It’s Time for OM5!

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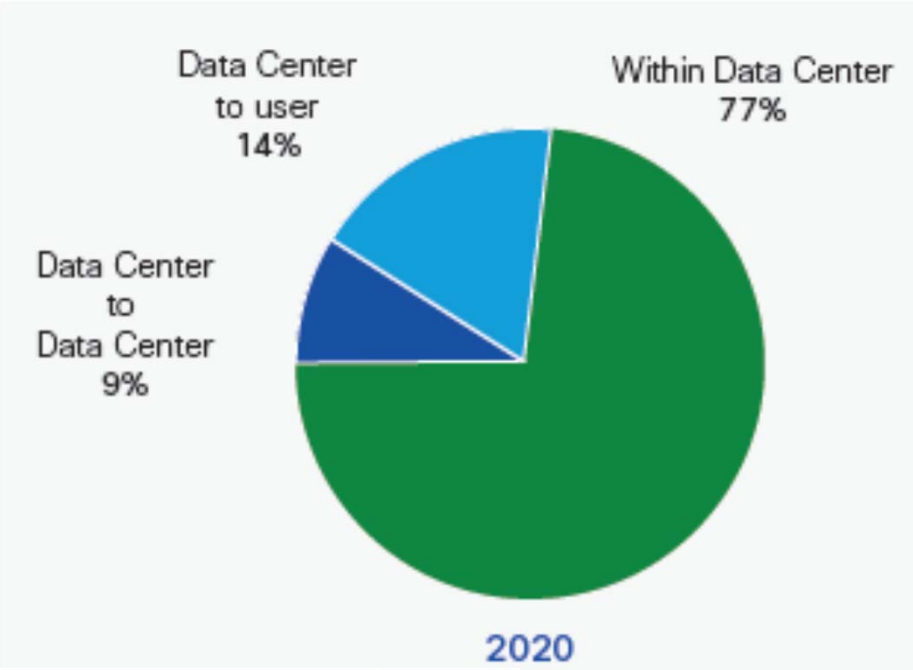
Agenda

- Fiber Market Drivers
- Multimode Fiber Types
- Multimode Application Standards
- Multimode Fiber Value Proposition
- Future of Multimode Fiber
- Conclusions

Data Center Traffic

Global Data Center Traffic By Destination in 2020

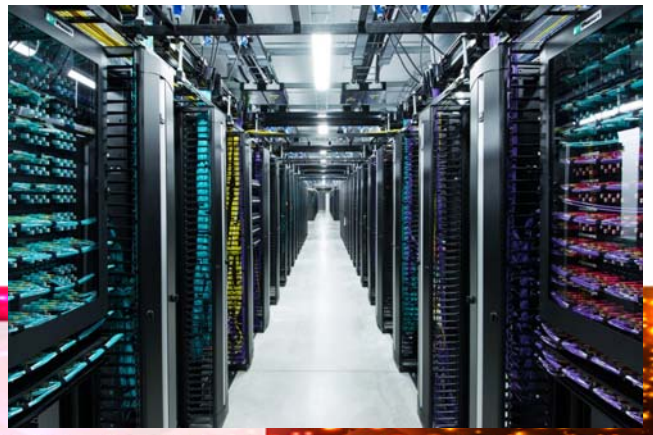


Cisco Global Cloud Index:
Forecast and Methodology, 2015-2020
November, 2016

- Global data center traffic will reach 14.1 zettabytes in 2020, from 3.9 zettabytes in 2015
- Hyperscale data centers will account for 47% of all installed data center servers by 2020
- Hyperscale data centers account for 34% of total traffic within data centers in 2015 and will make up 53% by 2020

What is happening today

- **Cloud Computing**
  - Migration to hosted services



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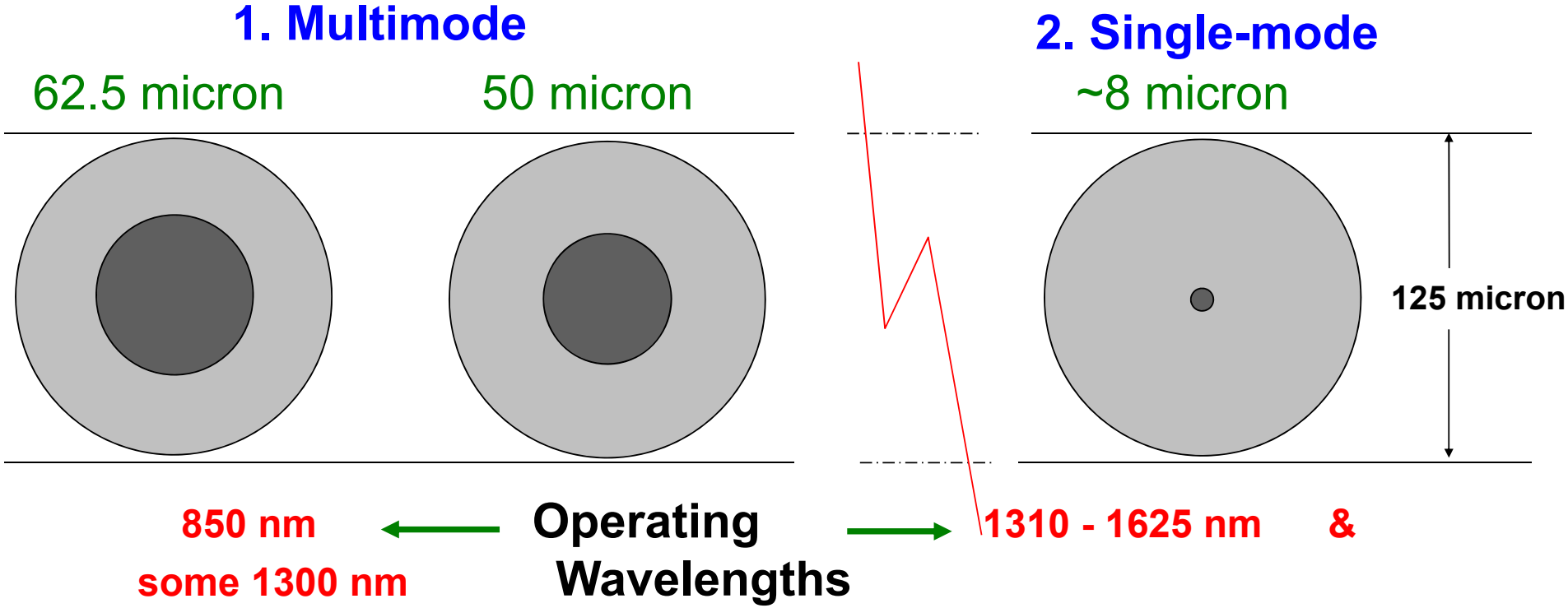
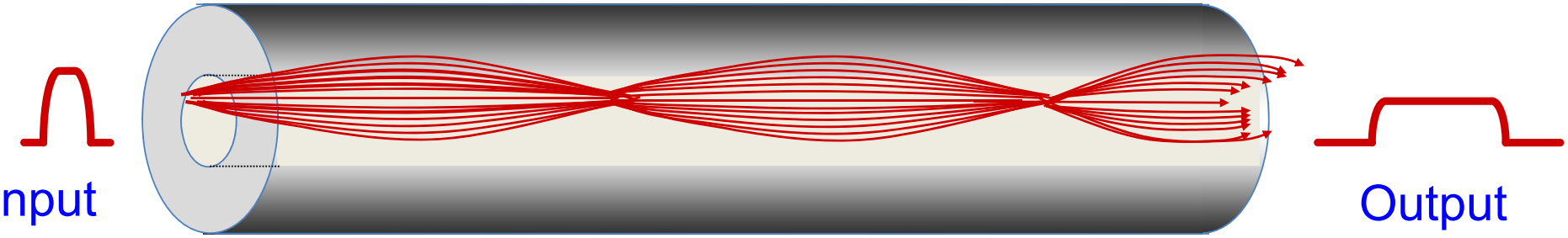
Two Basic Optical Fiber Types



Larger cores and lower wavelengths drive source and system costs down

Multimode Fiber

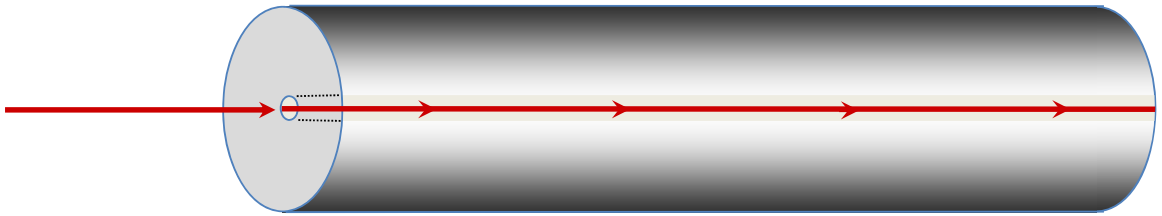
- Light Signal travels along many paths
- Pulse spreading occurs due to **Modal Dispersion** or **Differential Mode Delay** (DMD)
- Pulse spreading limits **Bandwidth**



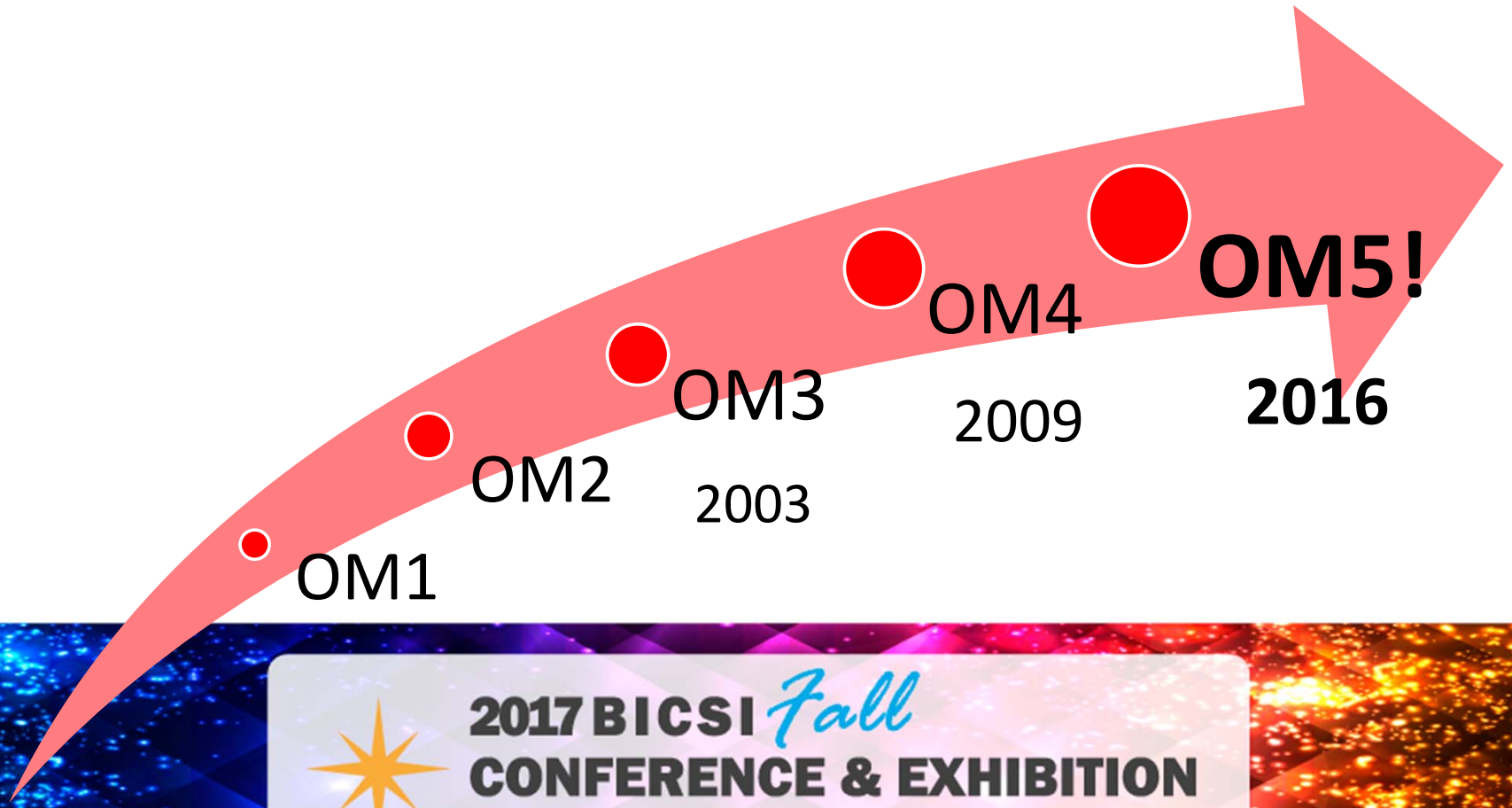
Singlemode Fiber

Small core guides only one mode

- Eliminates modal dispersion.
- Enables tremendous transmission capacity over very long distances.



Multimode Fiber Evolution



Multimode Fiber Types

*(described in the industry using primarily the **ISO/IEC 11801** designations)*

Fiber Type	Industry Standards					Attenuation - Typical Cabled Max. (dB/km)		Bandwidth (MHz-km) Overfilled Launch (OFLc)		Bandwidth (MHz-km) Effective Modal Bandwidth (EMB) (also know n as Laser BW)	
	ISO/IEC 11801 (draft)	IEC 60793-2-10	TIA-568.3-D	TIA/EIA 492AAAx	ITU-T	850nm	1300nm	850nm	1300nm	850nm	953nm
62.5/125	~~OM1~~[(1)]	A1b	~~TIA 492AAAA (OM1)~~	492AAAA	---	3.5	1.5	200	500	---	---
50/125	~~OM2~~[(2)]	A1a.1b[(3)]	~~TIA 492AAAB (OM2)~~	492AAAB	G.651.1	3.5	1.5	500	500	---	---
50/125	OM3	A1a.2b[(3)]	TIA 492AAAC (OM3)	492AAAC	---	3.0	1.5	1500	500	2000	---
50/125	OM4	A1a.3b[(3)]	TIA 492AAAD (OM4)	492AAAD	---	3.0	1.5	3500	500	4700	---
50/125	OM5 (draft)	A1a.4b[(3)] (draft)	TIA 492AAAE (OM5)	492AAAE	---	3.0	1.5	3500	500	4700	2470

[(1)] OM1 is typically a 62.5um fiber, but can also be a 50um fiber.

[(2)] OM2 is typically a 50um fiber, but can also be a 62.5um fiber.

[(3)] "b" designates Bend-Insensitive

ISO/IEC 11801 "Generic Cabling for Customer Premises"
IEC 60793-2-10 "Product Specifications - Sectional Specification for Category A1 Multimode Fibres"
TIA-568.3-D "Optical Fiber Cabling and Components Standard"
TIA/EIA-492AAAx "Detail Specification for… Class 1a Graded-Index Multimode Optical Fibers"
ITU-T G.651.1 "Characteristics of a 50/125 um Multimode Graded Index Optical Fibre Cable for the Optical Access Network"

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Standards Based Ethernet Link Distances

Application / Link Speed	Data Center Building Backbone		Lg. Data Center Building Backbone	Very Lg. Data Center Building Backbone		Building Backbone Campus Backbone	Campus Backbone
10 Gb/s 10GBASE-SR Duplex	OM3 Multimode Fiber				OM4 Multimode Fiber	OM4 Multimode Fiber (Engineered Solution)	
25 Gb/s 25GBASE-SR Duplex		OM4 MM Fiber					
40 Gb/s 40GBASE-SR4 4x Parallel Fiber			OM4 MM Fiber	OM3 Multimode Fiber (Engineered Solution)	OM4 Multimode Fiber (Engineered Solution)	OM4 Multimode Fiber (Engineered Solution)	
100 Gb/s 100GBASE-SR10 10x Parallel Fiber					OS1/OS2 Single-mode Fiber		
100Gb/s 100GBASE-SR4 4x Parallel Fiber		OM4 Multimode Fiber	OM3 Multimode Fiber (Engineered Solution)	OM4 Multimode Fiber (Engineered Solution)			
Link Distance	70m	100m	150m	200m	300m	400m	550m	1000m

Engineered Ethernet Solutions

Available and/or Announced

Application / Link Speed	Data Center Building Backbone		Lg. Data Center Building Backbone	Very Lg. Data Center Building Backbone				Building Backbone Campus Backbone		Campus Backbone
40 Gb/s BiDi Duplex	OM3 Multimode Fiber		OM4 MM Fiber	OM5 MM Fiber	OS1/OS2 Single-mode Fiber					
40 Gb/s SWDM4™ Duplex					OM4 MM Fiber		OM5 Multimode Fiber			
100 gb/s BiDi Duplex		OM4 MM Fiber	OM5 MM Fiber							
100 Gb/s SWDM4™ Duplex		OM4 MM Fiber	OM5 MM Fiber							
Link Distance	70m	100m	150m	200m	240m	300m	350m	400m	440m	550m	1000m

Latest Ethernet Developments

200/400 Gb/s Ethernet (IEEE802.3bs)

PMD	Link Distance	Fiber Count and Media Type	Technology
400GBASE-SR16	100 m OM4/OM5 (32-f MPO)	32-f MMF	16x25G parallel NRZ 850nm
400GBASE-DR4	500 m	8-f SMF	4x100G parallel PAM4 1300nm
400GBASE-FR8	2 km	2-f SMF	8x50G CWDM PAM4 8 wavelengths around 1300nm
400GBASE-LR8	10 km	2-f SMF	8x50G CWDM PAM4 8 wavelengths around 1300nm
200GBASE-DR4	500 m	8-f SMF	4x50G Parallel PAM4 1300nm
200GBASE-FR4	2 km	2-f SMF	4x50G CWDM PAM4 4 wavelengths around 1300nm
200GBASE-LR4	10 km	2-f SMF	4x50G CWDM PAM4 4 wavelengths around 1300nm

Publication expected in late 2017

25 Gb/s Ethernet (IEEE 802.3cc)

PMD	Link Distance	Fiber Count and Media Type	Technology
25GBASE-LR	10 km SMF	2-f SMF	1x25G NRZ
25GBASE-ER	40 km SMF	2-f SMF	1x25G NRZ

Publication expected in 2017

50/100/200 Gb/s Ethernet (IEEE 802.3cd)

PMD	Link Distance	Fiber Count and Media Type	Technology
50GBASE-SR	100 m OM4/OM5	2-f MMF	1x50G PAM-4 850nm
50GBASE-FR	2 km	2-f SMF	1x50G PAM-4 1300nm
50GBASE-LR	10 km	2-f SMF	1x50G PAM-4 1300nm
100GBASE-SR2	100 m	4-f MMF	2x50G PAM-4 850nm
100GBASE-DR	500 m	2-f SMF	1x100G PAM4 1300nm
200GBASE-SR4	100 m	8-f MMF	4x50G parallel PAM-4 850nm

Publication expected in 2018

IEEE 802.3 Industry Connections
New Ethernet Applications Ad Hoc (IEEE802.3 NEA Ad Hoc)

- **Work underway to develop a Call For Interest (CFI) proposing, "Next Generation 400 and 200 Gb/s Ethernet PHYs over Fewer Multimode Fiber Pairs"**
  - Suggests the use of Short Wavelength Division Multiplexing (SWDM) technology to reduce multimode fiber counts for standards based 200 and 400Gb/s Ethernet

Next-gen 400 and 200 Gb/s PHYs over Fewer MMF Pairs Call For Interest Consensus Presentation

IEEE 802.3

Draft 0.3

Technical options for Next-Gen MMF PMDs

Technology (per fiber)	1 fiber pair	2 fiber pairs	4 fiber pairs	8 fiber pairs	16 fiber pairs
25G-λ NRZ	25G-SR		100G-SR4		400G-SR16
50G-λ PAM4	50G-SR	100G-SR2	200G-SR4		
2x50G-λ PAM4	100G-SR1.2	200G-SR2.2	**400G-SR4.2**	400G-SR8	
4x25G-λ NRZ	100G-SR1.4	200G-SR2.4	**400G-SR4.4**	**Technology options for 200 & 400 Gb/s links over fewer MMF fiber pairs**	
4x50G-λ PAM4	**200G-SR1.4**	**400G-SR2.4**	800G-SR4.4		

Existing IEEE standard

In progress in 802.3bs/cd

Multi-Wavelength Nomenclature

SRm.n **m = # fiber pairs**
n = # wavelengths

Source: "Next-gen 400 and 200 Gb/s PHYs over Fewer MMF Pairs" Call For Interest Consensus Presentation, Draft 0.3, IEEE 802.3 NEA Ad Hoc, 03-14-17

Latest Fiber Channel Standards

32GFC – FC-PI-6

Variant	Link Distance	Fiber Count and Media Type	Technology
3200-M5-SN-S	20 m OM2	2-f MMF	1x28G NRZ 850nm
3200-M5E-SN-S	70 m OM3	2-f MMF	1x28G NRZ 850nm
3200-M5F-SN-I	100 m OM4	2-f MMF	1x28G NRZ 850nm
3200-SM-LC-L	10 km	2-f SMF	1x28G NRZ 1300nm

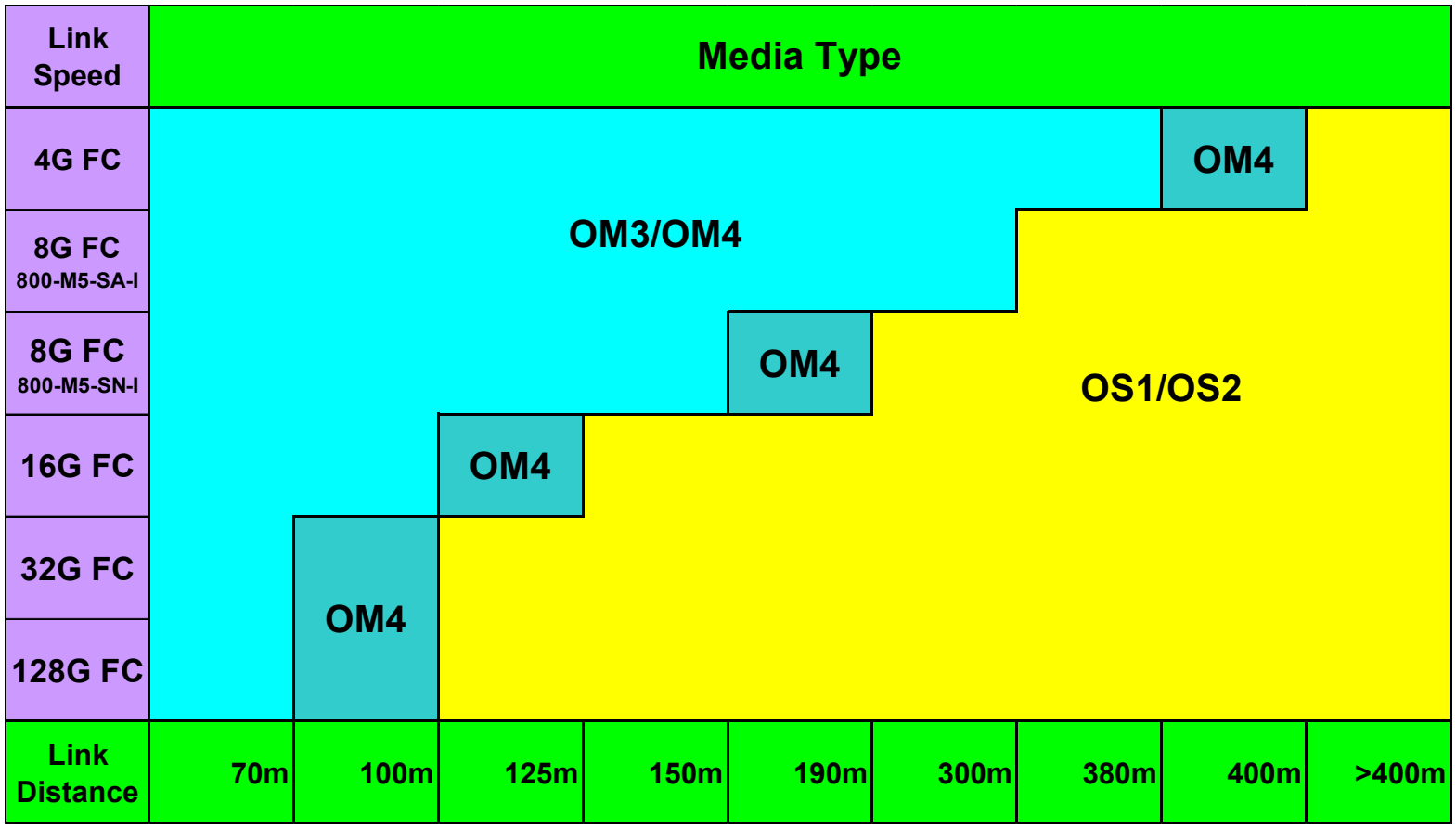
Published in 2013

128GFC – FC-PI-6P

Variant	Link Distance	Fiber Count and Media Type	Technology
128GFC-SW4	70 m OM3 100 m OM4	8-f MMF	4x28G parallel NRZ 850nm
128GFC-PSM4	500 m	8-f SMF	4x28G parallel NRZ 1300nm
128GFC-CWDM4	2 km	2-f SMF	4x28G CWDM NRZ 4 wavelengths around 1300nm

Published in 2016

Fiber Channel Link Distance



64/256GFC – FC-PI-7

Variant	Link Distance	Fiber Count and Media Type	Technology
64GFC	100 m OM4/OM5	2-f MMF	Under Discussion Could be WDM w/ NRZ or PAM-4
64GFC	10 km?	2-f SMF	Under Discussion
256GFC	100 m	8-f MMF	Under Discussion PAM-4 or NRZ
256GFC	2 km?	2-f SMF	Under Discussion

Technical agreement expected in late 2017

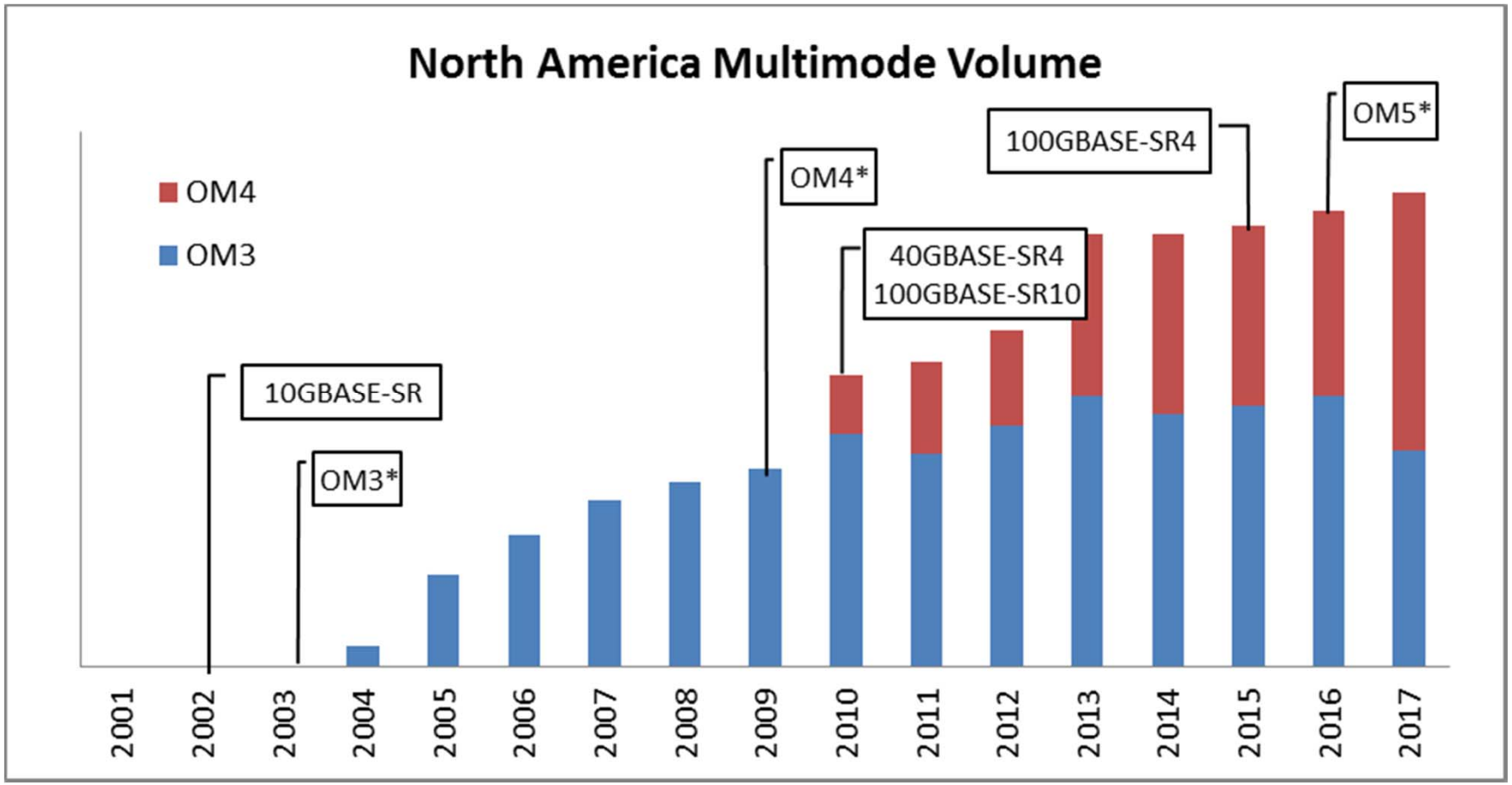
Next Generation Solutions

- **OM5 Fiber and Short Wavelength Division Multiplexing (SWDM)**
- **Multilevel Signaling**

Why do we need a new multimode fiber?
And why SWDM?

- Cannot continue to increase fibers as bandwidth increases
  - End user reluctant to run 2x16 – 32 fiber cables for a 400Gb/s
- SWDM allows multiple wavelengths to be used, reducing the number of fibers
- Utilizes same simplex LC and multi-fiber MPO connector technology
- Can provide duplex fiber 100Gb/s links
- Enables 400Gb/s transmission using 8-fiber technology, currently adopted in 40Gb/s links

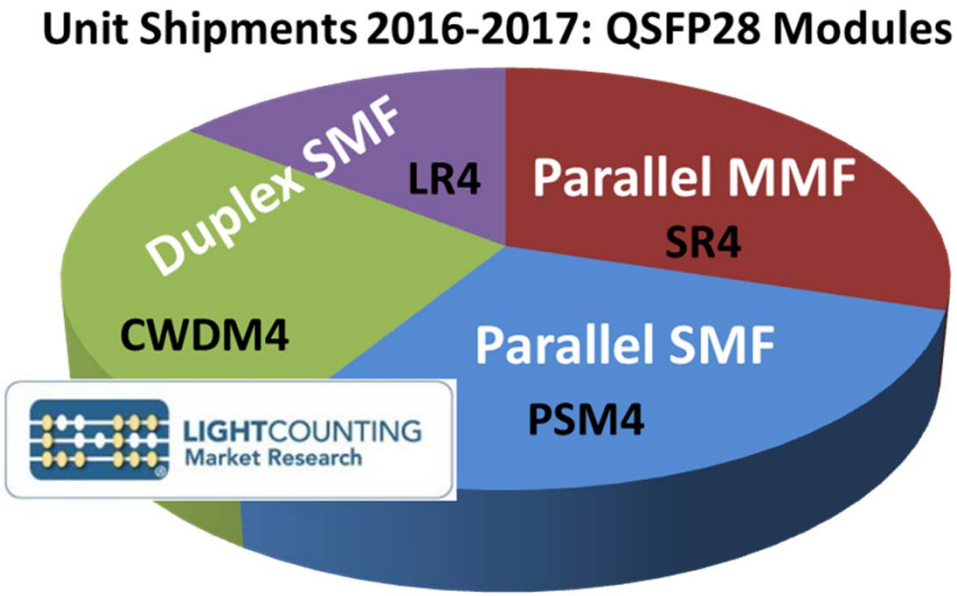
Continued Deployment & Growth of OM3/OM4 MMF
Continued Transition from OM3 to OM4



* Dates are ANSI/TIA standardization dates, not ISO/IEC

Source: Matthew Burroughs North America Multimode Reports

100GbE QSFP28 Consumption



- Chart shows units shipped
- Short-reach SR4 modules had the greatest individual contribution to 2016 shipments of QSFP28 modules

Chart courtesy of Dale Murray, LightCounting

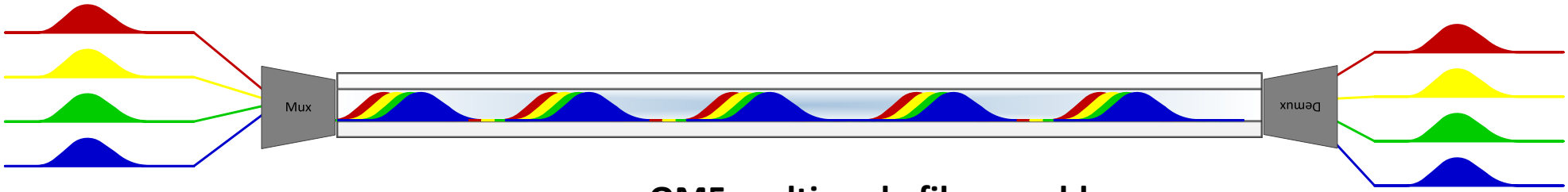
IEEE 802.3 Ethernet / Fiber Channel

- Wideband OM5 fiber included as an approved media type in current proposals
  - IEEE P802.3bs - 200GbE and 400GbE
  - IEEE P802.3cd - 50 Gb/s, 100 Gb/s and 200 Gb/s Ethernet

- IEEE 802.3 New Ethernet Applications (NEA) Ad Hoc
  - Next-gen 400 and 200 Gb/s PHYs over Fewer MMF Pairs
  - Will require WDM technology and/or multilevel signaling

- Wideband OM5 fiber included as an approved media type in FC-PI-7 Marketing Requirements Document (MRD)
  - 64/256GFC

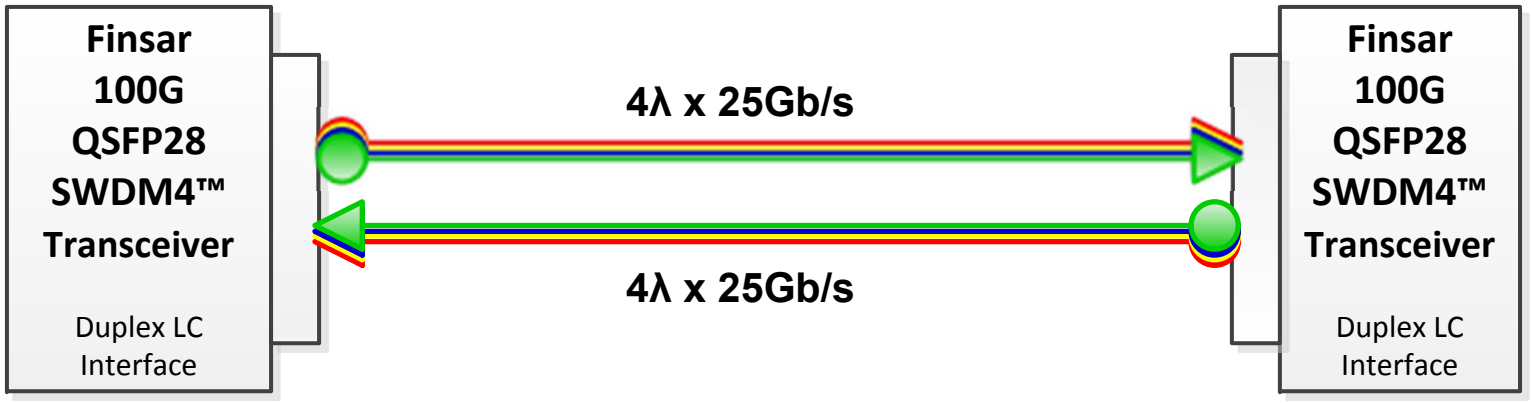
What can you do with OM5 fiber?



OM5 multimode fiber enables
Short Wavelength Division Multiplexing (SWDM)
Multiple wavelengths (colors) on the same fiber
40/100/200? Gb/s

Next Generation 100Gb/s Link

Finisar SWDM4™ QSFP28 Transceiver



- Announced at 2015 ECOC
  - Duplex (2-fiber) transmission over multimode fiber
  - Proprietary Solution

Link Distance Support	
Fiber Type	Link Distance (m)
OM3	75
OM4	100
OM5 (WideBand)	150

Next Generation 100Gb/s Link

FIT BiDi QSFP28 Transceiver

- Announced at OFC 2017
  - **Duplex Bi-Directional 100Gbps transmission**
    - **2 λ each operating at 50Gbps**
  - **Proprietary Solution**

Link Distance Support	
Fiber Type	Link Distance (m)
OM3	70
OM4	100
OM5 (WideBand)	150

LC Duplex SWDM transceivers

					Link Distance		
Speed	Vendor	Transceiver	Form Factor	λ	OM3	OM4	OM5
40Gb/s	FIT	BiDi	QSFP+	2	100	150	200
40Gb/s	Cisco/ Arista/ Brocade	BiDi	QSFP+	2	100	150	
40Gb/s	Finisar	SWDM4*	QSFP+	4	240	350	440
100Gb/s	FIT	Bdi	QSFP28	2	75	100	150
100Gb/s	Finisar	SWDM4**	QSFP28	4	75	100	150

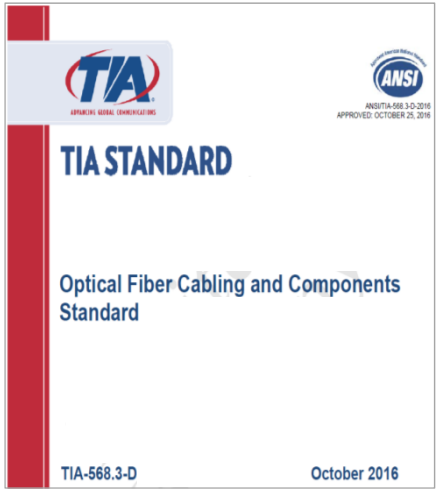
* Limited Availability
** Announced

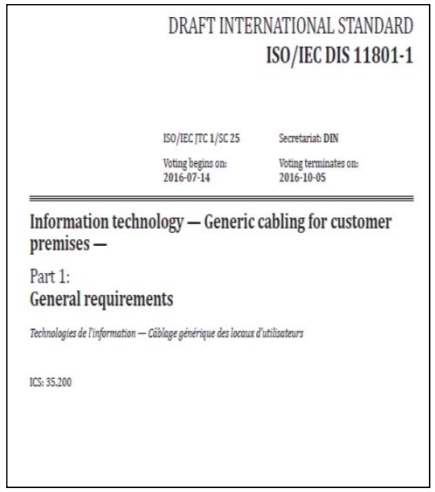
Wideband OM5 Standardization

Improved performance with multiple wavelengths

- OM5 MMF extends the 850nm performance of OM4 out to 953nm
- Standards:
  - **Fiber**: TIA-492AAAE (2016), IEC 60793-2-10 ed. 6 (1Q17)
  - **Structured Cabling**: ANSI/TIA-568.3-D (2016), ISO/IEC 11801 ed. 3 (target 4Q17)

Fiber Standards



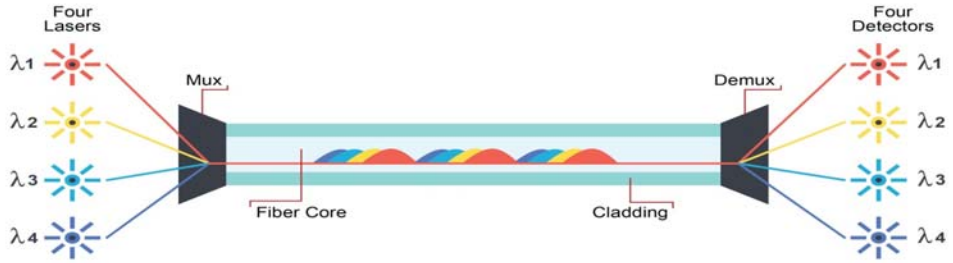


Structured Cabling Standards

Objectives

- Support 100Gb/s transmission on a single fiber over 4 wavelengths
- Wavelengths > 850nm benefit from increasing chromatic bandwidth.
- Low-cost WDM needs ~ 30nm spacing.
  - Resulting target wavelength region: 850nm to at least 950nm.
- Continue to support legacy 850nm OM4 applications
  - Maintain OM4 backward compatibility

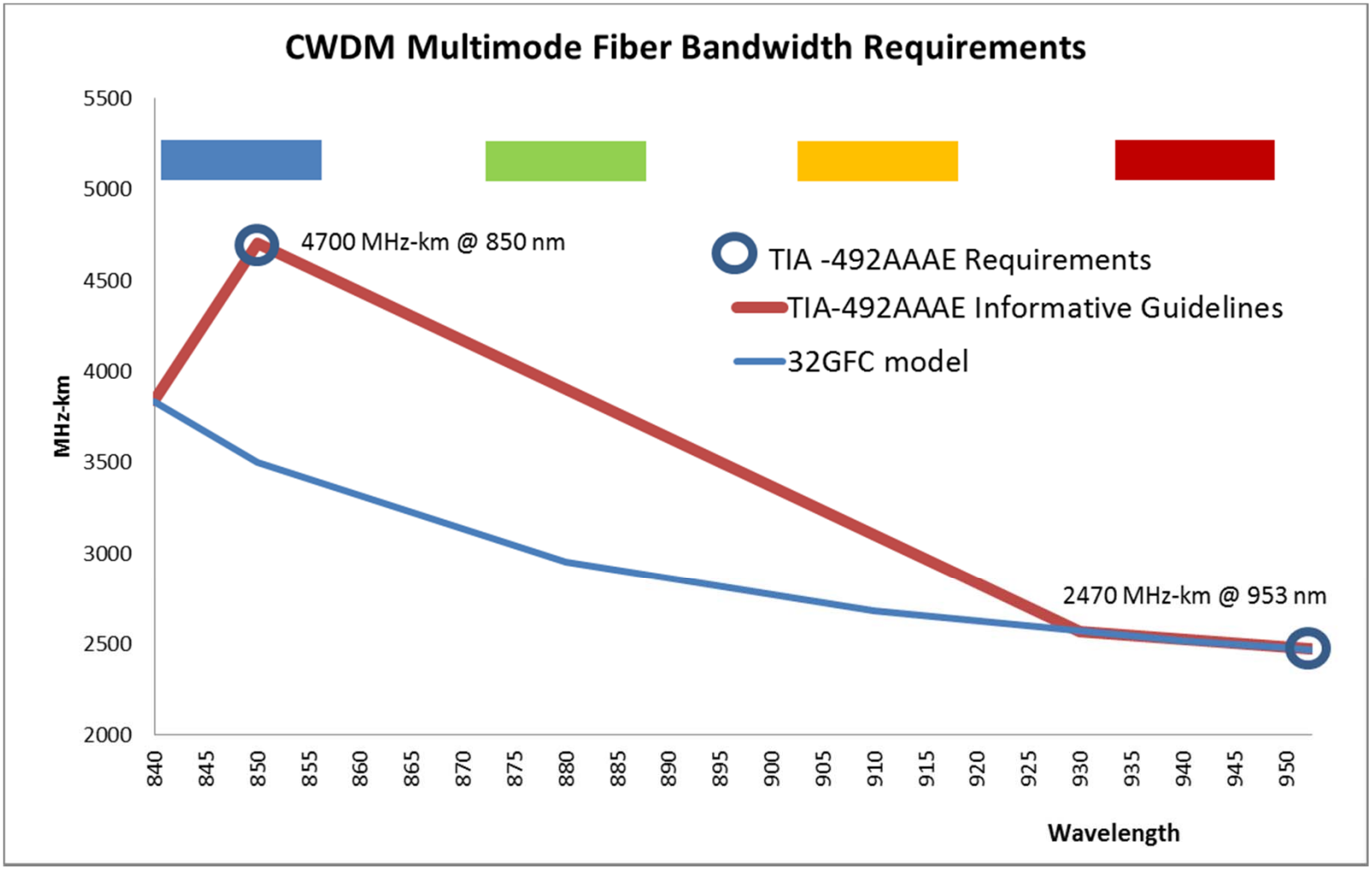
Standard Multimode Fiber



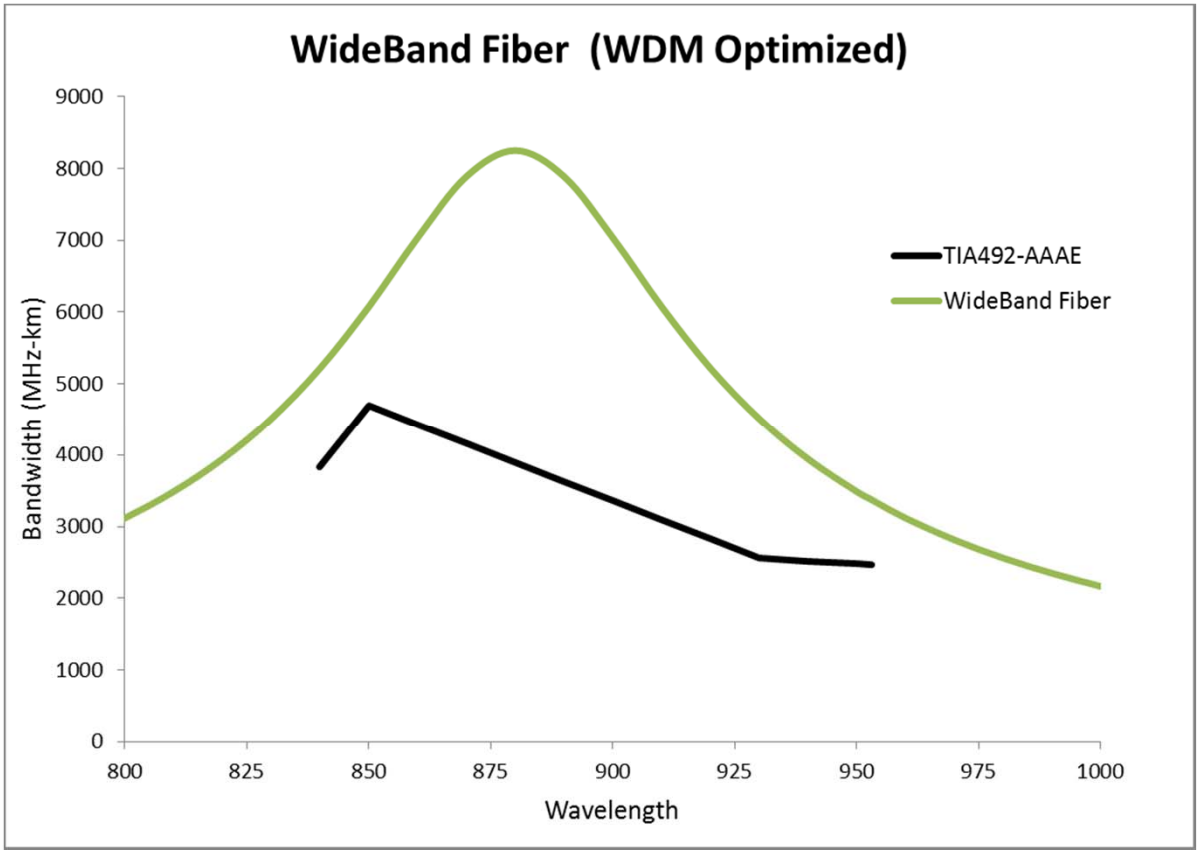
WideBand Multimode Fiber

Differences between OM4 and WideBand OM5 fiber

	OM4 Multimode Fiber	WideBand (OM5) Multimode Fiber
Zero Dispersion Wavelength	$1295 \le \lambda_o \le 1340$ nm	$1297 \le \lambda_o \le 1328$ nm
Zero Dispersion Slope	$S_0 \le 0.105$ ps/nm^2·km for $1295 \le \lambda_o \le 1310$ nm, and $\le 0.000375(1590-\lambda_o)$ ps/nm^2·km for $1310 \le \lambda_o \le 1340$ nm	$S_0 \le 4(-103) / (840(1-(\lambda o /840)^4))$ ps/nm^2·km
850nm Effective Modal Bandwidth (EMB)	4700 MHz-km	4700 MHz-km
953nm EMB	N/A	2470 MHz-km


CWDM Multimode Fiber Bandwidth Requirements
5500
5000
4500
4000
3500
3000
2500
2000
MHz-km
4700 MHz-km @ 850 nm
2470 MHz-km @ 953 nm
TIA -492AAAE Requirements
TIA-492AAAE Informative Guidelines
32GFC model
840
845
850
855
860
865
870
875
880
885
890
895
900
905
910
915
920
925
930
935
940
945
950
Wavelength

What is WideBand Fiber?



Wideband fiber field testing

- **No additional field testing required for wideband fiber**
  - **953nm attenuation requirement**
    - If 850nm and 1300nm attenuation requirements are met, 953nm requirements are also met
  - **953nm bandwidth requirement**
    - Performance insured by DMD measured by fiber manufacturers
  - **Chromatic dispersion**
    - Performance insured by fiber manufacturers

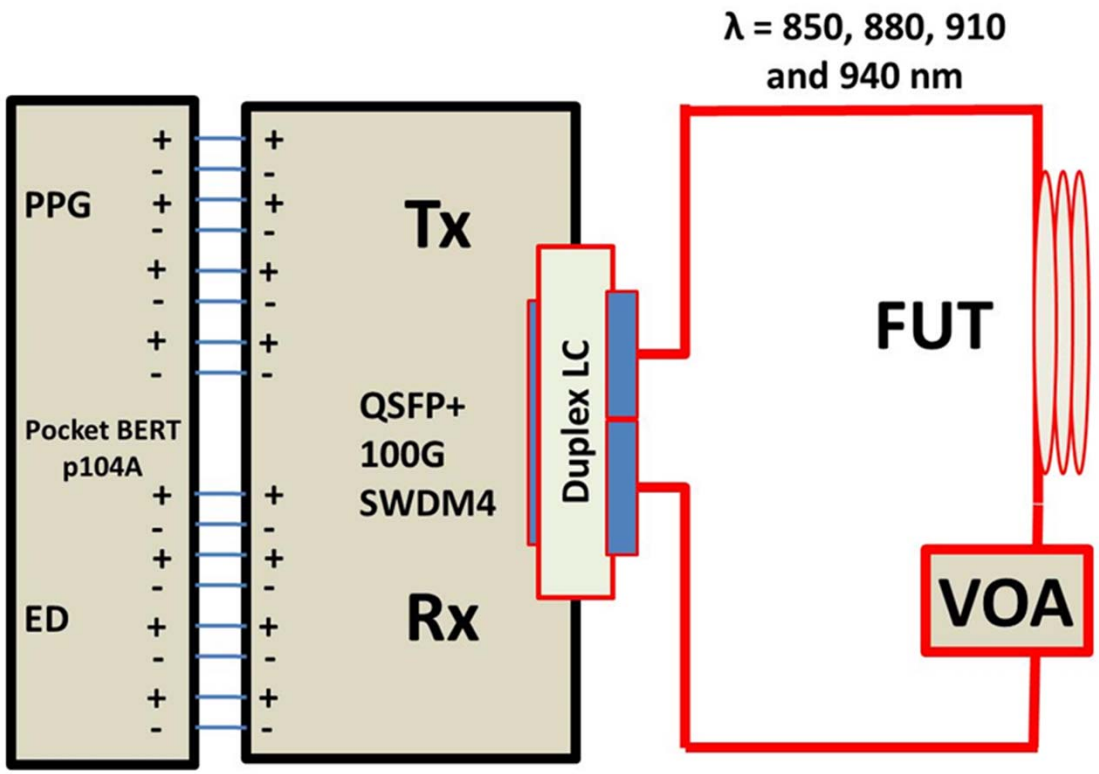
SWDM Alliance

- **SWDM Alliance**
  - Industry alliance to promote the use of SWDM technology
  - Create and promote an industry ecosystem that fosters adoption of SWDM for cost effective data center interconnections over duplex multimode fiber at or above 40 Gbps
  - The founding members of the SWDM Alliance are CommScope, Corning, Dell, Finisar, H3C, Huawei, Juniper, Lumentum, and OFS.

- **SWDM MSA**
  - Announced March 16, 2017
  - Defined optical specifications for four-wavelength SWDM to transmit 40 Gb/s and 100 Gb/s Ethernet signals ("40 GE SWDM4" and "100 GE SWDM4," respectively)

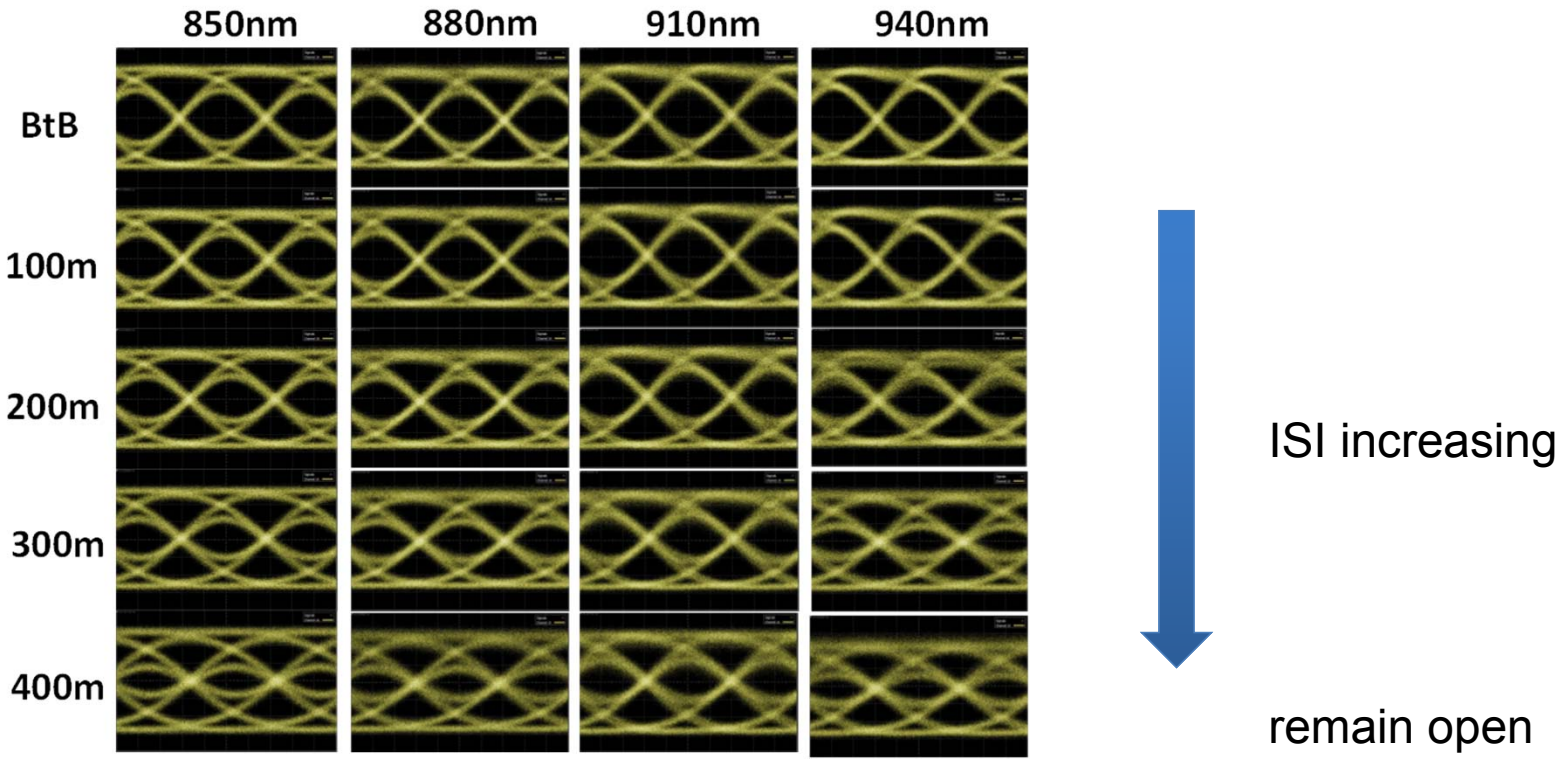
http://www.swdm.org/

4 x 25 G SWDM System Testing



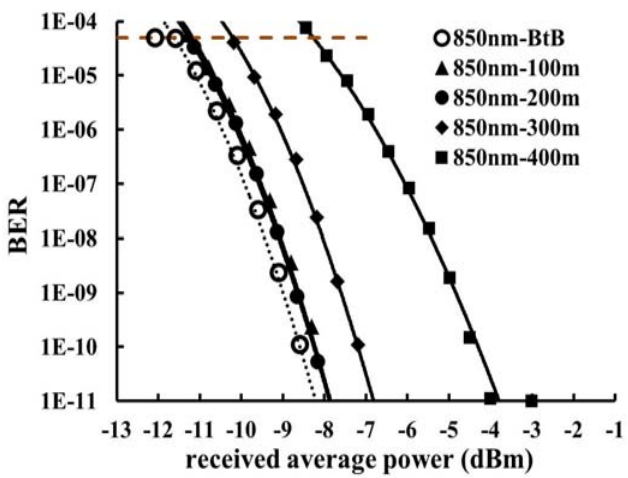
- 4 channels run simultaneously
  - 4 x 25.78 Gbps
  - PRBS 31
  - 850, 880, 910, 940 nm
- LaserWave *FLEX* Wideband Fiber
  - 100, 200, 300, 400 m
  - LC termination
- External cooling with a fan
- Transmitter characterization
  - RMS spectral width <0.6nm
  - EF meet IEEE802.3bm spec

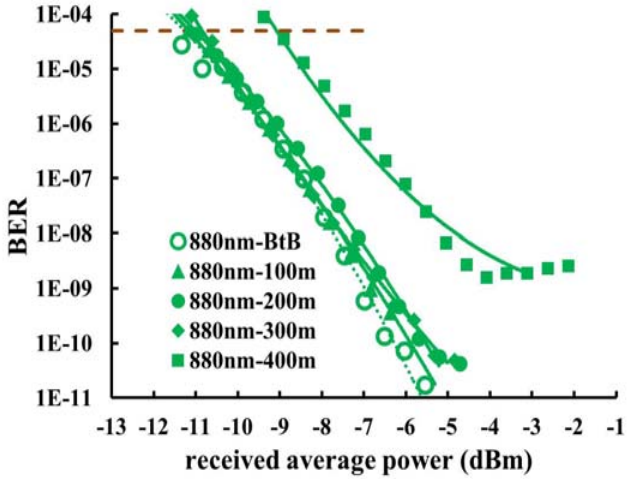
Optical Eyes: 100G SWDM over LaserWave *FLEX* Wideband Fiber

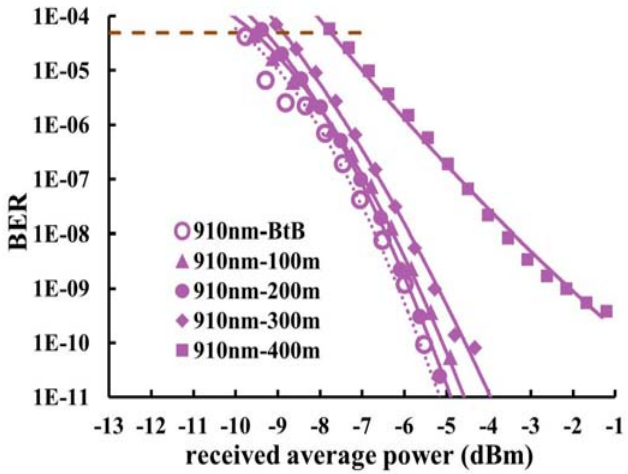


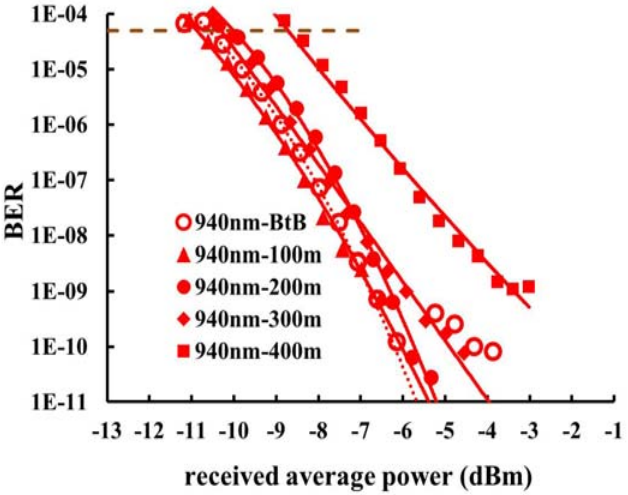
- NG-WBMMF F2 : 5500 MHz.km at 850 and 940 nm
- 100 G SWDM4 transceiver module #1

100G SWDM transmission over LaserWave *FLEX* Wideband Fiber







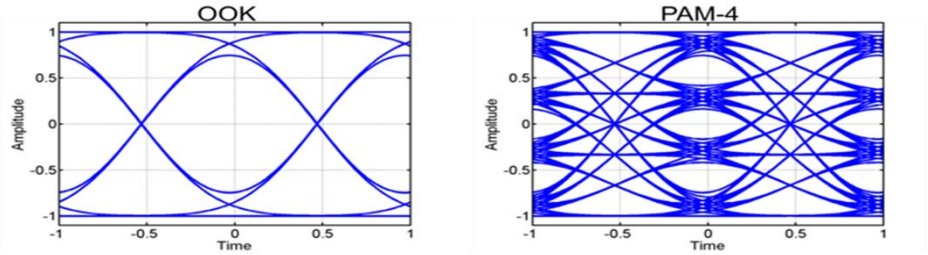


- **BER after 100 and 200m is barely increased from B2B results**
- **Pre-FEC BER : five orders better than 5×10^{-5} up to 300 m**

Multilevel signaling

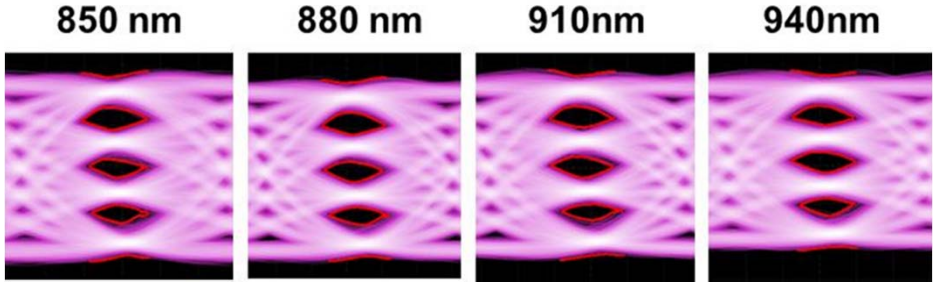
PAM-4 Signaling

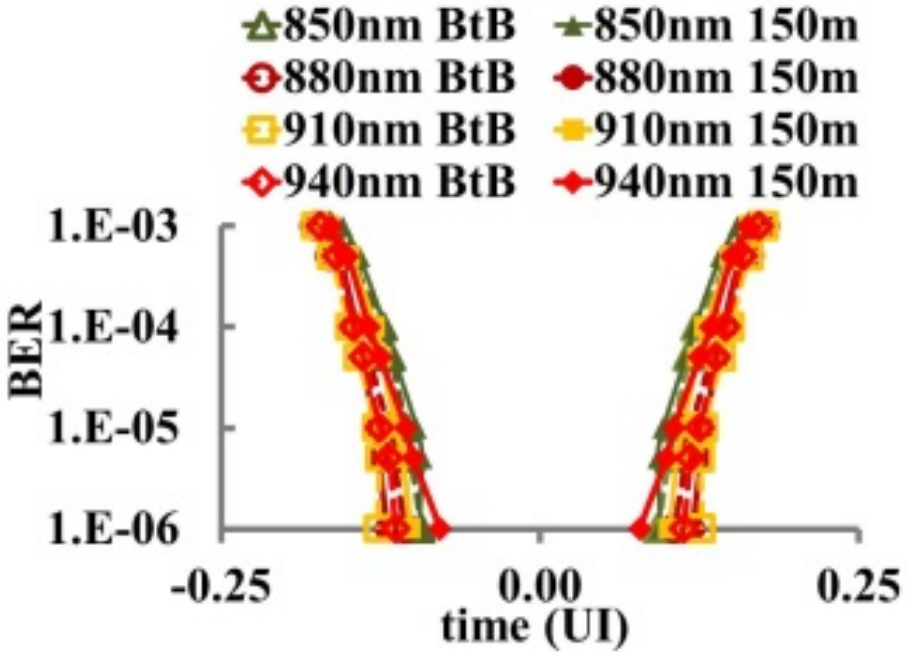
– Increases the bit rate 2x



- **Currently under discussion in IEEE and FC for next generation solutions**
  - Will leverage CWDM efforts to further expand fiber capacity
  - 50Gb/s/lane rates
- **Advanced modulation formats require higher receiver sensitivity than OOK**
  - Have to accommodate “multiple eyes” within same vertical interval
- **Receiver sensitivity requirements can be reduced via Equalization and/or FEC**

51.56 Gbps PAM4 Transmission over
LaserWave *FLEX* WideBand Fiber





Demonstrated capacity of 206 Gbps over a single multimode fiber!

Conclusions

- Bandwidth demands continue to grow, and application speeds are increasing to support those needs.
- OM5 is maturing rapidly
  - Fiber standardization is complete in TIA and IEC
  - Cable standardization is complete in TIA and technical work is complete in ISO
- Multilevel signaling work is underway at transceiver vendors
  - Proprietary solutions are available today
  - Path to 50G lanes and beyond
  - Next generation standards will leverage SWDM to further expand capacity