# Laser Optimized Fiber for 10+ Gb/s Applications

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IEEE 802.3cz Task Force interim 05/25/2021

## Supporters

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# Goal of presentation

1. Provide overview of the complementary Encircled Flux (laser) and "minEMBc" (fiber) specs and how they enable high data rate standards.
2. Provide, with hindsight, background on where the standards came from in TIA/IEEE work, which can be used as a reference.

## Outline

1. Summary
2. Background of Laser-Optimized Fiber (TUTORIAL)
   CHALLENGE: every fiber works with every laser every time.
   RESULT: Dual/Complementary Specifications for Fiber and VCSELS
3. Details of the Encircled Flux (EF) methodology for VCSELS
4. Details of the HR DMD and EMBc methodology for OM3 & OM4 fiber.
   INCLUDES details of the TIA/IEEE work for original 10Gb/s specs (TUTORIAL)
5. Challenges with OM2 and non-laser-optimized fiber
   802.3aq was 10GbE over legacy OM2 at 1300nm
   NEXT STEPS FOR OM2 and OM3 (SiP at 1300nm)
   NEXT STEPS FOR POF
6. Conclusion
7. References
8. Backup

# 1. Summary

The OM3 fiber proposed for 802.3cz is a “laser-optimized fiber” which has a fiber bandwidth measurement specifically paired with a complementary measurement of the transceiver.

**The transceiver** specification specifies the range of transceivers over which the fiber must be guaranteed. It in effect specifies the range of mode power distribution (MPD) which is allowed.

**The fiber** specification uses the high-resolution DMD measurement (HR-DMD) to simulate 10 ‘lasers’ which span the range of the transceiver specification. The minEMBc spec used for OM3 & OM4 takes the minimum of 10 bandwidths from 10 simulated lasers to construct the EMB. It in effect specifies the range of the mode group delays.

The laser/fiber coordination ensures that every fiber works with every laser, and vice versa.

# 2a. Background: OFL DID NOT PREDICT 1Gb/s PERFORMANCE

This presentation has some tutorial information the 10+Gb/s transceiver specs and the 10+Gb/s fiber specs. **Some of this will be familiar to subject matter experts** but it will help the project get on common ground.

During the development of the 1GbE standard [1] (802.3z) it was found that the OFL bandwidth was not a guarantee of the performance with a 1Gb/s VCSEL. Use was made of a 'Restricted Mode Launch" (RML) bandwidth from a fiber stub drawn down to 23.5μm core diameter [2] or a coupled power ratio [3]. This was a 'retrofit' to try to make the older 62.5μm OM1 fiber work with 1Gb/s VCSELS.

[1] Cunningham and Lane, ***Gigabit Ethernet Networking***. Indianapolis: Macmillan Technical Publishing, 1999

## 2b. Background of Laser-Optimized Fiber for 10Gb/s links (2)

During the development of the 10GbE standard [4] it was decided to develop both a new specification for the 50μm fiber (which became OM3) as well as the 10Gb/s VCSELS, which were new at the time as well. These specifications will be summarized in this presentation.

VCSELS are specified by an “encircled flux spec” [5], [3].

Fibers were first specified with a ‘DMD mask’ [5], [3] but now a ‘minEMBc’ measurement using DMD data is the common technique [6] [7]. In addition, the minEMBc technique was adapted to include an OFL-equivalent “OFLc”.

# 2c. Fiber Bandwidth Depends on Fiber and Laser

$$P(t) = \sum_{g=1}^{G} P_g \delta(t - \Delta\tau_g)$$

$$H(f) = \sum_{g=1}^{G} P_g \cos(2\pi f \Delta\tau_g) - i \sum_{g=1}^{G} P_g \sin(2\pi f \Delta\tau_g)$$

$$|H(f)| = \sqrt{\left(\sum_{g=1}^{G} P_g \cos(2\pi f \Delta\tau_g)\right)^2 + \left(\sum_{g=1}^{G} P_g \sin(2\pi f \Delta\tau_g)\right)^2}$$

Impulse Response P(t) of fiber depends on the mode delays Δτ_g (fiber) and the mode power distribution P_g (laser) [6]

The Effective Modal Bandwidth is the frequency f_3dB where the amplitude of the Fourier Transform of P(t) drops to 0.5

MPD (laser)

$$P_g$$

Mode delays (fiber)

$$\Delta\tau_g$$

3dB effective modal bandwidth

$$|H(f_{3dB})| = 0.5$$

## 3a. VCSEL Specification: Encircled Flux

$P_g$

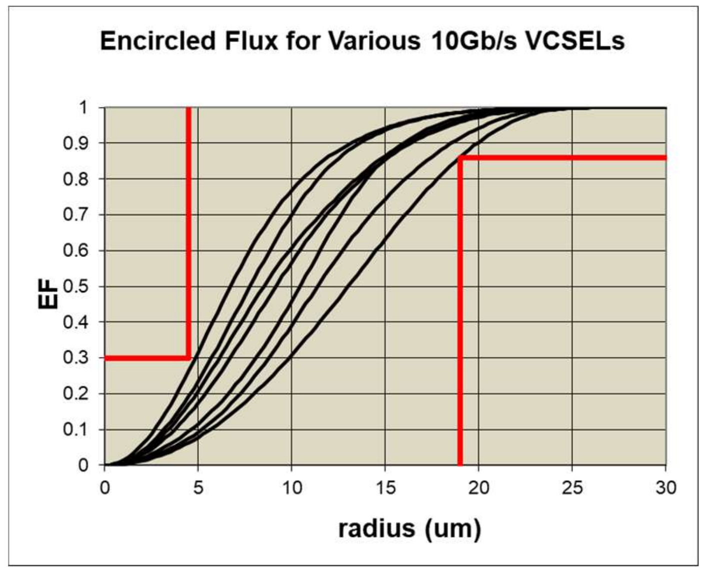
In the development of a dual specification for VCSELS and fibers, the VCSEL specification became an "encircled flux spec". The launch power from the transceiver into a fiber is measured as function of radius, and the normalized integrated power from r = 0 to r = R (with factor $2\pi$ r dr) is the encircled flux EF(R)

The specification is

a. EF < 0.3 at R = 4.5µm
b. EF at R=19µm EF>0.86

We can get a different bandwidth with each of these VCSELs.

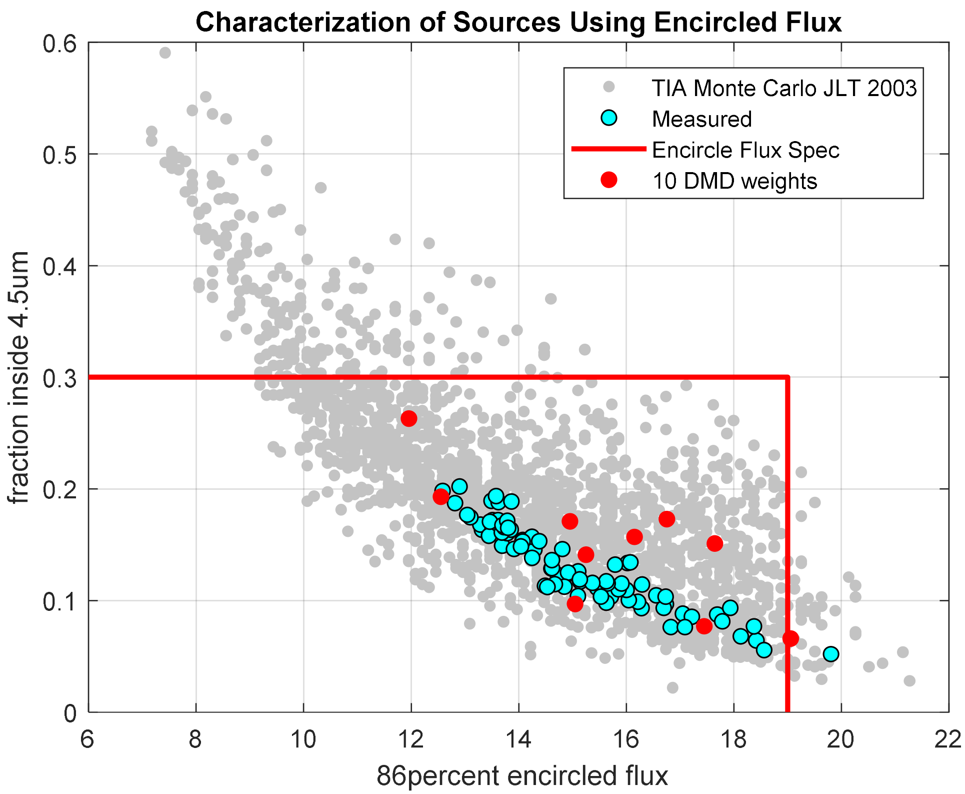
On the next slide we will display hundreds of VCSELS as an x-y plot of x= 86% radius vs. y=EF(4.5µm)




EF is normalized by the maximum value (may be 30µm or 35µm etc.)

# 3b. Ten "DMD weights" are used to specify the fiber

$P_g$ $\Delta\tau_g$




"Compliant" transmitters have EF inside the red box.

The red dots represent early 10Gb/s VCSELS used to create the EMBc fiber specification.

Grey dots are theoretical sources;
Aqua dots are measured lasers.

## To explain Fiber spec (minEMBc) we first review history $\Delta\tau_g$

Rather than just jumping to the minEMBc spec  we will devote some TUTORIAL slides explaining the origin.

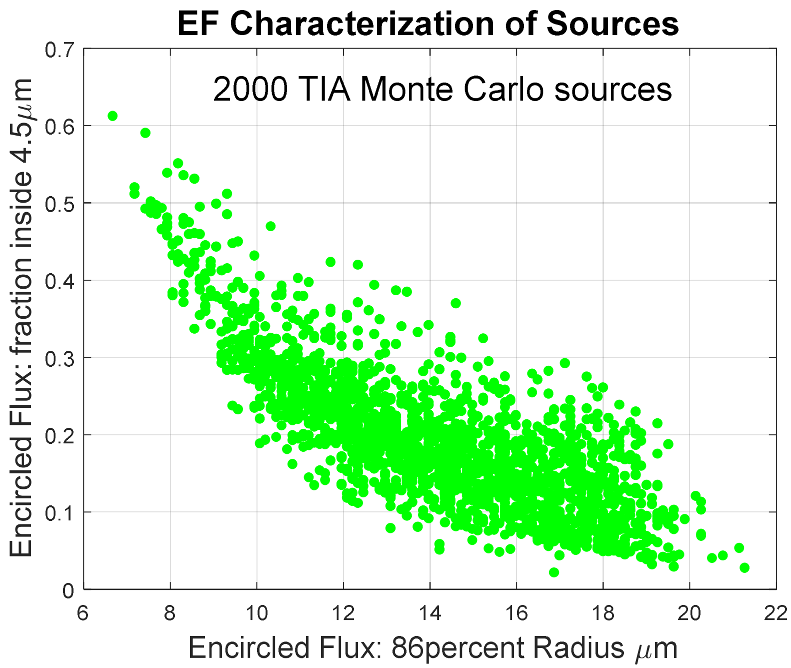
The point is the that fiber and laser specs are linked and had to be developed together

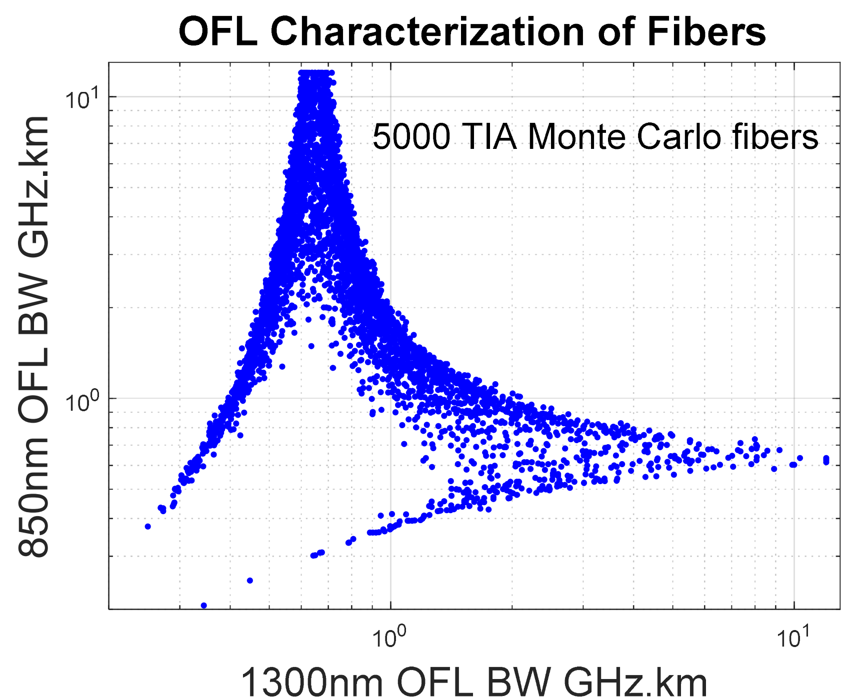
# 4a. EMBc Methodology is based on TIA Monte Carlo modeling

The 2000-2003 TIA/IEEE project to develop 10GbE developed both a spec for the laser (EF) and a spec for the fiber (eventually EMBc). May 2003 JLT p.1256 Pepeljugoski et al.[5]

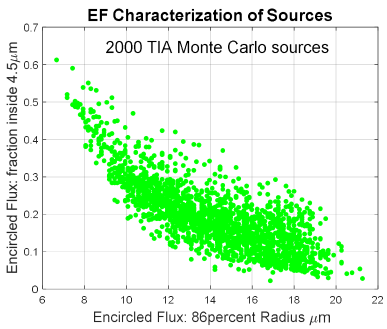
Modeling used 10,000 random laser-fiber pairs with various connections in the link (40,000 total).

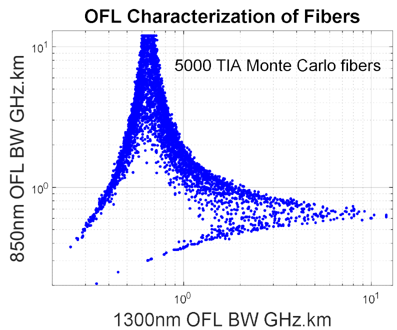
The EF characterization is used in transmitter spec, the OFL characterization is insufficient for a fiber spec. **NOT MANUF DISTRIB**.



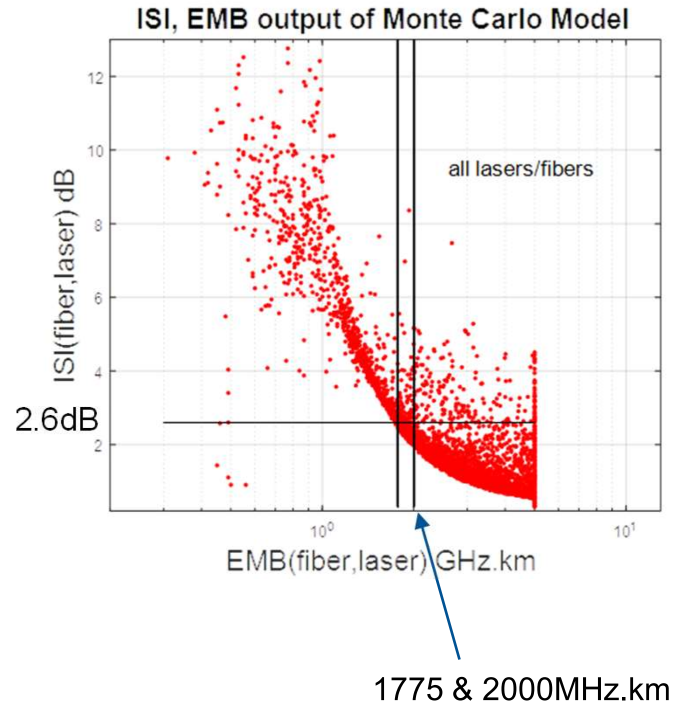
# 4b. TIA Monte Carlo modeling Input & Output




INPUT

RAW OUTPUT
10,000 points

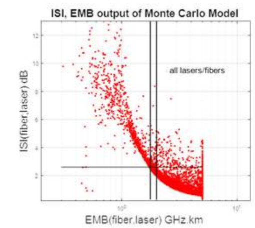



Input = (fiber, laser) pair, 300m link with transmitter/receiver assumptions.
Output = EMB (fiber, laser), ISI(fiber, laser),
Plus fiber characterization, laser characterization

A passing link has ISI < 2.60 dB (link budget allots 1.0dB to other sources).
Intersymbol interference <3.60dB common IEEE rule [1]

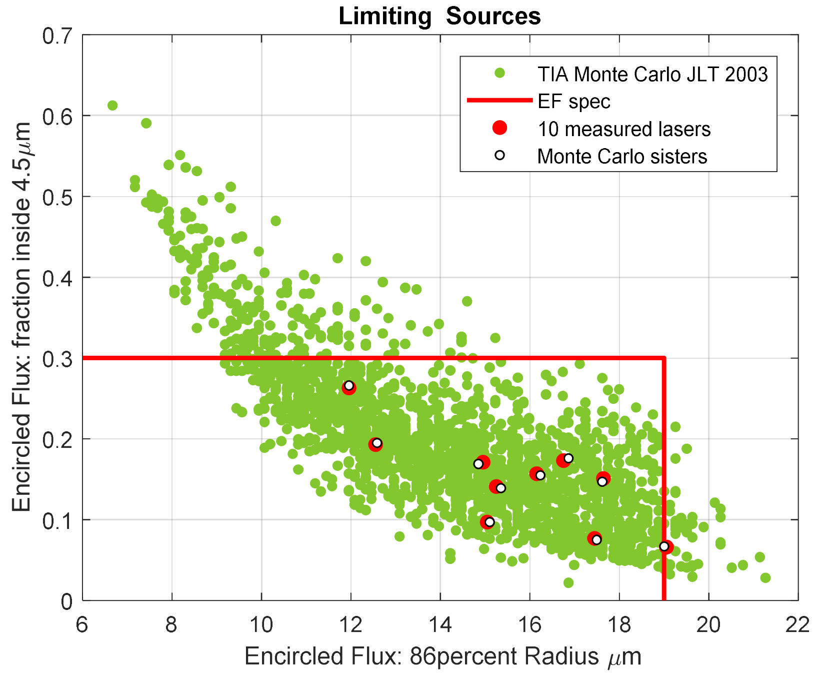
The laser spec and fiber spec need to eliminate points above 2.6dB
Objective -- 0.5% points above 2.6dB, 1% of points below 2000

May 2003 JLT has three papers related to the “project”



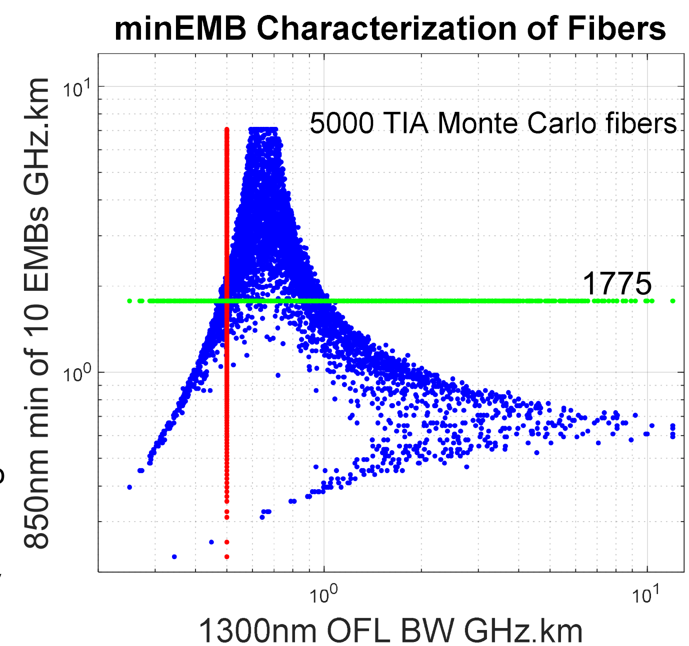

# 4c. Applying EF and minEMB screens

We eliminate lasers which fall out side the red box (mostly outliers).
There is a pre-screen for OFL1300>500MHz.km and OFL850 >1500MHz.km
We evaluate a “min EMB” using the 10 Monte Carlo lasers close to 10 actual 10Gb/s laser (red), and take the minimum of the 10 EMBs. We then adjusted the threshold until we hit the target failure rate.

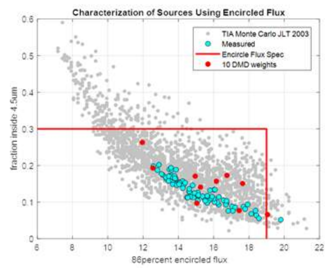



It is easy to see which lasers are screened out

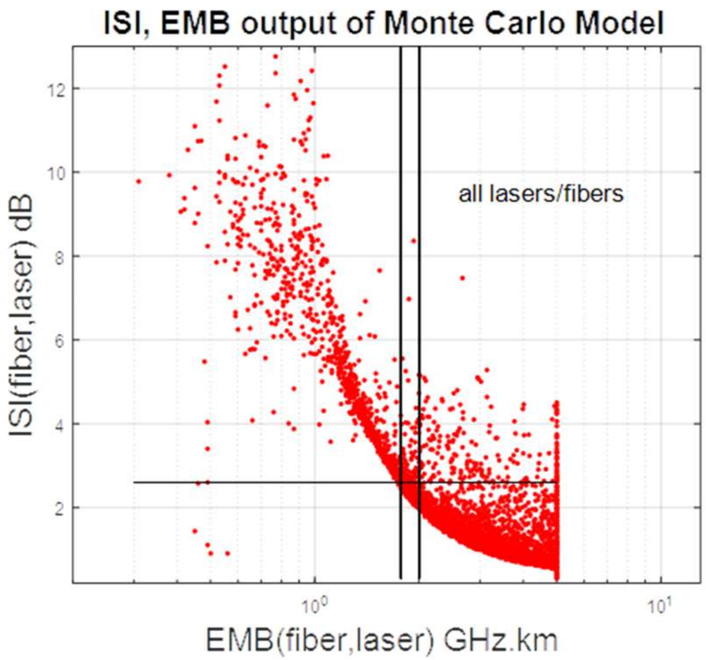
This plot shows the OFL1300 and “minEMB” screen but OFL850 also applied… Maybe there is better way to plot it.



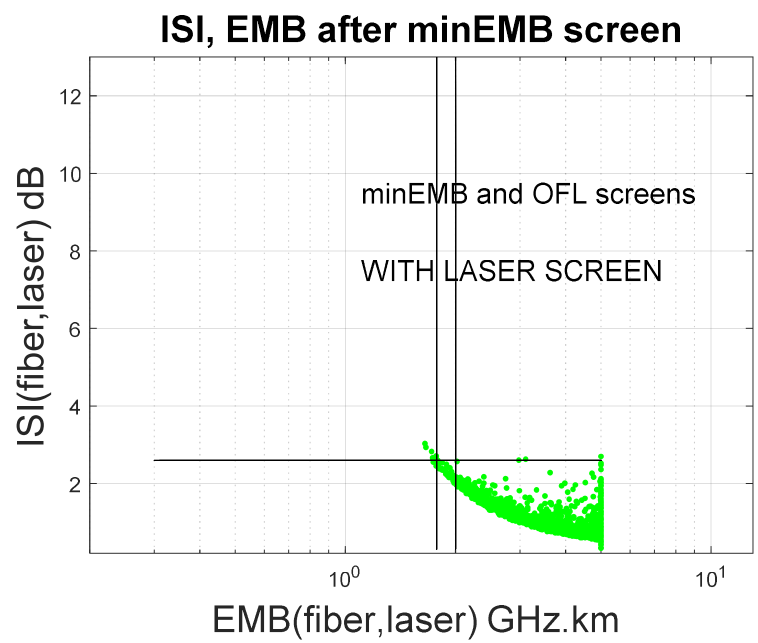
# 4d TIA Monte Carlo results using minEMB and EF screens




10,000 pairs

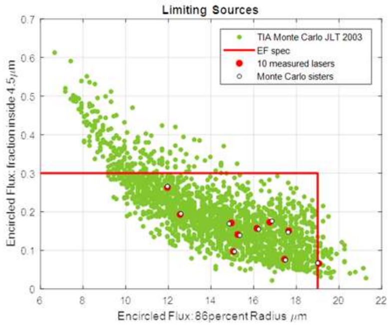


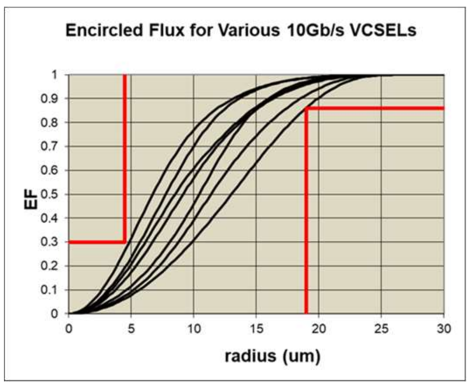

6300 pairs with minEMB screen
5500 pairs with EF screen added



# 4e IMPLEMENTATION OF minEMBc = “calculated minEMB”

[8] IEC EF spec 61300-1_ed4_2016 section 10.2 (launch conditions for type A1b fibre) and Appendix A
[9] IEC EMBc spec 60793-2-10_ed7_2019 . See Annexes A-E, with minEMBc & “DMD weights” in Annex D.




The EMBc measurement to calculate an effective modal bandwidth for a particular fiber with a particular laser takes the individual pulses from a HRDMD measurement of the fiber and adds them up with a weighting corresponding to the encircle flux curve of the particular standard.
The IEC standard includes weightings to use to mimic the standard 10 lasers (and now an 11th for OFL BW)

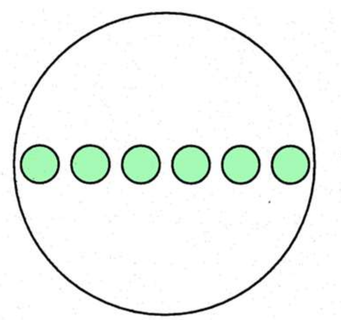
**OM3 spec: minEMBc > 1770MHz.km** (equation D.1)

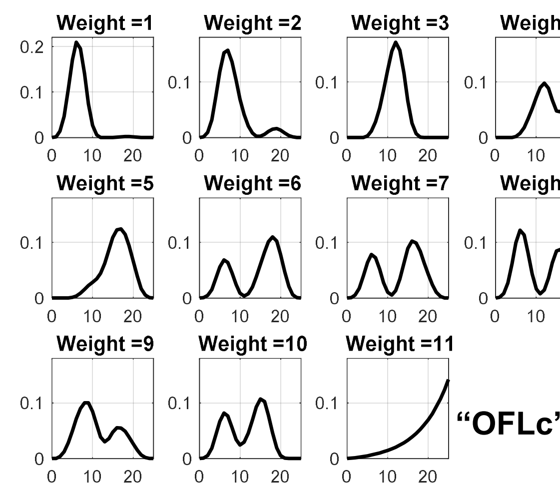
# 4e The High Resolution DMD (HRDMD) measurement

In the HRDMD measurement a small spot (like from a single-mode fiber) is scanned across the core of the multimode fiber, for example in 1μm steps. At each offset position k the output pulse P_k(t) is saved, for a total of K pulses from 0μm to 25μm. {early DMDs just saved centroid, or peak, or RMS pulse width}

At each launch position a different mix of mode groups is excited, and creating the appropriate weighting function W_k, it is possible to generate an output pulse P(t) reflecting the desired mode power distribution

$$P(t) = \sum_{k=1}^{K} W_k P_k(t)$$





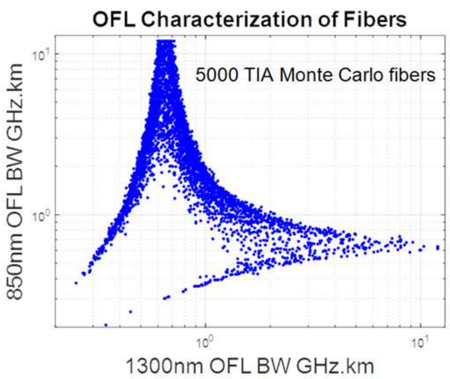

[9] IEC EMBc spec 60793-2-10_ed7_2019 . See Annexes A-E, with "DMD weights" in Annex D.

## 5. Challenges with OM2 and non-laser-optimized fiber

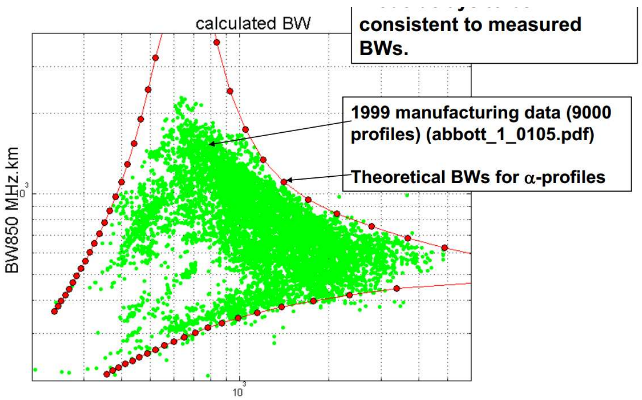
# 5a. Challenges with OM2 (500MHz.km OFL at 850, 1300)

IEEE project 802.3aq developed a methodology for 10GbE at 1300nm over OM2 fiber. The project required an "offset launch" and significant electronic dispersion compensation. The problem is that OM2 OFL BW at 850nm, 1300nm does not give a lot of insight into "EMB" for arbitrary laser launch –the offset launch helped put MPD in an area of greater profile control.

802.3aq abbott_01_0705.pdf




It was difficult to estimate worst case OM2 fibers in 802.3aq



# 5b. NEXT STEPS FOR OM2 and OM3 (SiP at 1310nm)

1. Est. worst case 1300nm guidance for OM3 fiber (on To Do list) with 10 weights
   a. Fiber consensus – to validate
2. Est. worst case 1300nm guidance for generic OM2 fiber (put on To Do list) with 10 weights
   a. Fiber consensus – less likely
3. Launch conditions for SiP / provide SiP samples
   a. ? Encircled Flux Spec? 802.3ae, IEC EF spec 61300-1_ed4_2016
   b. ? Offset Launch? 802.3aq

The fact that one SiP transmitter works with one OM2 or OM3 fiber does not establish that every SiP transmitter works with every OM2 or OM3 fiber (which is what we need in IEEE 802.3).

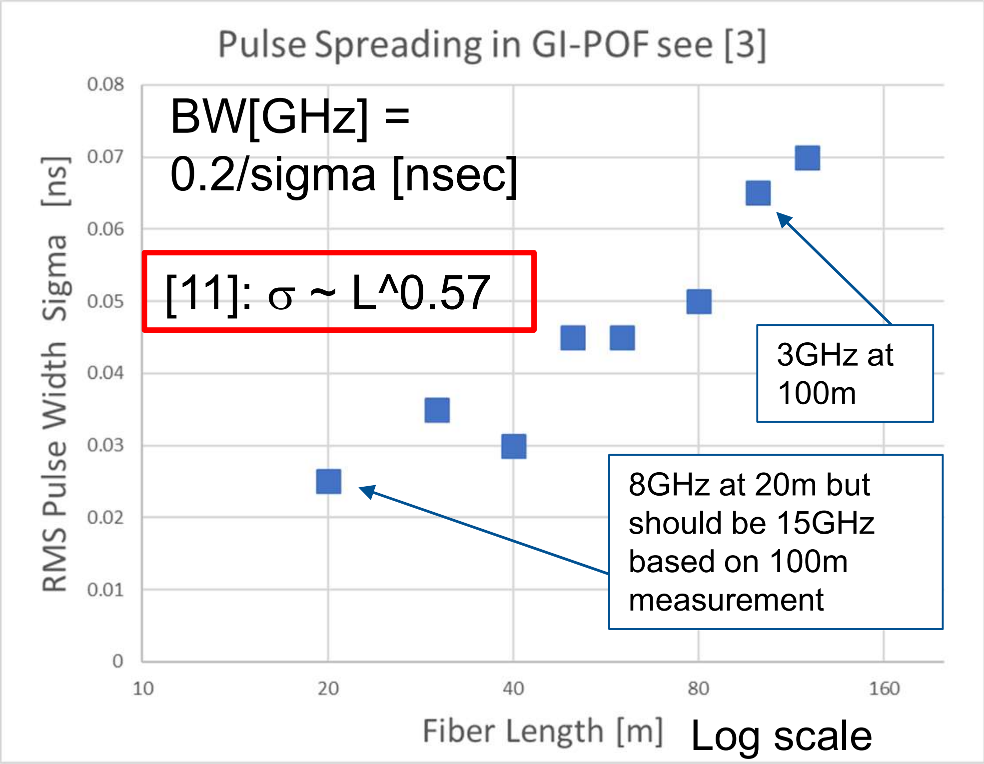
# 5c. Challenges with POF

[10] IEC 60793-2-40 edition 5 Feb 2021
GI-POF A4i fibers have been proposed for 802.3cz ($55\mu$m core, NA 0.24)
BW is "OFL BW >350MHz.km measured on 100m-500m length".

Two challenges in 802.cz
1. **OFL BW only** – need EMB with 10 wts.
2. GI-POF fiber shows **large mode coupling** [3], [11] and the measured OFL BW at 100m is expected to over-predict the bandwidth at 15m.

If the length dependence is L^0.57 then the apparent BW[MHz.km] at 15m is only 155MHz.km, not 350MHz.km ( 3500MHz→23300MHz if linear and 10,300MHz if 0.57). Note this was a different GI-POF fiber.

Need updated info for A4i




Sketched from [3] DiGiovanni et al., "Design of Optical Fibers for Communications Systems", Chapter 2 in ***Optical Fiber Telecommunications IVA***. New York: Elsevier, 2002. (Section 5 is "Plastic Optical Fiber") and [11]White et al. ***PTL*** 1999.

# 5d. NEXT STEPS WITH POF FIBER FOR 802.3cz

1. Need to update 1999 results [11] [3] for BW vs. length or RMS broadening vs. length with A4i POF and other POF candidates for 802.3cz.
   a. OFL BW vs. length and
   b. minEMBc vs. length per IEC A1a standards.
2. POF suppliers to supply A4i samples to 802.3cz project participants for testing.
3. Any published results for #1 in more recent literature, even if A4h etc. (?)
4. Determine if A4i needs to be specified with EMB like OM3.

# 6. Conclusion

For 10+ Gb/s in data centers a lot of work has gone into devising specifications for fiber and laser so that every laser works with every fiber and vice versa.

In order to have multiple vendors supplying interoperable equipment it is necessary to be sure that everything is as solid as possible.

Fiber bandwidth measurements are critical to making systems work reliably and they must be made with sources corresponding to actual transceivers.

802.3cz project team needs to apply learnings from 802.3ae etc.

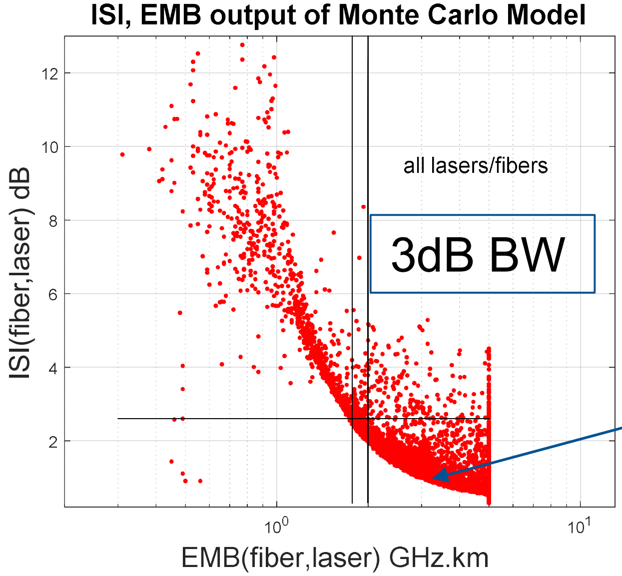
# 7. References

[1] Cunningham and Lane, ***Gigabit Ethernet Networking***. Indianapolis: Macmillan Technical Publishing, 1999.
[2] RML bandwidth: ANSI/TIA-455-204-1-2013, approved 10/1/2013, "FOTP-204. Measurement of Bandwidth on Multimode Fiber". Section 4.2.2 "Restricted mode launch (RML)"
[3] DiGiovanni et al., "Design of Optical Fibers for Communications Systems", Chapter 2 in ***Optical Fiber Telecommunications IVA***. New York: Elsevier, 2002. (Golowich section 4, "MM Fiber Applications. Section 5 is "Plastic Optical Fiber").
[4] 10GbE standard: 802.3ae https://www.ieee802.org/3/ae/index.html
[5] Pepeljugoski et al., "Development of System Specification for Laser-Optimized 50-μm Multimode Fiber for Multigigabit Short-Wavelength LANS", *Journal of Lightwave Technology* Vol. 21, No.5, May 2003 pp. 1256-1275. https://www.osapublishing.org/jlt/abstract.cfm?uri=jlt-21-5-1256
[6] Abbott et al., "Fibers for Short-Distance Applications", Chapter 7 in ***Optical Fiber Telecommunications VIA***. New York: Elsevier, 2013. https://www.sciencedirect.com/science/article/pii/B978012396958300007X
[7] Chen et al., "Multimode Fibers for Data Centers", Chapter in ***Handbook of Optical Fibers*** (G.-D. Peng, ed.). New York: Springer Nature Singapore Pte Ltd, 2018.
[8] IEC EF spec 61300-1_ed4_2016 section 10.2 (launch conditions for type A1b fibre) and Appendix A
[9] IEC EMBc spec 60793-2-10_ed7_2019 . See Annexes A-E, with "DMD weights" in Annex D.
[10] IEC 60793-2-40 edition 5 Feb 2021 A4i BW is Table I.3
[11] White et al., "Intermodal Dispersion and Mode Coupling in Perfluorinated Graded-Index Plastic Optical Fibers", *IEEE Photonics Technology Letters*, Vol. 11 No. 8 August 1999 pp.997-999.

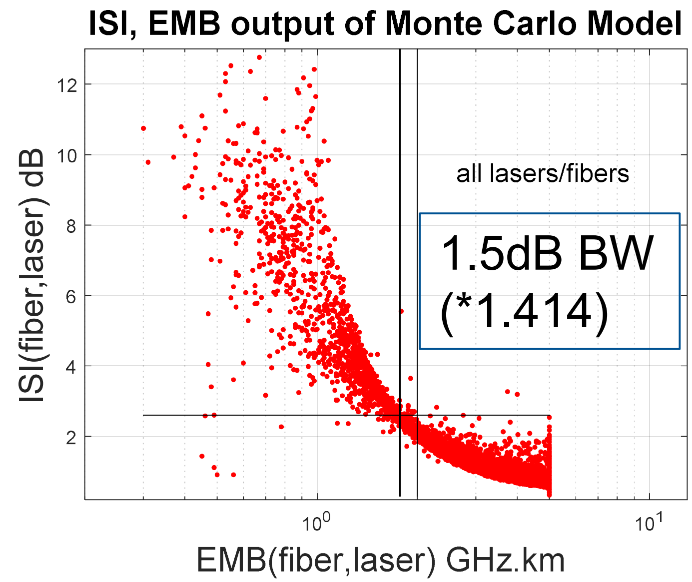
# 8. BACKUP

# 8a. Why the scatter in output of TIA Monte Carlo Model?

1. The points about 2.6dB are failing fiber/laser links.
2. The reason there appear to be failing links with EMB >2000 is that the 3dB BW needs to be adjusted to match a Gaussian filter consistent with the rest of the link. For example, using the 1.5dB BW and multiplying by 1.414x fixes most of the problem.
3. Many of these fibers "fail" the minEMB screen (i.e. BW less than 2000 with another laser)

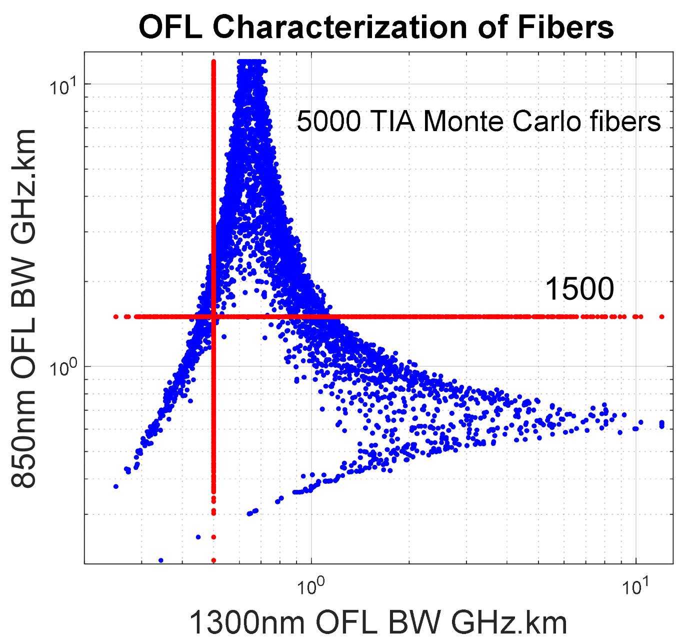


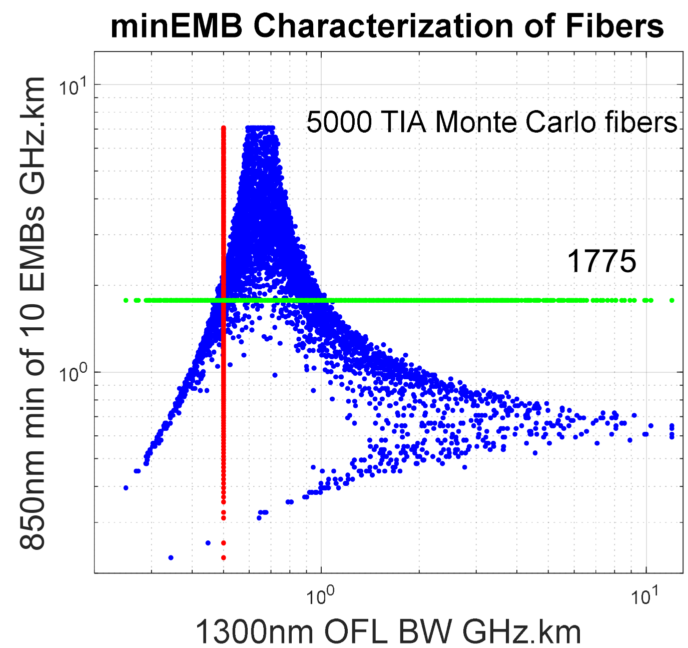

The "correct" bandwidth for a nonGaussian H(f) would give the ISI(EMB) curve on the edge of this region



# 8b. Does the screen include OFL850, OFL1300, minEMB?

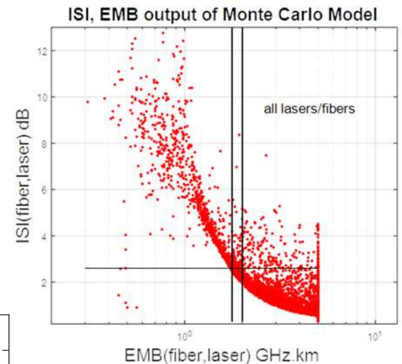
The screening of the fibers in TIA Monte Carlo work involves screening out fibers with OFL1300<500, OFL850<1500, and adjusting the threshold for the minEMB value. The single-color scatter plots don't make this clear. We could redo the plot on right below coloring points with OFL850<1500 red to make it clearer. The OFL=1500 screen was more important with the first DMD mask screen and less important for minEMB.



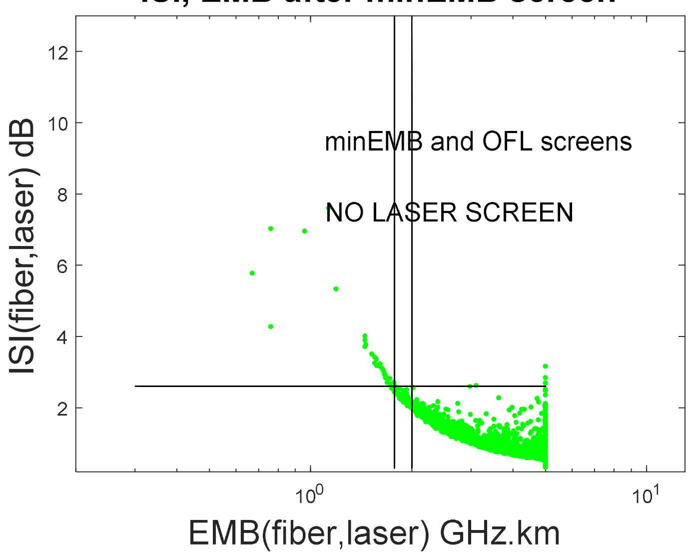
# 8c What is effect of laser EF screen vs. fiber BW screen?

10,000 pairs



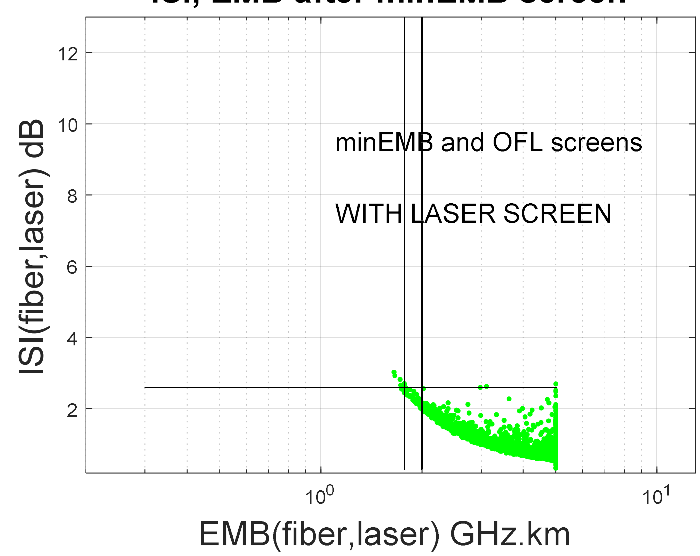

6300 pairs

ISI, EMB after minEMB screen




5500 pairs

ISI, EMB after minEMB screen



# 8d What's with the 1775MHz.km – isn't OM3 spec 2000MHz.km?

In IEC 607923-2-10 Annex D the fiber specification for OM3 is given in two ways.

The first (which is also explained in reference [5]) uses "masks" on the DMD measurement to screen out all but 0.5% of the TIA Monte Carlo fiber with ISI greater than 2.6dB. This was 'defined' as 2000MHz.km.

The 2nd method is to use the minEMBc technique with minEMBc>1770 MHz.km.

The informative guidance in Annex E is to use the formula EMB = 1.13*minEMBc to get a EMB consistent with the 802.3ae link model spreadsheet.

This is the 1775MHz.km used in this presentation (for tutorial purposes)

The x-axis in this scatter plot of Monte Carlo results is not the EMB of the fiber with the 10 DMD weights, it is the EMB of the fiber with one of the 2000 "lasers".
What we see on this plot is that we need to screen the fiber (& laser) so that the EMB of (fiber,laser) pairs is about 1770-1775 and then correctly evaluate the bandwidth so we are focused on this sharp edge of the Monte Carlo region.
The minEMBc method does this very well so that minEMB>1770 with 10 DMD weights translates into minEMB>1770 for "all" lasers to good approximation.

ISI, EMB output of Monte Carlo Model