variable distribution with **Equivalent Launch Power, P_{eq}** $= P_i = P_j = P_k = P_s,\ \eta = 1$ and $D_{ijk} = 6$ (non-degenerate):

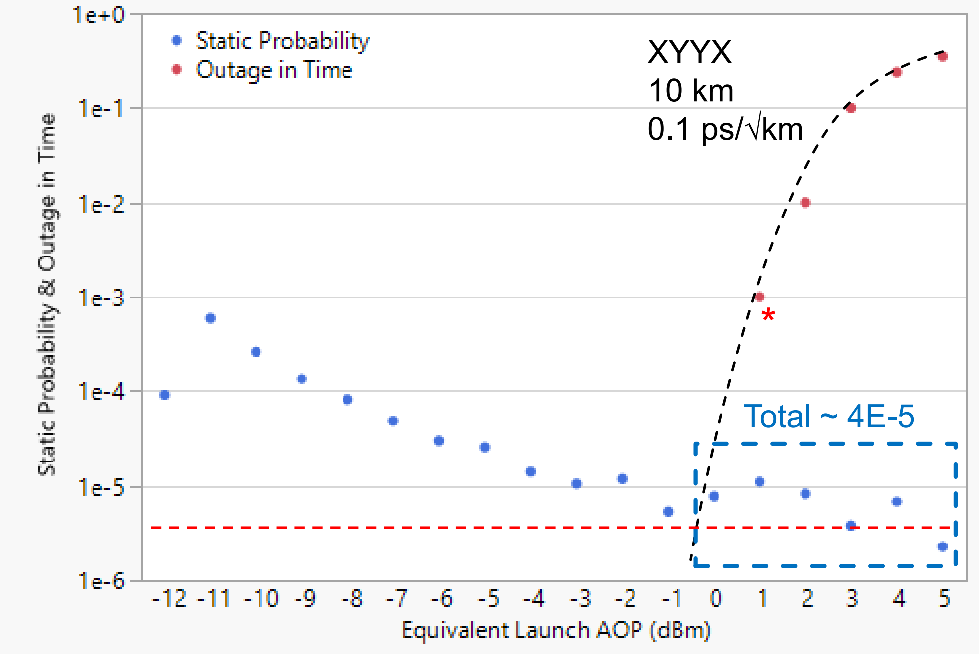
$P_{ijk}/P_s = (2\gamma L e)^2 e^{-\alpha L} P_{eq}{}^2$, where $P_{eq} = \frac{D_{ijk}}{6}\sqrt{\frac{P_i P_j P_k}{P_s}\eta}$



- 800GBASE-LR4 baseline proposal [3], 10km fiber
- Assumed distributions for this example:
  - ZDW: Normal(1313, 2.5nm), truncated [1300, 1324nm], 1306nm = -2.8σ
  - Laser Frequency: Normal(0, 100GHz), truncated [-200, 200 GHz]
  - OMA: Normal(4.4, 0.7 dBm), truncated [2.0, 5.0 dBm]
- 1,000,000 LR4 Monte Carlo iterations
- Save only 5389 of 4,000,000 channels with P_{FWM}/P_{Sig} > -50dB
- 181 channels have P_{FWM}/P_{Sig} > -30 dB, equiv. to > ~ 1dB penalty

800GBASE-LR4 Example: Time-dependent effect of PMD





* extrapolated

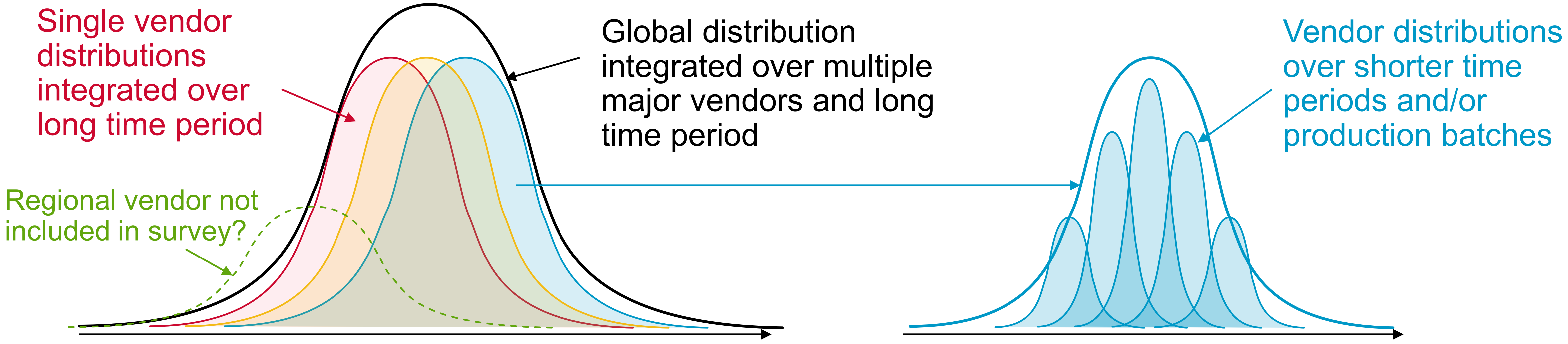
- 800GBASE-LR4 baseline wavelength plan [3]
- Same transmission simulation setup as [2], scaled to 112.5 GBd
- PMD = 0.1 ps/√km (major vendors max spec limit [6])
- Same conditions as in the definition of P_{eq}:
  - o Equal launch power, XYYX polarization interleaving
  - o ZDF = ½ (f_1+f_2), giving FWM efficiency = 1 at channel 0
- Define FWM outage as penalty > 1 dB
- Each distribution is interpreted as the fraction of time that PMD will cause a given FWM penalty on a link with the stated equivalent launch power

- Channels with outages in time > ~4E-6 (~2min/year) have insufficient stability to be usable in service
- The total fraction of unusable channels with outage in time > 4E-6 in this example is 4E-5.
- This is the probability that should be considered when assessing the robustness of 800GBASE-LR4 proposals against FWM, not the product of static and time-varying outages

Use of fiber survey data to achieve low static probabilities

- At 200G/lane, worst case values in published fiber standards make it difficult to define an LR4 PMD meeting all corner cases for transmission performance
  - The use of fiber survey distributions can be used to define LR4 PMDs that have static FWM outage probabilities low enough to be commercially viable [3]
  - Several contributions have presented vendor distributions of fiber ZDW [5,8] and PMD [6] that are tighter than published fiber standards, as well as distributions of cable segmentation in DCI/Metro links [7] that are shorter than the 10km objective
- Statistical data is beneficial, but some care should be taken when applying it:
  - Distributions are a snapshot of a process over a specific period of time. Distributions at other times past or future aren't guaranteed to be the same.
  - Extrapolation of distributions beyond the histograms could be inaccurate. Small changes in the tail of the ZDW distribution result in order of magnitude changes in the FWM outage probability.
  - Vendor selection and installation practices will vary depending on geography. Rural areas may have fewer, longer cable segments than in urban areas.
  - The ZDW range of segments within a single link may be more highly correlated than a vendor's full ZDW distribution since they were likely manufactured around the same time

Interpreting fiber parameter distributions



- A global parameter distribution is made up of individual distributions from major vendors, as described in [5]
- The distributions are assumed to represent the vendors' full process capability integrated over a significant time period
- Small or regional vendors not included in the survey might lie outside the global distribution
- Global distributions are most applicable for calculating industry-wide FWM outage probabilities

- Each vendor's distribution is further made up of individual distributions from multiple batches from multiple manufacturing facilities
- The distribution from a single "batch" could be significantly narrower than the total vendor distribution
- Batch distributions are more applicable to describe properties like ZDF uniformity of a specific network constructed of fiber cables procured from one vendor in a short time period

Conclusions

- Given the ineffectiveness of polarization interleaving to suppress FWM over time on high PMD fiber, the focus must be on defining wavelength grid, power budget and fiber specs to ensure commercially viable LR4 links with low **static** outage probability. Possible solutions include:
  - Define the wavelength grid outside of the expected ZDW distribution [3]
  - Use a maximum sum of penalties rather than a sum of maximum penalties for the power budget to allow for higher maximum FWM impairment [3]
  - Use higher sensitivity receivers (APD or SOA-PIN) to reduce TX launch OMA [9-10]
  - At high PMD, XYYX polarization interleaving makes it less likely to observe a bad channel at t=0 than with aligned polarization. It should be considered whether polarization interleaving is more of a help or a hindrance for network operations.
- The use of statistical fiber survey data will be essential to defining a 800G-LR4 PMD with acceptably low static outage probability:
  - Manufacturers' ZDW distributions narrower than 1300-1324nm
  - 10km links made of shorter fiber cable segments with different ZDW. More data is necessary to determine an appropriate intra-link ZDW range.
  - Non-uniform ZDW on a single fiber cable segment, if manufacturers' data becomes available.
  - Manufacturers' PMD distributions narrower than published specs, if polarization interleaving is used

References

1) johnson_3ca_1_0716, “Four-wave mixing in O-band for 100G EPON”
2) johnson_3df_optx_01_220414, “FWM Analysis of PAM4 LR/ER PMDs”
3) rodes_3df_01a_2211, “Towards an 800G-LR4 IMDD Specification Consensus - Nov. 2022 update”
4) liu_3df_01b_2207, “Effective suppression of inter-channel FWM for 800G-LR4 and 1.6T-LR8 based on 200Gb/s PAM4 channels”
5) cole_3df_01a_2211, “Update to Modern SMF Parameters for Calculating PMD (Physical Medium Dependent) Penalties”
6) kuschnerov_3df_01a_221012, “800G LR4 DGD penalty and fiber specifications”
7) kuschnerov_3df_01_2211, “Further discussion of DGD penalty and specification for 800G LR4”
8) rodes_3df_01a_220329, “On Technical Feasibility of 800G-LR4 with Direct-Detection”
9) yu_3df_01a_2203239, “Proposed 800G LR4 Baseline with PAM4 IMDD”
10) lin_3df_01_220609, “On the technical feasibility of 800G LR4”
11) kuschnerov_3df_02a_221012, “Update on component and channel characterization for optical 200G PAM4”

Thank you!