Clarifying Issues Related to Spreadsheet Model using Full Link Simulation for 25G on MMF

Kasyapa Balemarthy
Robert Lingle Jr.

September 26-28, 2012

IEEE 802.3bm Task Force

Spreadsheet

ofs
A Furukawa Company

- **Spreadsheet has served us/802.3 very-well for a very long time**
  - Simple, closed-form expressions for all impairments
    - Adopts Gaussian models for link filters/fiber
    - All noise sources modeled as independent AWGN
  - Quick computation via Excel → no need for detailed link model
  - Easily compare contributions of different impairments
- **Reach of 25G systems limited by Mode Partition Noise**
- **However, some confusion about treatment of Mode Partition Noise in the spreadsheet exists**
  - Model deficiencies?
    - Is required ISI-scaling already included? (see lingle_01_0712_optx)
    - Is the spreadsheet using the worst-case bit pattern?
  - Parameter uncertainties:
    - Is mode partition noise parameter $k_{MPN} = 0.3$ reasonable?
    - parameterization of RMS spectral width

Full link model

- **VCSEL modes computed from generalized Laguerre polynomials**
  - Pepeljugoski *et al.*, IEEE JLT vol. 21, no. 5, pp.1242-1255, 2003
  - Spectrum chosen from above reference, spectral width scaled appropriately
- **Transmitter employs PRBS sequences and NRZ pulse with given rise-time**
- **Multimode fiber**
  - Modes, their group delays and chromatic dispersion computed using mode solver
  - Differential modal attenuation included via measured loss data
  - Mode power distribution computed via overlap integrals for each VCSEL mode
  - Interaction between VCSEL-fiber modes properly accounted for
- **Receive filter: Fourth-order Bessel-Thomson filter**

- **Received waveform for each VCSEL mode i computed:**

$$r_i(t) = \sum_j MPD_{ij} \left| E_{ij}(t) \right|^2$$

Bit error rate in the presence of MPN

- **Ogawa-Agrawal (OA) model employed to compute the mean and std. dev. of received waveform:**

$$\mu_r(t) = \sum_i \mu_i r_i(t) \qquad \sigma_r(t) = k_{MPN}\left[\sum_i \mu_i r_i^2(t) - \mu_r^2(t)\right]^{0.5}$$

  - μ_i: mean mode powers (from VCSEL spectrum)
  - $r_i(t)$: Received waveform for VCSEL mode i (normalized w.r.t. OMA)
  - k_{MPN}: mode partition noise parameter

- **Bit error rate estimated from:** $BER = \frac{1}{2} \cdot \mathrm{erfc}\left(\sqrt{\frac{S^2\mu_r^2}{\sigma_n^2 + S^2\sigma_r^2}}\right)$
  - S: OMA, σ_n: thermal noise variance
  - OA-model does not discuss BERs but it can be re-cast as above
  - Independent of the OA-model, we have shown that above expression is correct for low-to-moderate MPN:
    - Balemarthy & Lingle, ECOC 2012, Th.2.B.4
- **Sampling BER at optimum instant and averaging over bit patterns yields the average BER (in the presence of MPN)**

“Full” OA model and its simplification

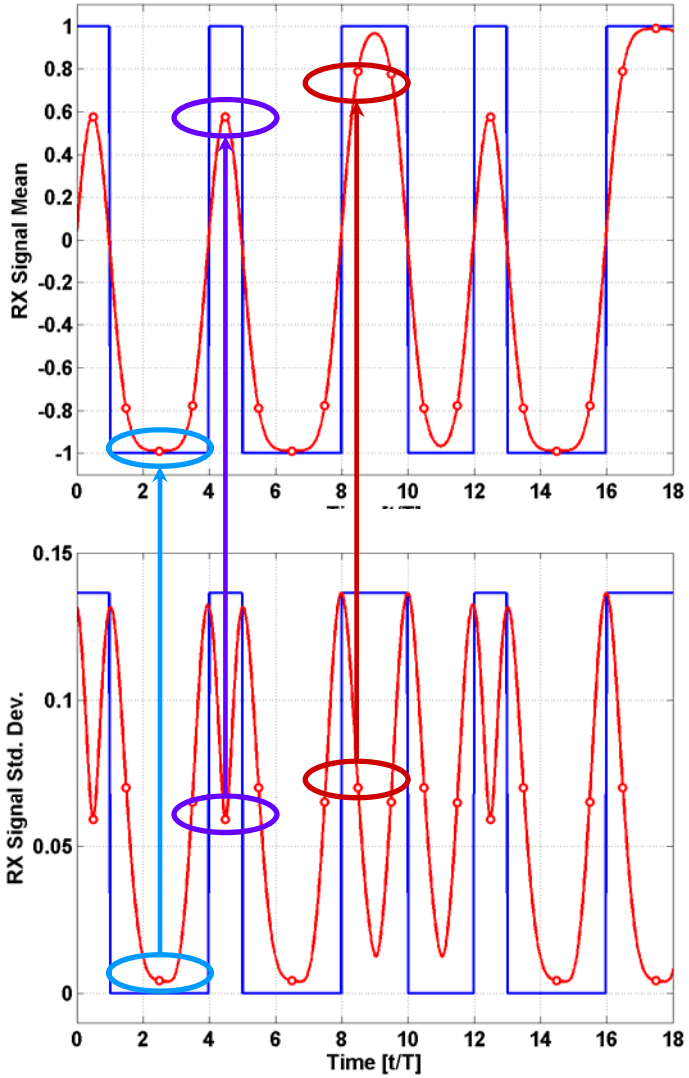
A Furukawa Company

- **“Full” OA-model uses any arbitrary spectrum to begin with**
- **OA model make two further assumptions:**
  - Assumes a Gaussian spectrum with infinite number of modes
  - Assumes inner-most eye can be approximated by a cosine
- **These assumptions result in closed-form expressions for the mean and std. dev. of the received sample → used by the IEEE spreadsheet**
  - For the inner-most eye and
  - At the optimum sampling instant
- **We only use the “Full” OA model in the link simulation, not the simplified one used by the spreadsheet**

Bit patterns

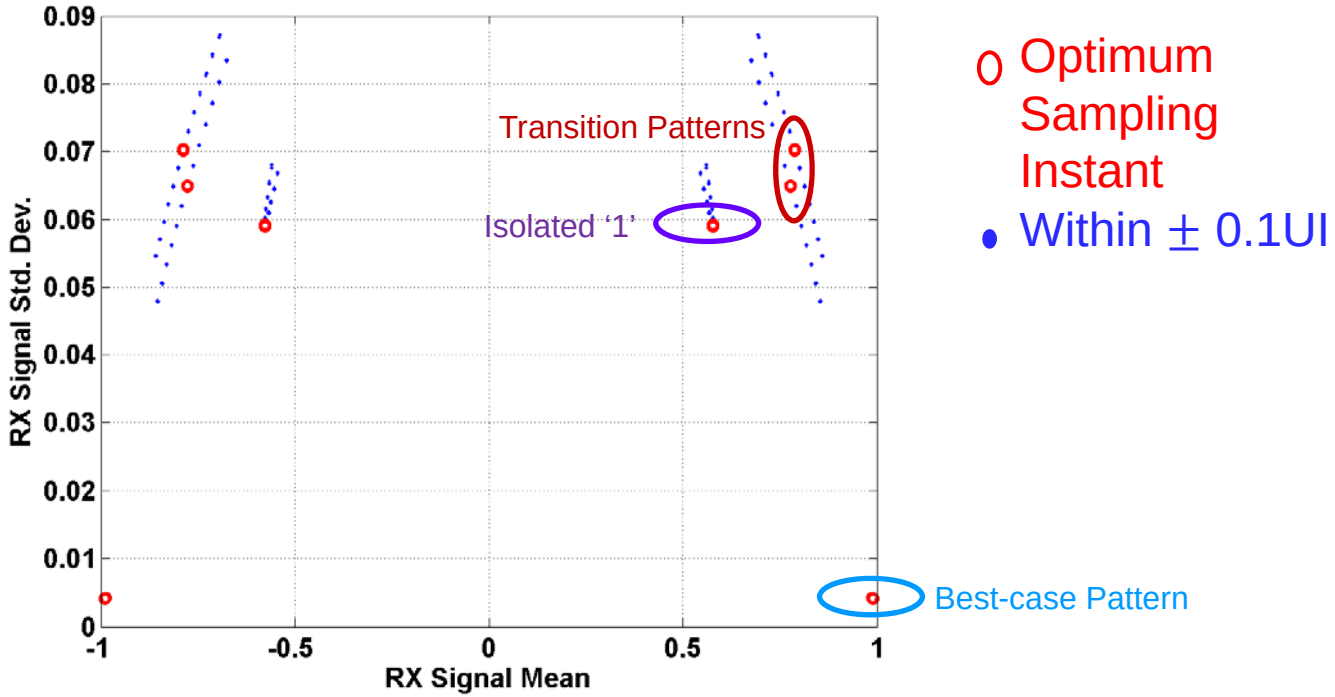
- **Inner-most eye results in the worst-case bit pattern for links without MPN**
  - Corresponds to the isolated ‘1’ pattern: “000010000”
  - Used by the OA-model and current spreadsheet even for MPN penalty computation
- **Is this the worst case eye pattern for MPN? For total penalty?**
- **How much would averaging over BER improve results?**
- **Investigate question by using the full link model**

Mean and standard deviation of Rx Waveform with MPN



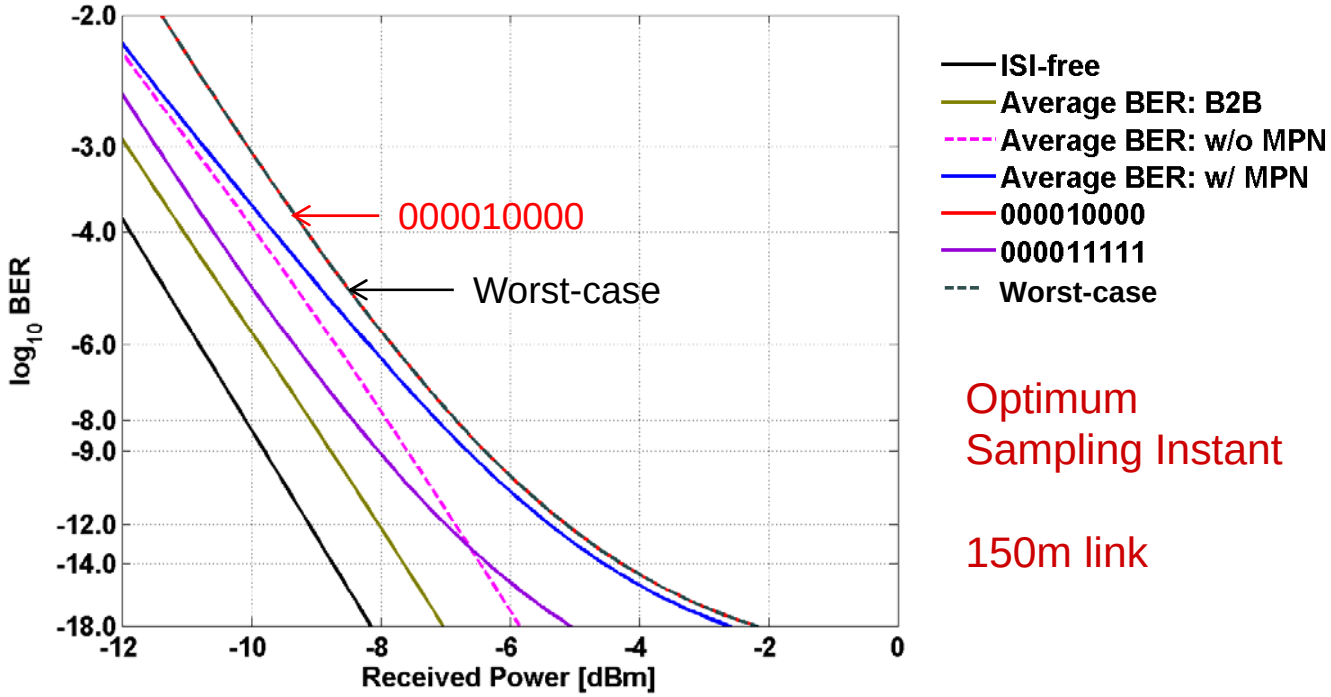
- **150m link, $k_{MPN} = 0.3$, $\sigma_\lambda = 0.6$nm**
- **Best case pattern (very little ISI) has extremely low MPN std. dev.**
  - **Blue** ovals
- **Isolated ‘1’ has moderate MPN std. dev.**
  - **Violet** ovals
- **Transition patterns have lower ISI than Isolated ‘1’, but seem to have higher MPN than Isolated ‘1’**
  - **Maroon** ovals

Correlation between signal mean and its std. dev. due to MPN



- **At the optimum sampling instant, the isolated '1' pattern indeed has lower MPN than the transition patterns**
- **Over a ±0.1UI interval, the transition patterns have modestly lower and higher MPN, and sometimes lower MPN than the isolated '1' pattern**

Bit error rate curves for different bit patterns

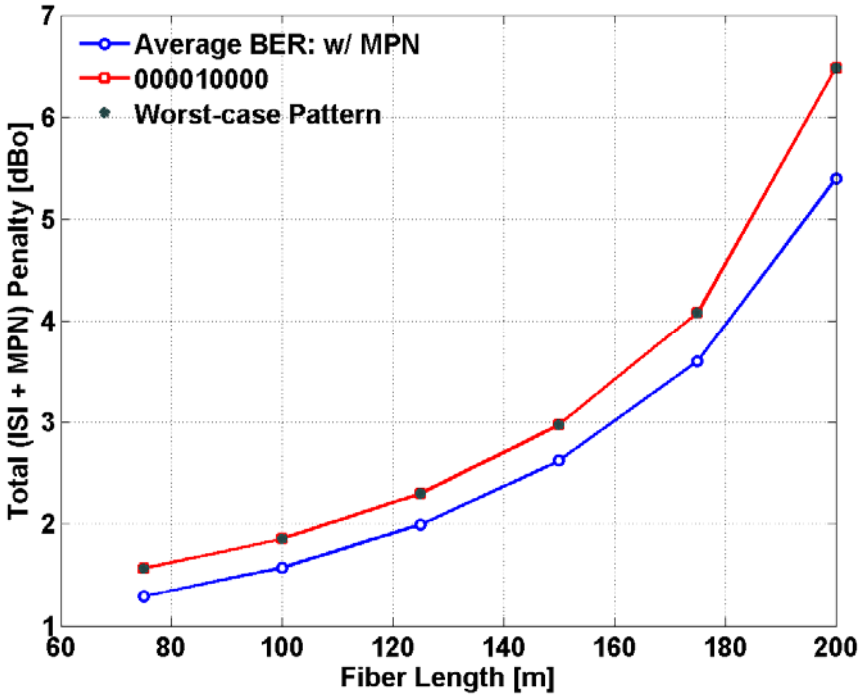


Optimum Sampling Instant

150m link

- **Pattern that has the worst-case BER is selected numerically**
  - black dashed curve
- **Isolated ‘1’ pattern is the worst-case pattern**
  - Black dashed curve overlaps the red solid curve
- **Transition pattern has lower BER than the isolated ‘1’ pattern**
  - and even lower than the average BER

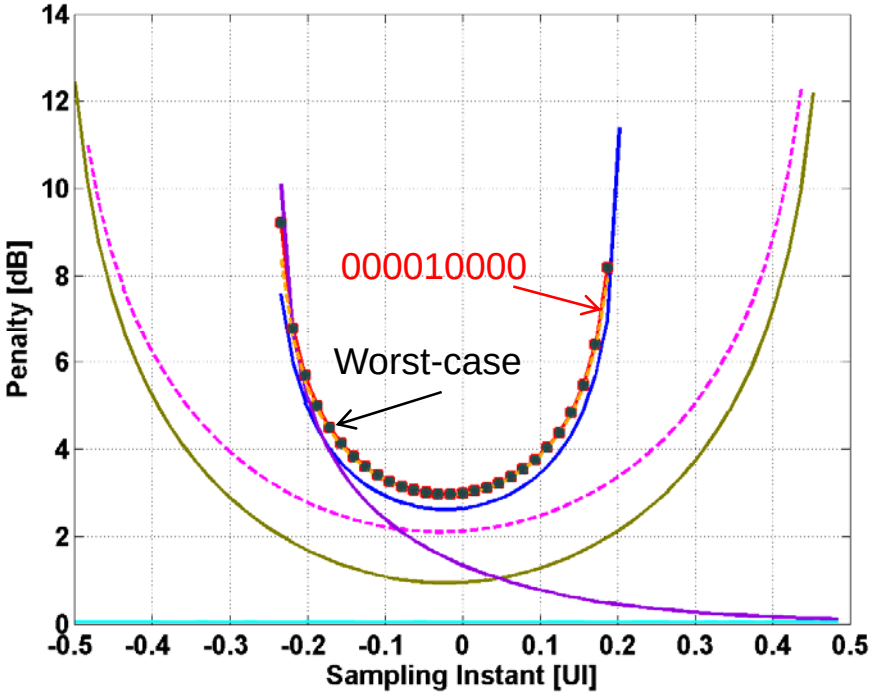
Total (ISI + MPN) penalty for different fiber lengths



- Optimum sampling instant
- Penalty computed from BER curves at a desired BER of 10^{-6} w.r.t. ISI-free link
  - Mimics FEC
- Penalty is the total ISI + MPN penalty

- **Even for different fiber lengths, the isolated '1' is the worst-case pattern**

Impact of sampling instant on the worst-case pattern at 150m

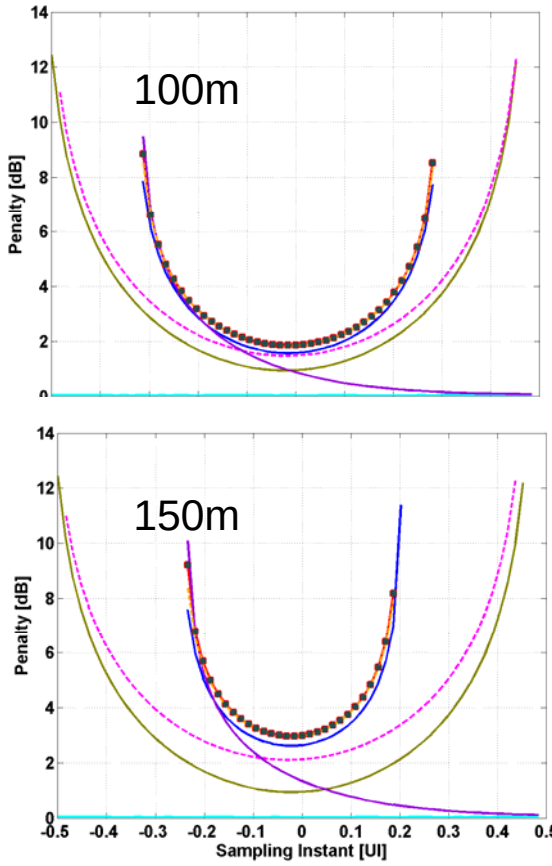


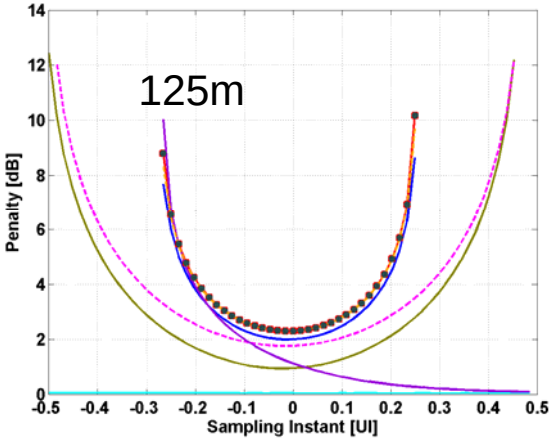
- Average BER: B2B
- Average BER: w/o MPN
- Average BER: w/ MPN
- 111111111
- 000010000
- 000011111
- 101010101
- Worst-case

- Penalty computed from BER curves at a desired BER of 10^{-6} w.r.t. ISI-free link
  - Mimics FEC
- Penalty is the total ISI + MPN penalty

- **BERs and Penalties can be computed as a function of the sampling instant for each bit pattern**
- **Isolated ‘1’ is the worst-case bit pattern for all sampling instants**

Impact of fiber length on the worst-case pattern for various sampling instants





Average BER: B2B
Average BER: w/o MPN
Average BER: w/ MPN
111111111
000010000
000011111
101010101
Worst-case

- Penalty computed from BER curves at a desired BER of 10^{-6} w.r.t. ISI-free link
  - Mimics FEC
- Penalty is the total ISI + MPN penalty

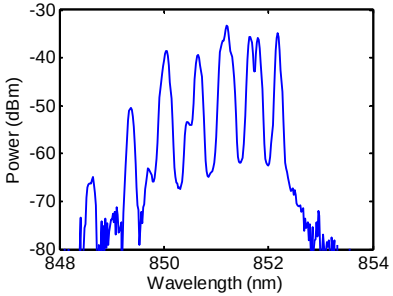
- **For all different lengths, for all sampling instants, the isolated ‘1’ is the worst-case pattern**

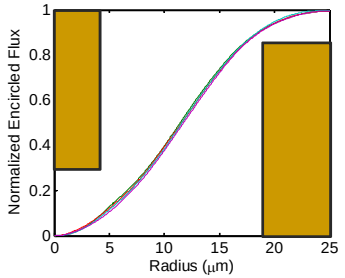
Observations I

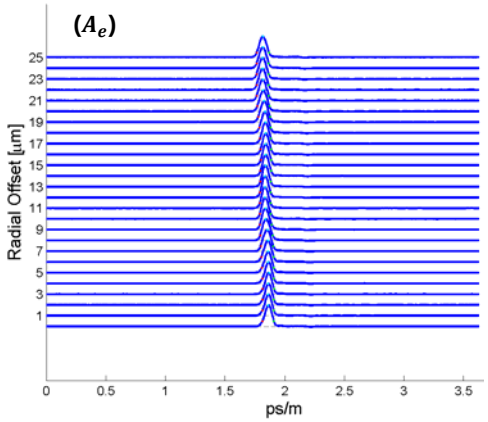
- **Isolated ‘1’ has the higher ISI than transition patterns but its MPN may be lower**
  - sensitive to sampling instant tolerances
- **But the isolated ‘1’ has the worst-case penalty, independent of sampling instants and fiber lengths**
- **Spreadsheet, as it stands, is doing the right thing with the worst-case pattern choice**

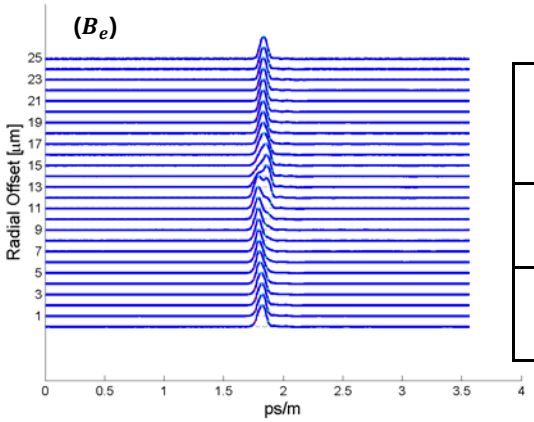
System measurements at 25Gbps

- **Previously reported in lingle_01_0112_NG100GOPTX, January 2012**
  - Experiments courtesy: Yi Sun, X. Jiang of OFS and C.P. Caputo, S. E. Ralph of Georgia Tech
- **25Gbps VCSEL from Emcore**
  - 0.62nm RMS spectral width
- **OM4 Fiber**



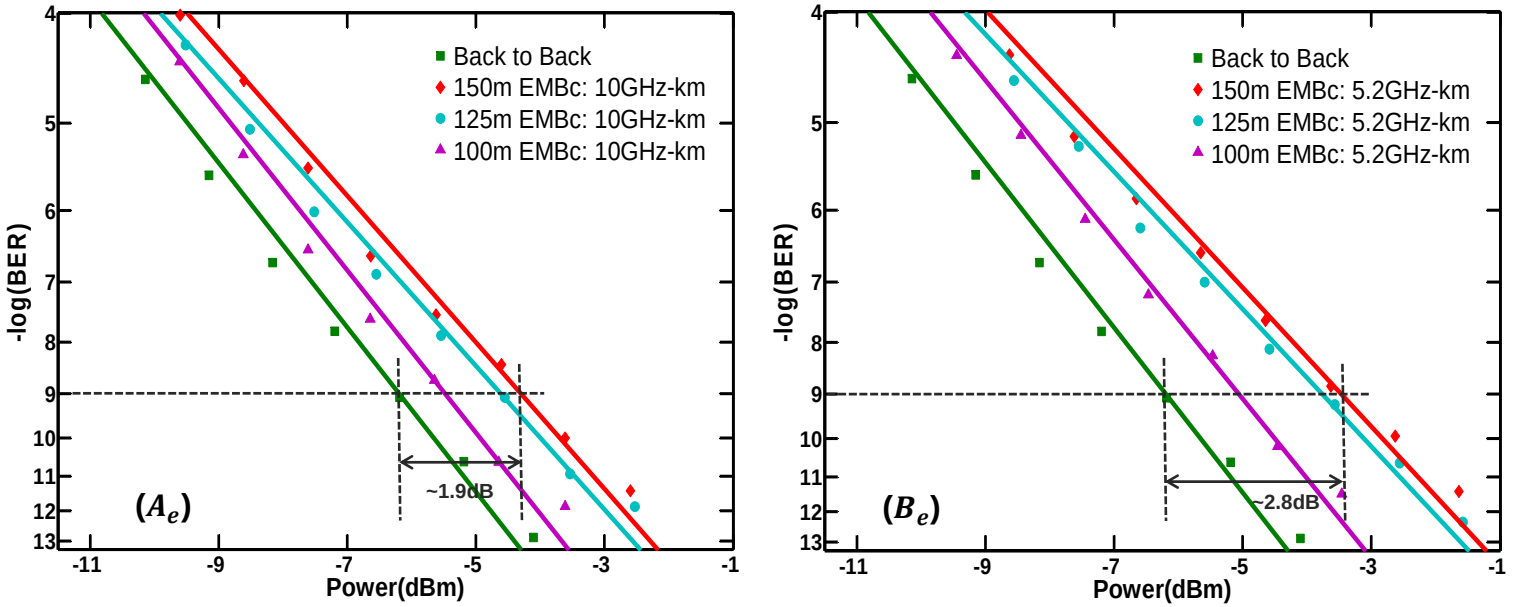






Fiber	EMBc	DMD $(0-18\mu m)$	DMD $(0-23\mu m)$
A_e	10 GHz-km	0.066	0.069
B_e	5.2 GHz-km	0.102	0.102

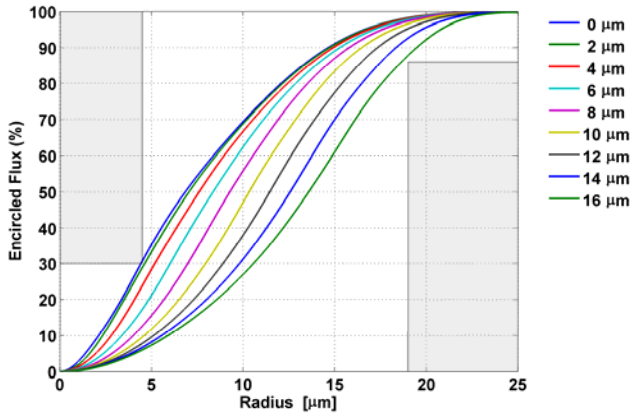
Experimental BER curves

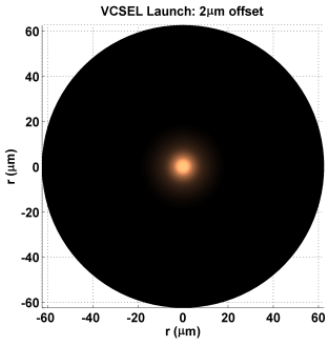


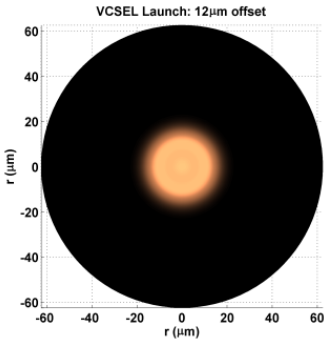
- **Previously reported in lingle_01_0112_NG100GOPTX, January 2012**
- **BER curves can be approximated by straight lines**
- **Mode partition noise may not be significant for this VCSEL for a 150m link at room temperature.**

Numerical modeling

- **Approximate the VCSEL spectrum from the experiment via EF-match**







- **OM4 fibers simulated using mode solver**

Fiber	EMBc	DMD $(0-18\mu m)$	DMD $(0-23\mu m)$
A_n	9.2 GHz-km	0.0347	0.0927
B_n	5.9 GHz-km	0.0451	0.1385

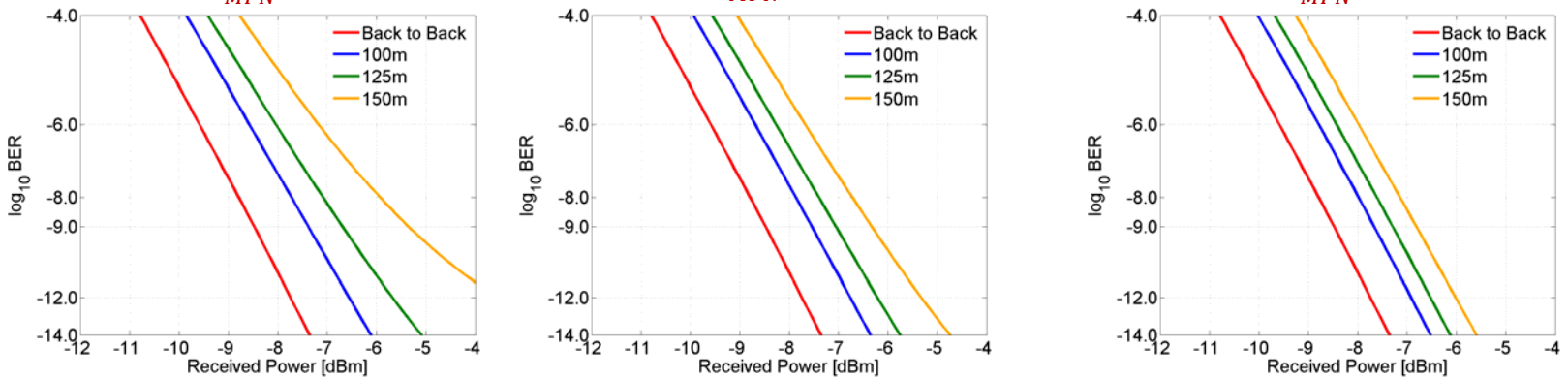
- **PRBS sequences are processed**
- **Mode partition noise modeled using full Ogawa-Agrawal model**
- **BER averaged over both ISI patterns and MPN**

Simulated BER curves

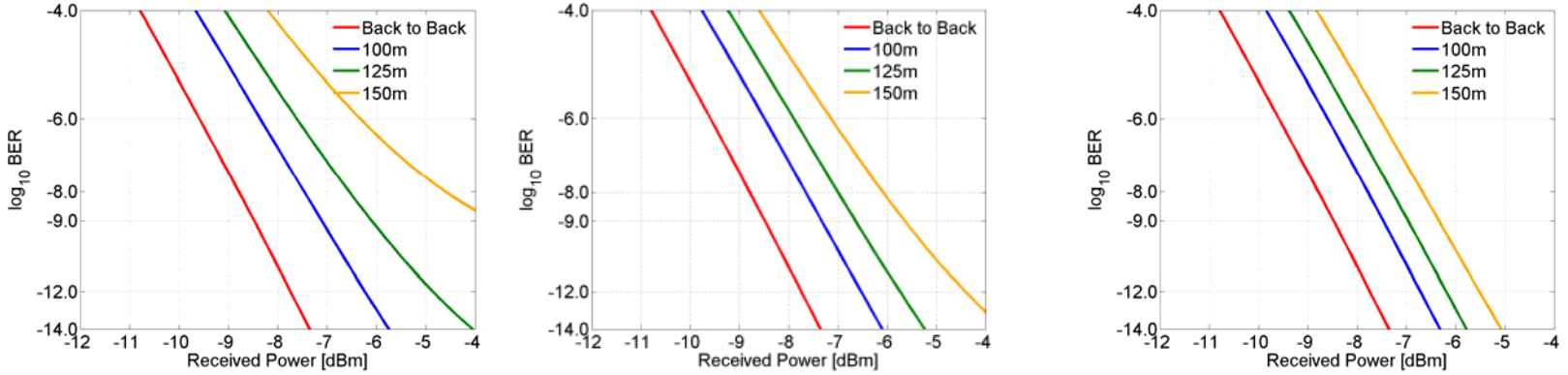
ofs
A Furukawa Company

$k_{MPN} = 0.3$ $k_{MPN} = 0.2$ $k_{MPN} = 0.1$

(A_n)

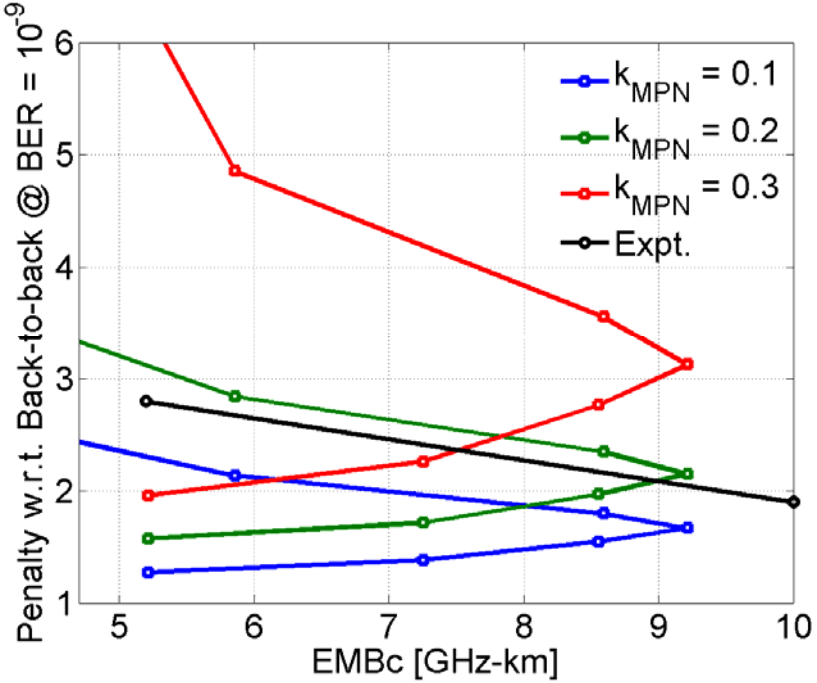


(B_n)



- **Each column corresponds to a different k_{MPN}, each row to a different fiber; impact of ISI and MPN is calculated**
- **BER curves are not straight lines for $k_{MPN} = 0.3, 0.2$ (particularly for the 150m link) but are straight lines for $k_{MPN} = 0.1$**
- **Suggests k_{MPN} may be in the 0.1-0.2 range**

Comparison between experimental and simulated results



- **150m link**
- **Simulate fibers with various modal bandwidths; repeat with $k_{MPN} = 0.1, 0.2, 0.3$**
- **Experimental results lie between the simulated results for $k_{MPN} = 0.1$ and those for $k_{MPN} = 0.2$ → mode partition parameter is in the 0.1-0.2 range**

Observations II

- **Experimental results show no apparent evidence of mode partition noise**
  - Straight-line BER curves
- **Established that MPN is present but is weaker than typically assumed**
  - Mode partition parameter k_{MPN} likely to be in the 0.1-0.2 range instead of 0.3 (as used by the spreadsheet)
  - Is this because VCSEL is not in its worst-case of mode-partitioning at room temperature?
- **Further studies of link performance versus VCSEL temperature dependence are in progress**
  - 10G studies using commercial transceivers
  - 25G studies using VCSEL dies

Conclusions

ofs
A Furukawa Company

- **Full-link modeling employed**
- **Showed that worst-case pattern is the isolated ‘1’ pattern, independent of sampling instant and fiber length**
- **Comparison between experimental and simulated data can be used to bound the mode partition noise parameter k_{MPN}.**
  - k_{MPN} may be in the 0.1-0.2 range instead of 0.3 for this VCSEL at room temperature
  - Need further study of temperature effects and additional devices