What's New in Short Reach Optical Links?

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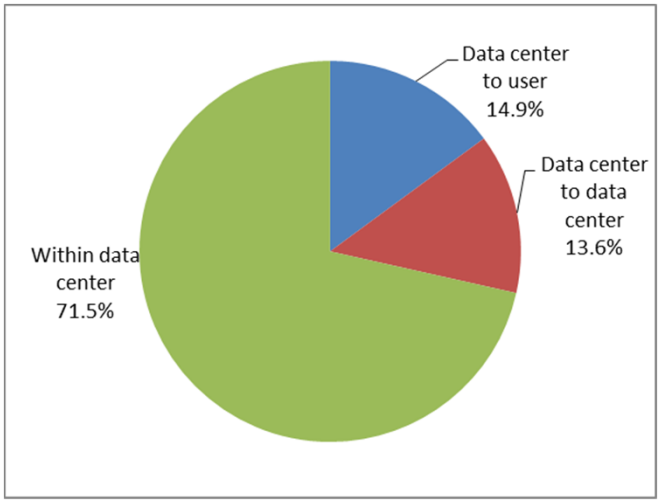
IP Traffic Growth

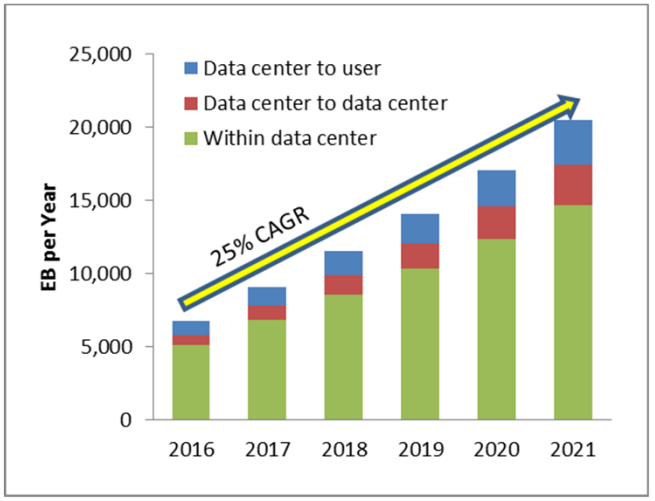
Year	Global Internet Traffic
1992	100 GB per day
1997	100 GB per hour
2002	100 GB per second
2007	2,000 GB per second
2017	46,600 GB per second
2022	150,700 GB per second

- Trends driving growth in the future
  1. Growth in mobile-to-mobile devices (smart meters, video surveillance, healthcare monitoring, transportation, and package or asset tracking)
  2. Smartphone growth and increased video usage, coupled with higher definition video
  3. IoT connectivity, including mobile-to-mobile applications
  4. Application traffic growth, driven by video

Cisco Visual Networking Index:
Forecast and Methodology, 2017-2022
November 26, 2018

Data Center Traffic



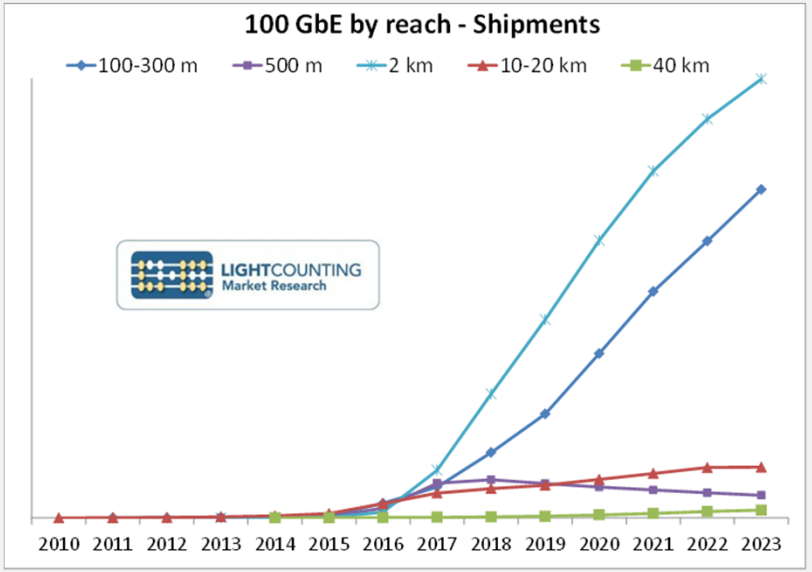


Source: Cisco Global Cloud Index: Forecast and Methodology, 2016-2021 January 2018

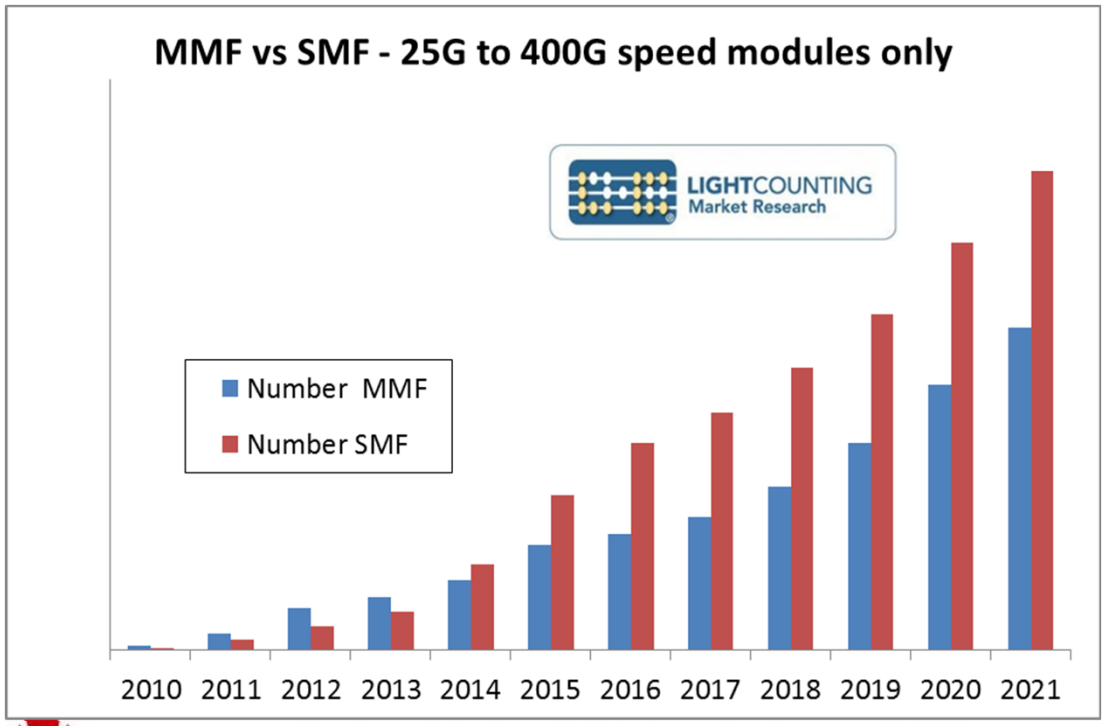
- Global data center traffic will reach 20.6 Zettabytes in 2021, from 6.8 Zettabytes in 2016
- Total East-West traffic will be 85%
- Traffic is growing at a 25% CAGR

100 GbE
Strong growth for 100GbE SR4

- LightCounting 100GbE QSFP28 consumption:
  - Currently, data centers utilizing 100G switching are primarily Cloud DCs and some leading-edge enterprise DCs.
  - A significant portion of these early adopters are utilizing 100GBASE-SR4 solution
- LightCounting predicts strong 100GbE growth from 2018 to 2023
- Uptake of 100GbE MMF modules portends need for 400GbE MMF modules in the future



Multimode transceivers – continued growth



- Multimode transceiver shipments continue to grow throughout the period
  - Note: This only includes high speed (≥ 25 Gb/s) transceivers
- Singlemode shipments also show growth

Latest Developments

Multimode Fiber Types

Multimode

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

	Industry Standards					Attenuation - Typical Cabled Max. (dB/km)		Bandwidth (MHz-km) Overfilled Launch (OMBc)		Bandwidth (MHz-km) Effective Modal Bandwidth (EMB) (also known as Laser BW)	
Fiber Type	**ISO/IEC 11801-1 Nov. 2017**	**IEC 60793-2-10 Aug. 2017**	**TIA-568.3-D Oct. 2016**	**TIA/EIA 492AAAx various**	**ITU-T Dec. 2008**	**850nm**	**1300nm**	**850nm**	**1300nm**	**850nm**	**953nm**
62.5/125	~~OM1~~	A1b	~~TIA-492AAAA (OM1)~~	492AAAA	---	3.5	1.5	200	500	---	---
50/125	~~OM2~~	A1a.1b[(1)]	~~TIA-492AAAB (OM2)~~	492AAAB	G.651.1	3.5	1.5	500	500	---	---
50/125	OM3	A1a.2b[(1)]	TIA 492AAAC (OM3)	492AAAC	---	3.0[(2)]	1.5	1500	500	2000	---
50/125	OM4	A1a.3b[(1)]	TIA 492AAAD (OM4)	492AAAD	---	3.0[(2)]	1.5	3500	500	4700	---
50/125	OM5	A1a.4b[(1)]	TIA 492AAAE (OM5)	492AAAE	---	3.0	1.5	3500	500	4700	2470

[(1)] *"b" designates Bend-Insensitive*
[(2)] *ISO/IEC 11801 has a max. cabled attenuation of 3.5dB/km*

ISO/IEC 11801-1	"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"

Single-Mode Fiber Types

Fiber Type	Industry Standards				Attenuation Typical Cabled Max. (dB/km)		
	ISO/IEC 11801 November 2017	IEC 60793-2-50	TIA/EIA	ITU-T	1310 nm	1385 nm	1550 nm
~~Std SM~~	~~OS1~~	~~B1.1~~	~~492CAAA~~	~~G.652.A or B~~	~~1.0~~	~~N.A.~~	~~1.0~~
Std SM	OS1a	B1.3	492CAAB	G.652.C or D	1.0	1.0	1.0
Low Water Peak SM	OS2[(1)]	B1.3	492CAAB	G.652.C or D	0.4	0.4	0.4

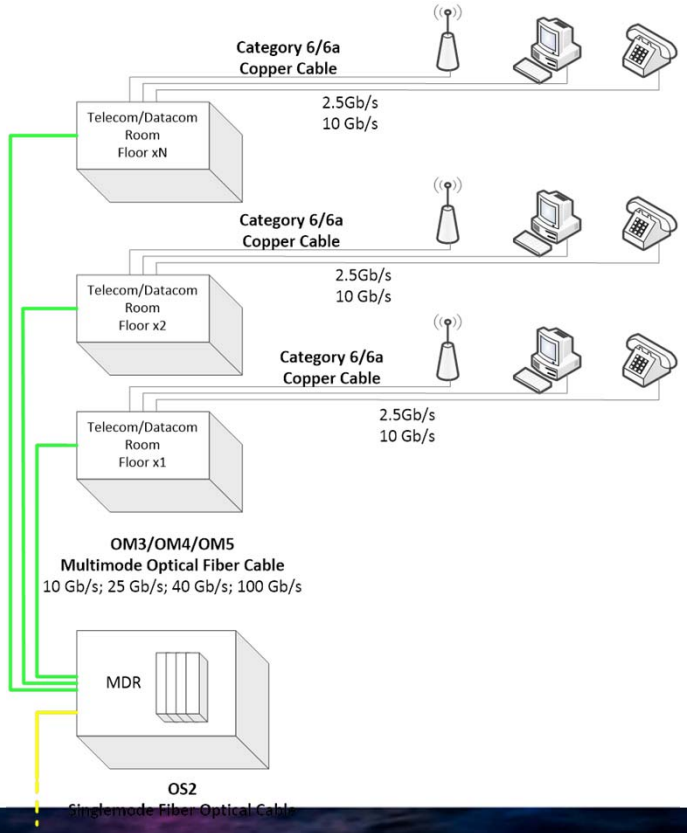
(1) OS2 is referenced in the standard **ISO/IEC 24702** *"Generic Cabling for Industrial Premises"*

IEC 60793-2-50 "Product Specifications - Sectional Specification for Class B Single-Mode Fibres"
TIA/EIA-492CAAA "Detail Specification for Class IVa Dispersion-Unshifted Single-Mode Optical Fibers"
TIA/EIA-492CAAB "Detail Specification for Class IVa Dispersion-Unshifted Single-Mode Optical Fibers with Low Water Peak"

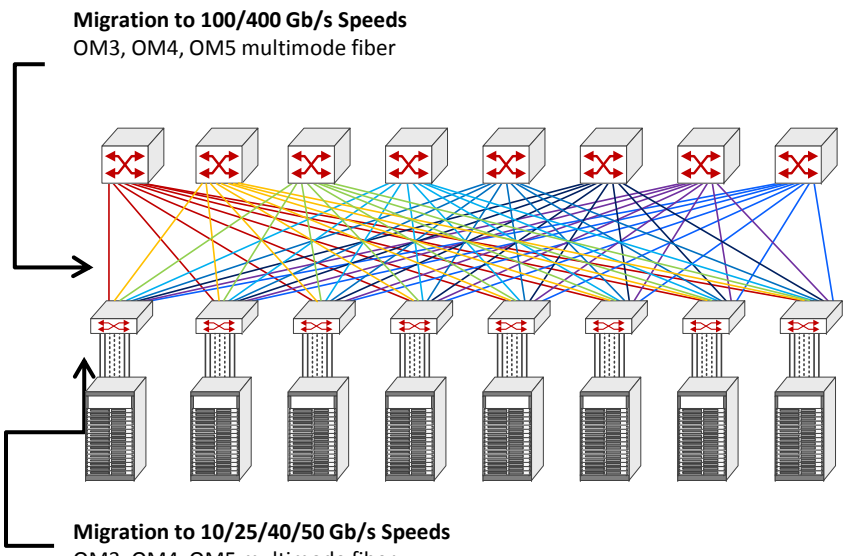
Application Space

Enterprise Local Area Network (LAN)

- Riser Backbone – Primarily 10 Gb/s, migration to 40/100 Gb/s speeds
- New construction and office retrofit
- OM3, OM4, and OM5 fibers are standards based solutions for LAN networks



Data Center



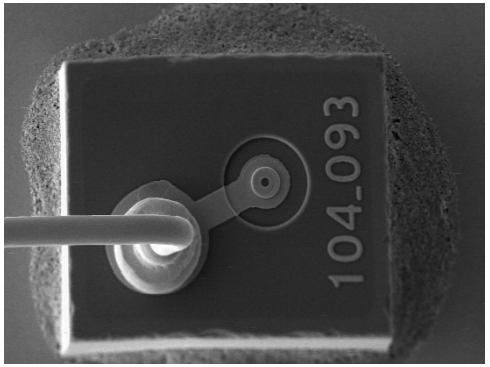
Why Multimode Fiber instead of Singlemode?
VCSEL-MMF links enjoy cost & power advantages

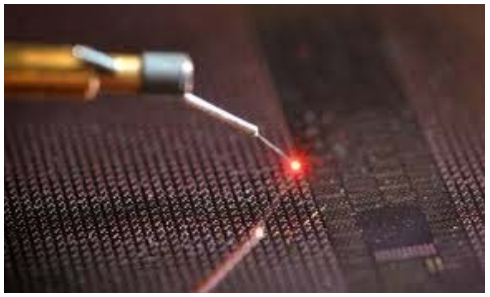
- Relaxed alignment tolerances (~10x) for laser, mux/demux, and connectors
- MMF connectors more resilient to dirt
- Lower drive currents (5-10mA vs. 50-60mA)

and on-wafer testing

- Benefits will persist when comparing 400G technologies for short reach
  - Gearbox function is needed to convert native 50G PAM-4 to 100G PAM-4 with DR4 & FR4
  - Laser RIN reduction for PAM-4 is as, or more, difficult for DFBs as VCSELs
  - Packaging for 1310nm sources at 100 Gb/s per lane PAM4 has required significant development

– All these combine to give multimode links a continued cost advantage over singlemode links

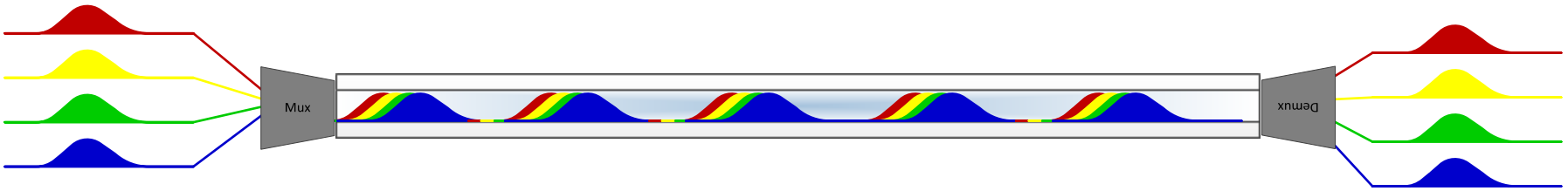




Why do we need a new multimode fiber? And why SWDM?

- 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

What can you do with LaserWave WideBand (OM5) Fiber?



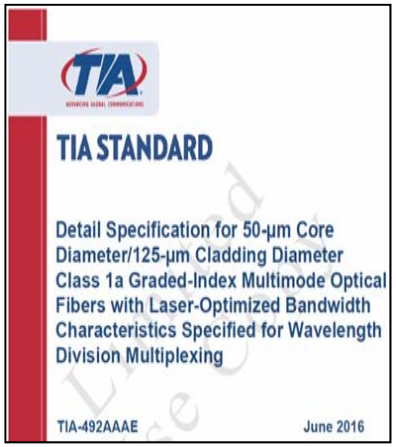
LaserWave WideBand Fiber enables DUPLEX fiber links to support 100Gb/s speeds on a single fiber using:

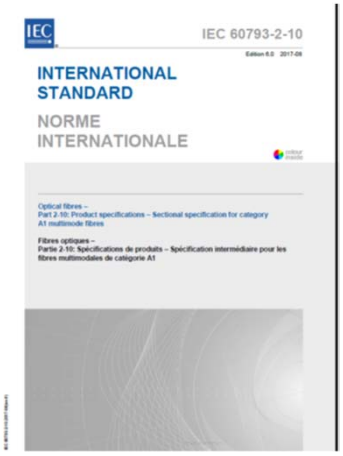
1. 2 wavelengths, each operating at 50Gbps
2. 4 wavelengths, each operating at 25Gbps

Wideband OM5 Standardization

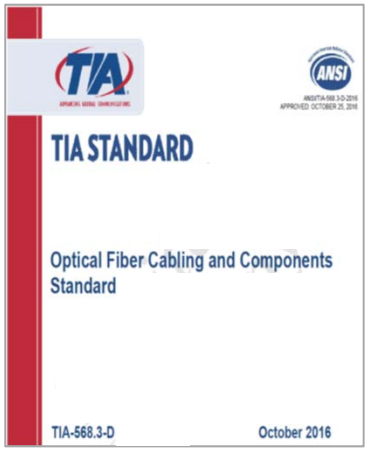
Improved performance with multiple wavelengths

- OM5 MMF extends the 850nm performance of OM4 out to 953nm
- Standards:
  - **Fiber:** TIA-492AAAE (2016), IEC 60793-2-10 ed. 6 (August 2017)
  - **Structured Cabling:** ANSI/TIA-568.3-D (2016), ISO/IEC 11801-1 (November 2017)





Fiber Standards



Structured Cabling Standards

Differences between OM4 and WideBand OM5 fiber

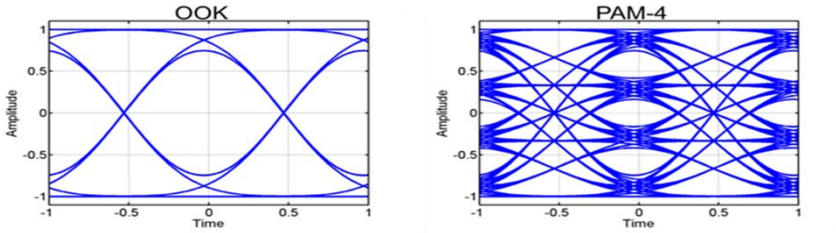
	OM4 Multimode Fiber	WideBand (OM5) Multimode Fiber
Zero Dispersion Wavelength	$1295 \le \lambda_o \le 1340$ nm	$1297 \le \lambda_o \le 1328$ nm
Zero Dispersion Slope	$S_0 \le 0.105$ ps/nm^2·km for $1295 \le \lambda_o \le 1310$ nm, and $\le 0.000375(1590-\lambda_o)$ ps/nm^2·km for $1310 \le \lambda_o \le 1340$ 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

OM5 fiber field testing

- No additional field testing required for OM5 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

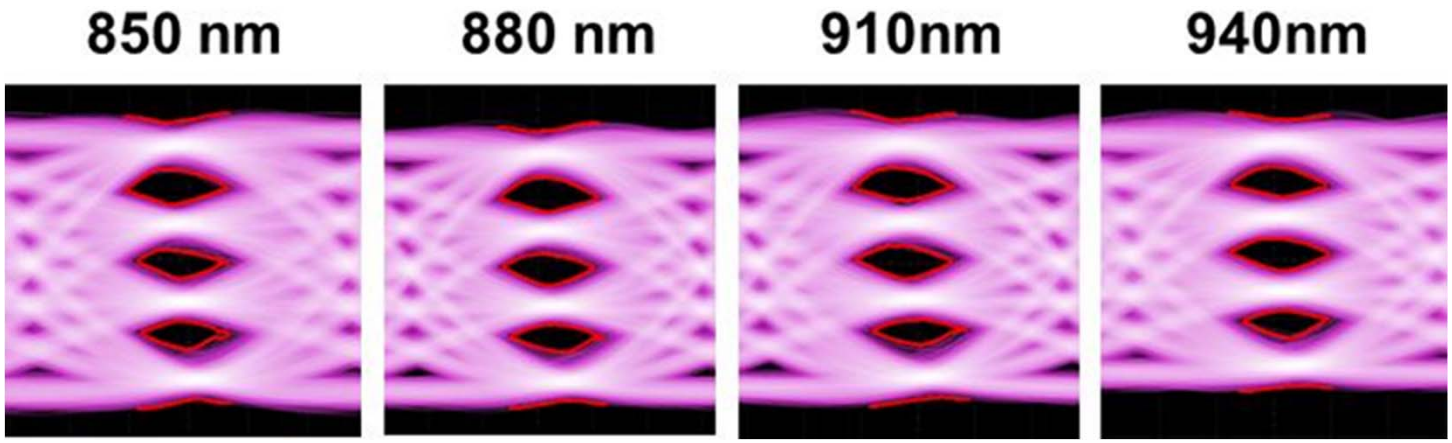
Multilevel signaling

- PAM-4
  - Increases the bit rate 2x



- **Currently in IEEE and FC discussion for next generation solutions**
  - Would leverage CWDM efforts to further expand fiber capacity
  - Enables 50Gb/s/lane rate
- **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**

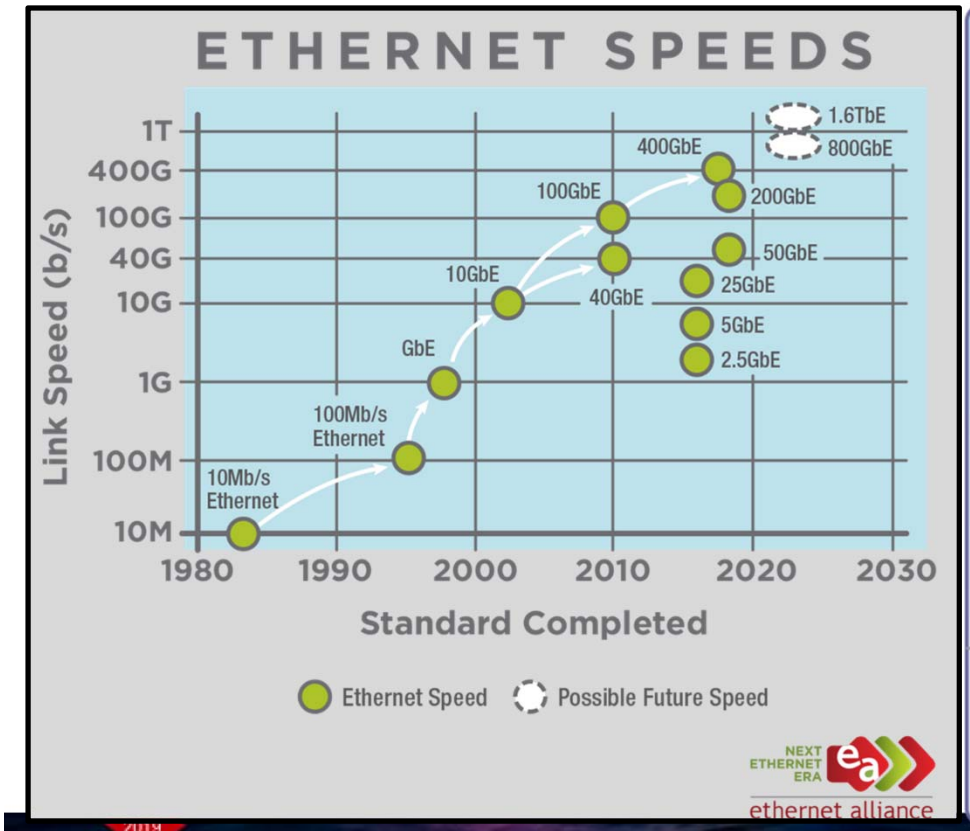
51.56 Gbps PAM4 Transmission over LaserWave WideBand (OM5) Fiber

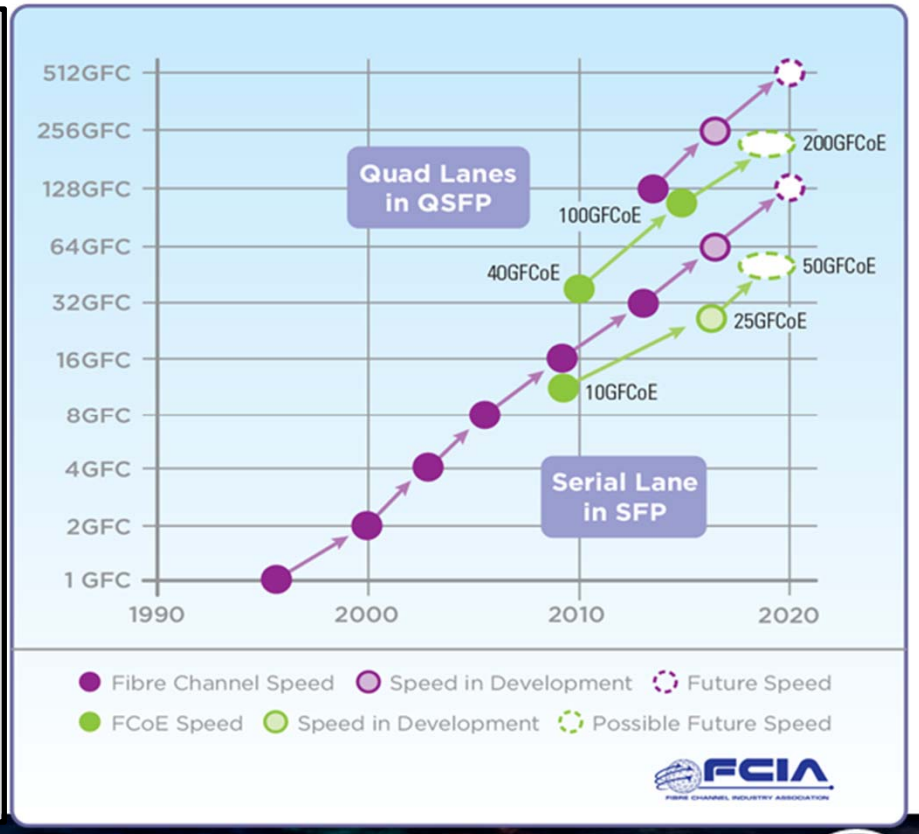


Demonstrated capacity of 206 Gbps over a single multimode fiber!

Applications Roadmap

Evolution of Short Reach Applications





Latest Ethernet Standards

40G & 100G Ethernet (IEEE 802.3ba)

PMD	Link Distance	Fiber Count and Media Type	Technology
40GBASE-SR4	100 m OM3 150 m OM4	8-f MMF (12-f MPO)	4x10G parallel NRZ 850nm
40GBASE-eSR4 (extended reach)*	300 m OM3 400m OM4	8-f MMF (12-f MPO)	4x10G parallel NRZ 850nm
40GBASE-LR4	10 km	2-f SMF	4x10G CWDM NRZ 4 wavelengths around 1300nm
100GBASE-SR10	100 m OM3 150 m OM4	20-f SMF (24-f MPO)	10x10G parallel NRZ 850 nm
100GBASE-LR4	10 km	2-f SMF	4x25G CWDM NRZ 4 wavelengths around 1300nm
100GBASE-ER4	40 km	2-f SMF	4x25G CWDM NRZ 4 wavelengths around 1300nm

Published in 2010

*non-standard solution

40G & 100G Ethernet (IEEE 802.3bm)

PMD	Link Distance	Fiber Count and Media Type	Technology
40GBASE-ER4	30 km (40 km engineered link)	2-f SMF	4x10G CWDM NRZ 4 wavelengths around 1300nm
100GBASE-SR4	70 m OM3 100 m OM4	8-f MMF (12-f MPO)	4x25G parallel NRZ 850 nm
100GBASE-eSR4 (extended reach)*	200-300 m OM3 300-400 m OM4	8-f MMF (12-f MPO)	4x25G parallel NRZ 850 nm

Published in 2015

*** non-standard solution**

25 Gb/s Ethernet (IEEE 802.3by)

PMD	Link Distance	Fiber Count and Media Type	Technology
25GBASE-SR	100 m OM4	2-f MMF	1x25G NRZ

Published July 2016

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

Published Dec. 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

Published Jan. 2018

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

Approved IEEE Standards Board Dec. 2018

LC Duplex SWDM transceivers

				Link Distance		
Speed	Transceiver	Form Factor	λ	OM3	OM4	OM5
40Gb/s	BiDi	QSFP+	2	100	150	200
40Gb/s	SWDM4	QSFP+	4	240	350	440
100Gb/s	BiDi	QSFP28	2	70	100	150
100Gb/s	SWDM4	QSFP28	4	75	100	150
100Gb/s	eSWDM4*	QSFP28	4	200	300	400

* Announced

SWDM Multi-Source Agreement (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/msa/

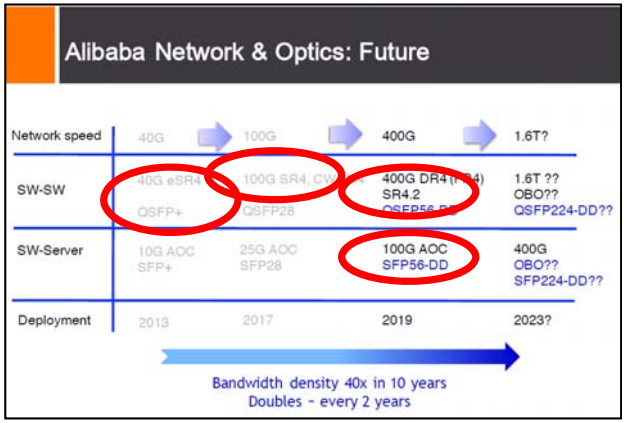
400G BiDi MSA

- Announced July 9, 2018
- Define “optical data link specifications and promoting adoption of interoperable 100 Gb/s and 400 Gb/s optical transceivers for 100 meter link distance based on a dual wavelength bidirectional transmission technology in multi-mode optical fiber (MMF).”
- Reach
  - 70m OM3
  - 100m OM4
  - 150m OM5
- Specification published September 1, 2018
- https://www.400gbidi-msa.org/

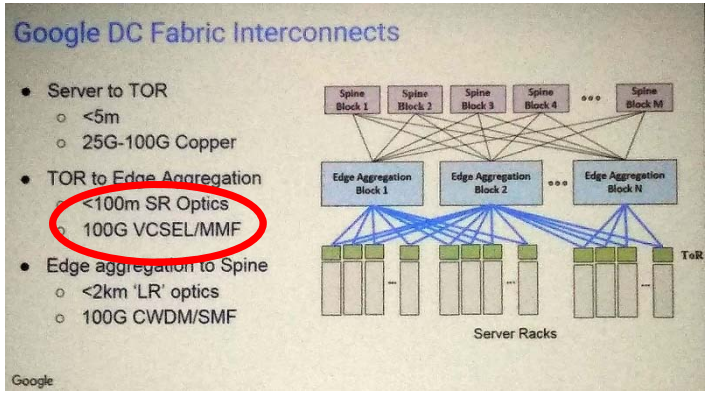
Latest Ethernet Developments

The hyperscale cloud market will continue to deploy multimode fiber!

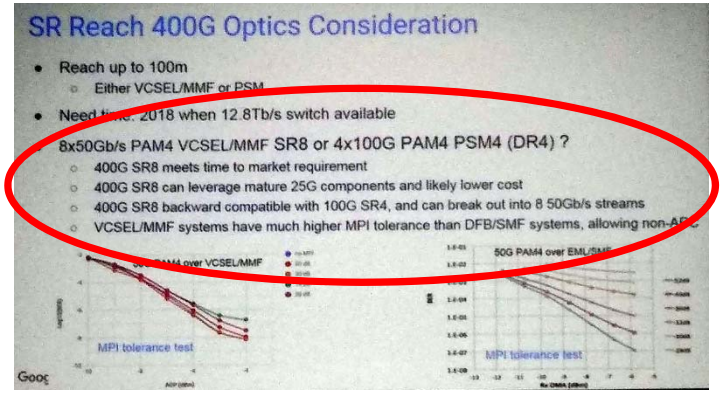
- Google
  - Deploying 100GBASE-SR4
  - Roadmap to 400GBASE-SR8
  - Z. Shen of Google proposed 400GBASE-SR8 for 802.3cm
- Alibaba
  - Deploying 100GBASE-SR4
  - Roadmap to 400GBASE-SR4.2
- Baidu
  - Deploying 100GBASE-SR4
  - Roadmap to 400GBASE-SR4.2
- Other Big Cloud in US
  - Growing interest for 400G-SR4.2, including breakout



C. Xie, Alibaba OIF Q4 2018 Shanghai



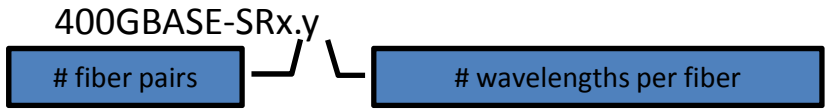
C. Gang, Baidu, 2018 Optinet, Shanghai



400 Gb/s Ethernet (IEEE 802.3cm)

PMD	Link Distance	Fiber Count and Media Type	λ	Connector Interface	Optical Modulation
400GBASE-SR8	100 m OM4/OM5	16-f MMF	1 850nm	16-f MPO (1 row) 24-f MPO (2 row)	50G PAM-4
400GBASE-SR4.2	100 m OM4 150 m OM5	8-f MMF	2 850/910nm Bi-Directional	12-f MPO (1 row)	50G PAM-4

- Task Force Approved - May 2018
- 400GBASE-SR8 Baseline adopted – May 2018
- 400GBASE-SR4.2 Baseline adopted – July 2018
- Draft 1.0 – October 2018
- Target completion – December 2019



IEEE P802.3cm MMF Task Force is working quickly

- Consensus developed in New Ethernet Applications (NEA) Ad Hoc meetings over ~ 1 year
- Call-for-interest at November IEEE 802 Plenary to consider next-gen 200 & 400 Gb/s links; a Study Group was approved by 802.3 Working Group
- IEEE P802.3cm Task Force first met in May to begin selecting baseline proposals; next meeting in July
  - 400GBASE-SR8 Baseline adopted – May, 2018
  - 400GBASE-SR4.2 Baseline adopted – July, 2018
- Draft 2.0 released to 802.3 working group ballot stage - March 2019

400GBASE-SR4.2

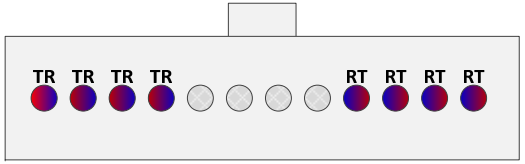
- First standards based application using wavelength division multiplexing (WDM)
  - Takes advantage of Wideband OM5 fiber
    - Baseline adopted with reach objectives
      - 70m OM3
      - 100m OM4
      - 150m OM5
- Two wavelength solution
- New nomeclature
  - SRx.y
    - X – number of fibers
    - Y – number of wavelengths
- Standard 12-fiber MPO connector interface, using 8 active fibers

– Proprietary/MSA solutions currently available for 40/100G WDM duplex links

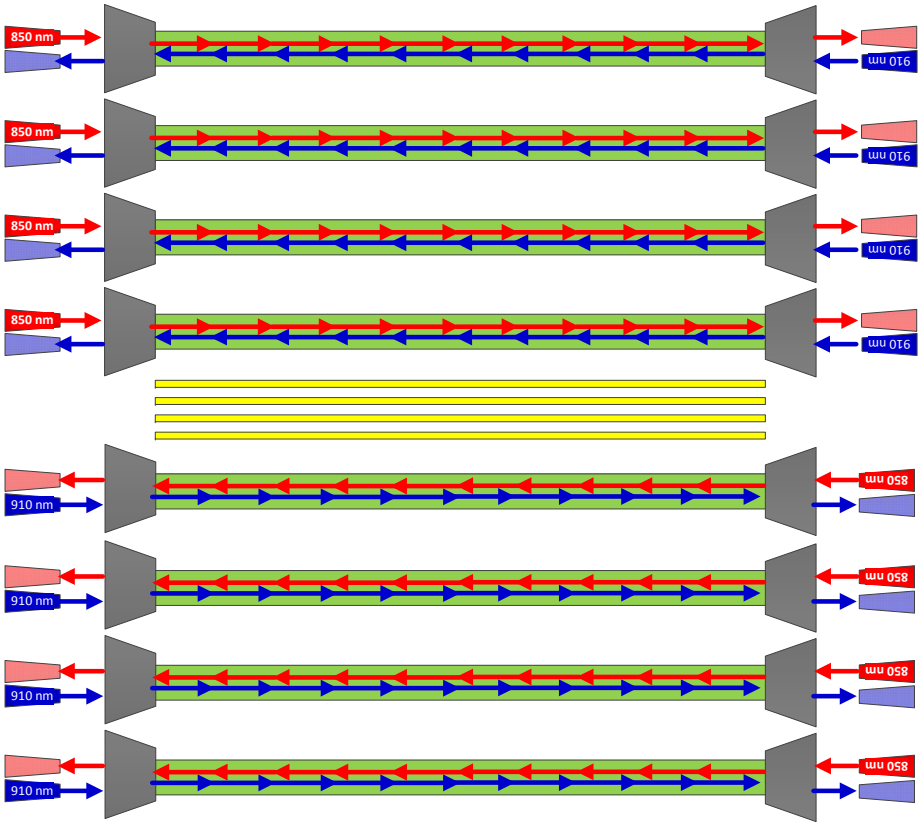
400GBASE –SR4.2

400Gb/s Bi-Directional Transmission

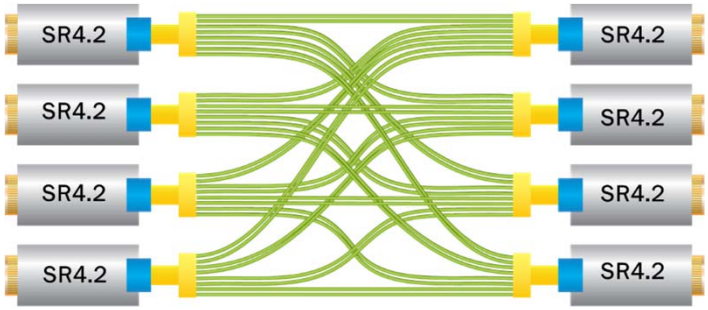
- Uses same 4-pair infrastructure implemented for 40GBASE-SR4 and 100GBASE-SR4
  - 12-fiber MPO interface

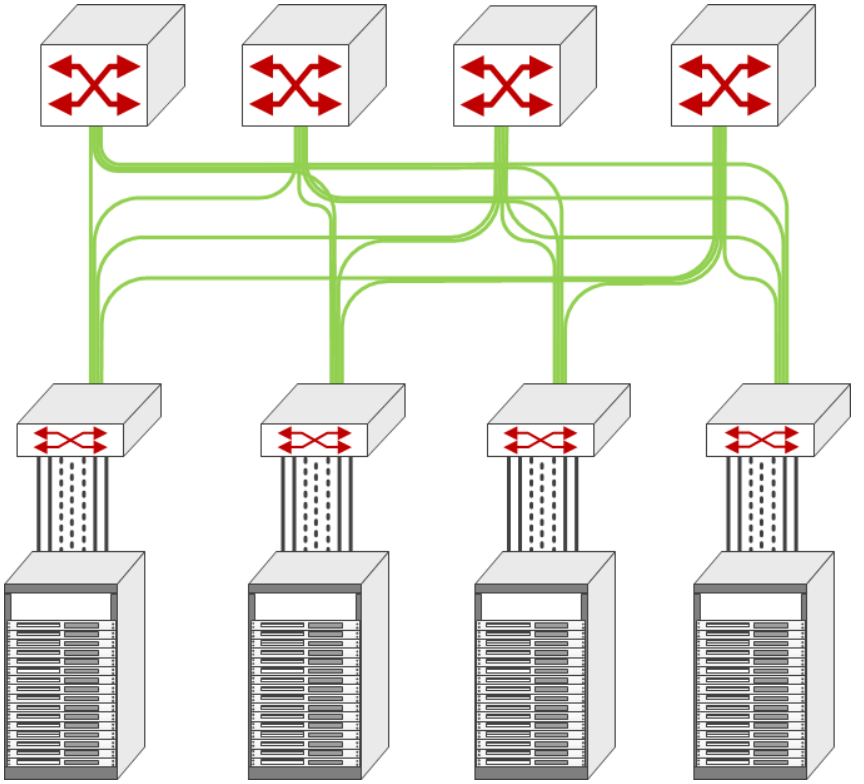


- Operates at two different wavelengths
  - 850nm
  - 910nm



400GBASE-SR4.2 Shuffle Application

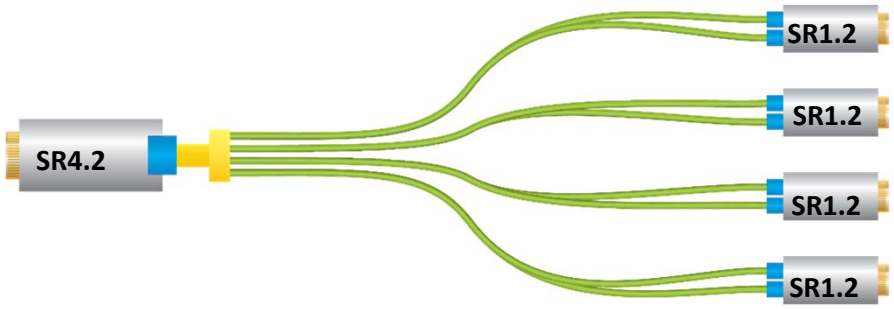


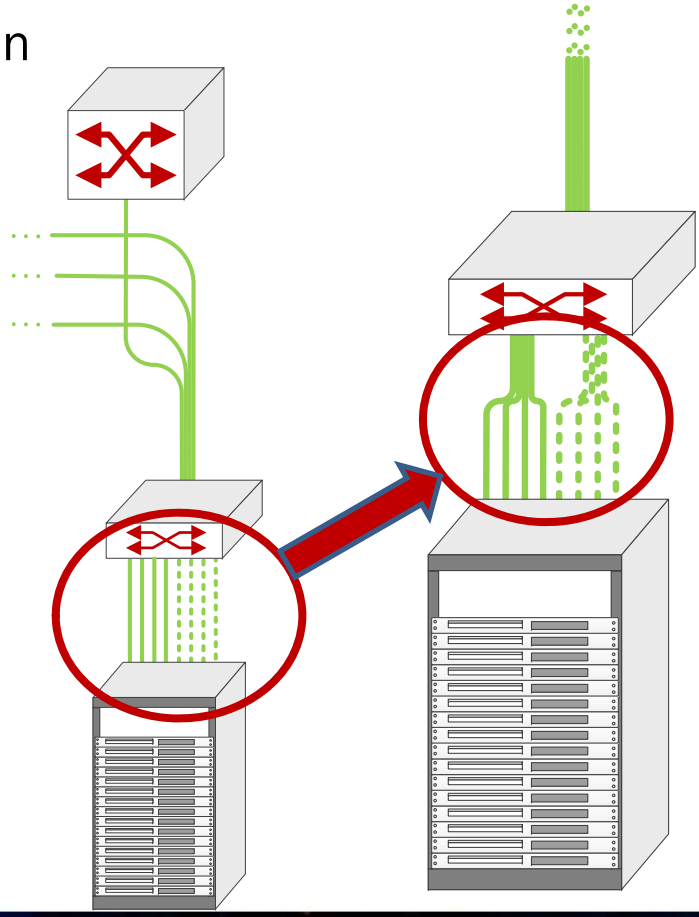


Data Center Switch Matrix

- 4x400Gb/s Modules
- 4x switch faceplate density
  - Replaces four 100Gb/s modules with one 400Gb/s module
- Replace 16 separate cable assemblies with a single shuffle matrix
- Note: Shuffle application is not limited to the speeds noted above

400GBASE-SR4.2 Fanout Application



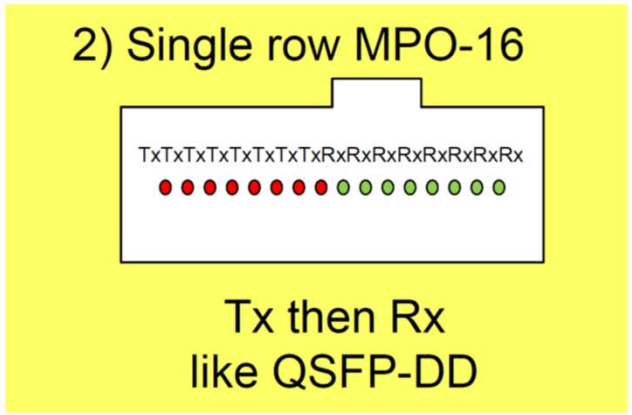


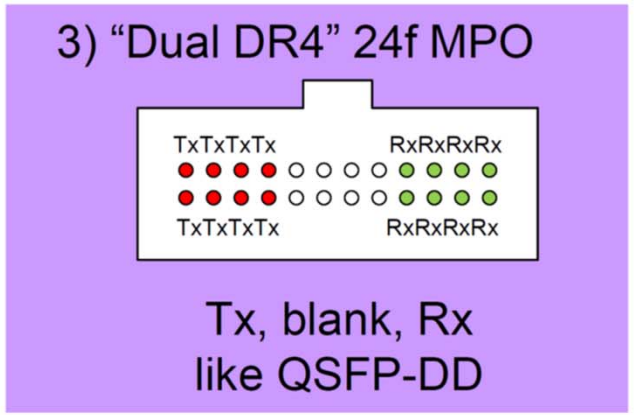
Switch – Server Links

- 400Gb/s module - breakout to 4 x 100Gb/s modules
- 4x switch faceplate density
  - Replace 4 100Gb/s modules on switch with 1 400Gb/s module
- Replace 4 separate cable assemblies with a single shuffle matrix
- Applications are not limited to the speeds above

400GBASE-SR8

- Two connector choices (Media Dependent Interfaces [MDIs]):



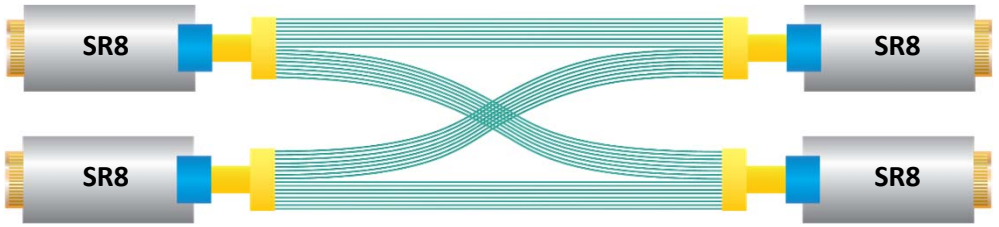


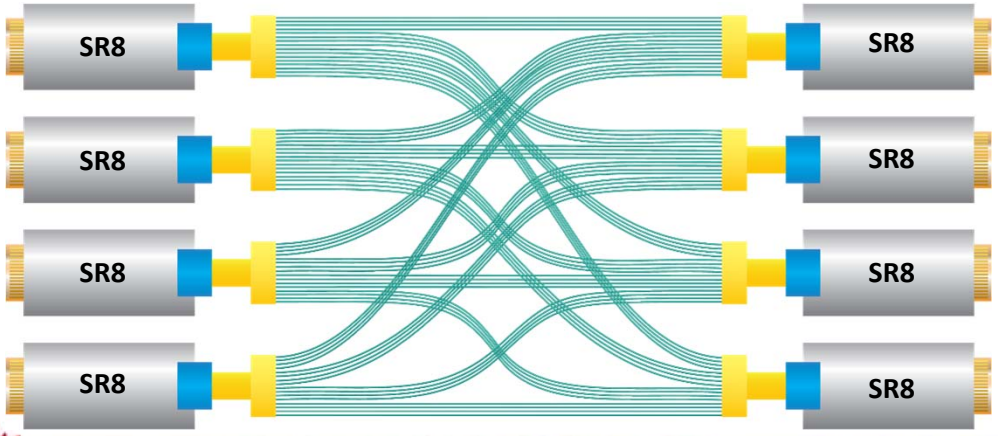
- Used in breakout, shuffle, and point-to-point applications
  - Breakout – 50 or 100Gb/s links to server
  - Shuffle – switch to switch links to decrease switch port counts
  - Point to Point – switch to switch links

400GBASE-SR8

[Left] SR8 point-to-point link

[Right] 2 x 2 fiber shuffle allows a 32-port 400G switch to be used as 64 port 200G switch



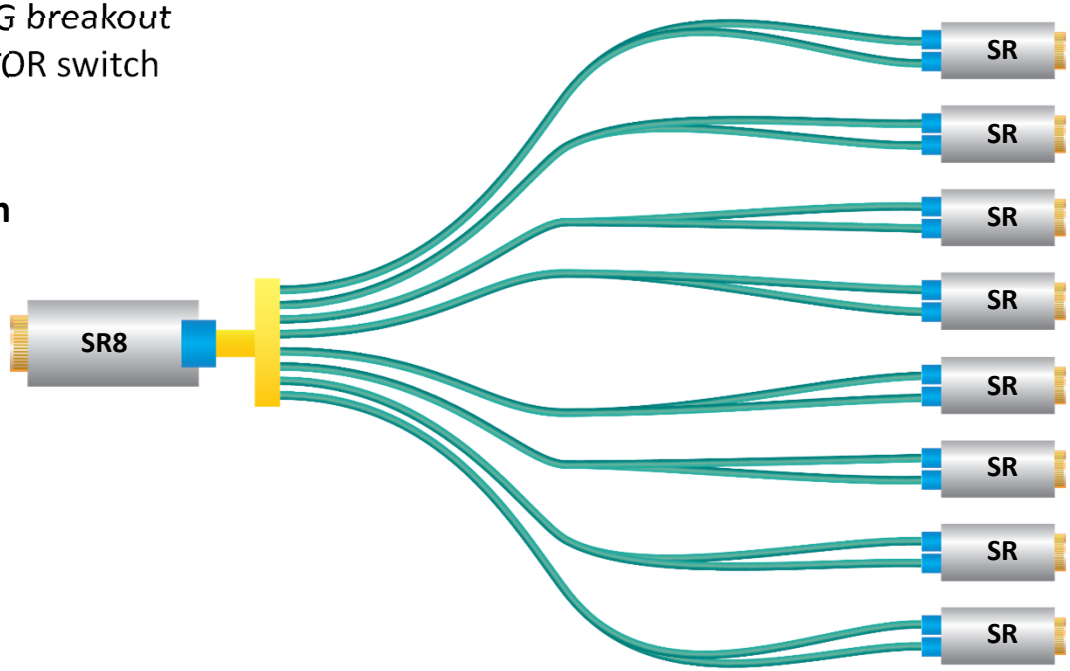


[Left] 4 x 4 fiber shuffle allows a 32-port 400G switch to be used as 128 port 100G switch

400GBASE-SR8 breakout

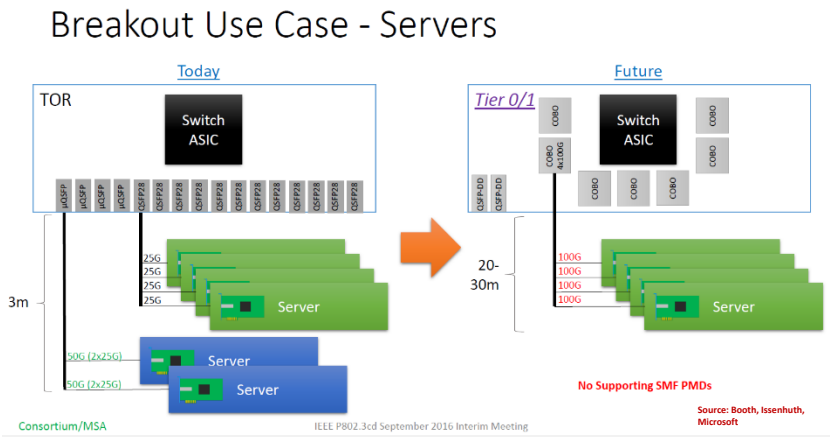
[Right] SR8 module shown in 8 x 50G *breakout* mode to connect a 400G port on a TOR switch to 8 x 50G server ports

May be short reach AOC application



Next Generation: 100 Gb/s VCSELs
Possible next steps

- VCSEL/MMF-based links are expected to evolve to 100 Gb/s PAM4 (50 Gbaud PAM4) VCSELs in the 2021 timeframe
- Will initially support short-reach server interconnects in a 30 m 800GBASE-SR8 breakout application
- 100 m switch links will follow
  - 100m MMF 800G-SRx.y based on 100G optical modulation



VCSEL-based links over MMF will continue to evolve

- 100 Gb/s VCSELs expected in 2021 – will initially support short-reach server interconnects

Data Rate	Ethernet Standard or Proprietary Module	# pairs	# λ's	Optical Modulation	OM3	OM4	OM5
100	100GBASE-SR4	4	1	25G NRZ	70	100	Same
100	100G – SWDM4	1	4	25G NRZ	75	100	150
100	100G – BiDi	1	2	50G PAM4	70	100	150
400	400GBASE-SR16	16	1	25G NRZ	70	100	Same as OM4
50	50GBASE-SR	1	1	50G PAM4	70	100	
100	100GBASE-SR2	2	1	50G PAM4	70	100	
200	200GBASE-SR4	4	1	50G PAM4	70	100	
400	**400GBASE-SR8**	**8**	**1**	**50G PAM4**	**70**	**100**	
400	**400GBASE-SR4.2**	**4**	**2**	**50G PAM4**	**70**	**100**	**150**
800	**800GBASE-SR8**	**8**	**1**	**100G PAM4**	**30m over MMF**		
4/800	**4/800GBASE-SRm.n**	**4/8**	**TBD**	**100G PAM4**	**100m over MMF**		

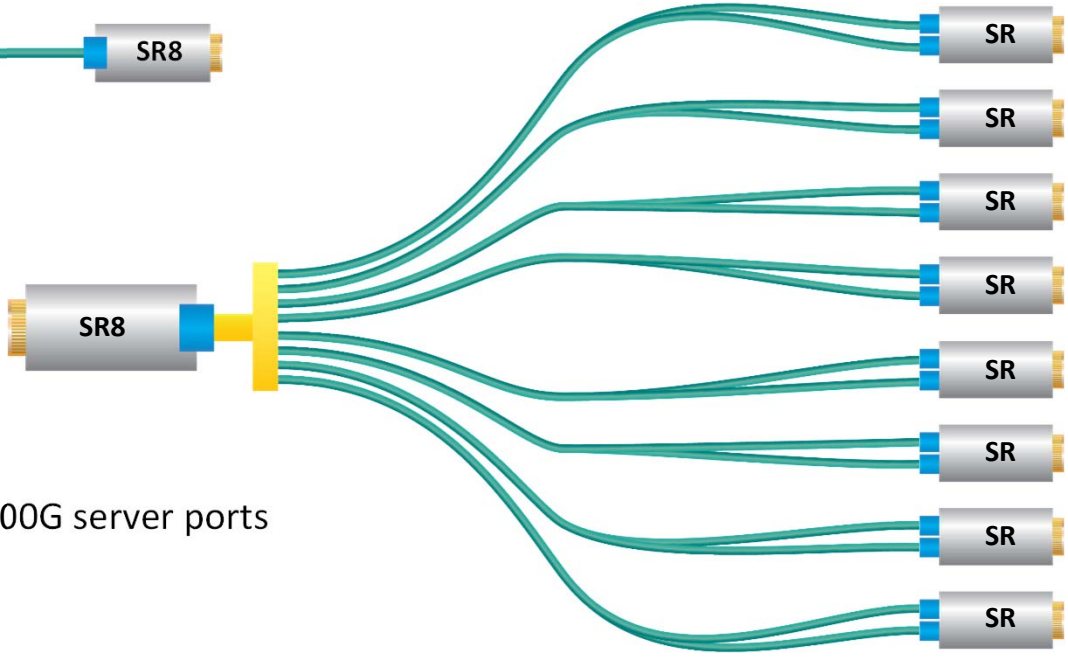
≤ 30m breakout to server will be first use of 100G/lane VCSELs

Existing transceiver types; Objectives in standardization (proposed values); Projected future technology (anticipated values)

800GBASE-SR8

- First application of 100G VCSELs in ~2021 - 8-way breakout capability to 100G servers

[Above] SR8 point-to-point link



[Right] SR8 breakout -
800G switch port connected to 8 x 100G server ports

Latest Fibre Channel Standards

64GFC – FC-PI-7

Variant	Link Distance	Fiber Count and Media Type	Technology
64GFC	100 m OM4/OM5	2-f MMF	PAM-4
64GFC	10 km	2-f SMF	PAM-4

- Will become a standard June 2019
- Split off 256GFC in September 2017 – separate document

256GFC – FC-PI-7P

Variant	Link Distance	Fiber Count and Media Type	Technology
256GFC	100 m OM4/OM5	8-f MMF	PAM-4

- New project initiated October 2017 – split from FC-PI-7
- Latest proposal February 2019 was to only include multimode reach from FC—PI-7
  - If this is approved, will be done as amendment to FC-PI-7 – no separate FC-PI-7P

128GFC - FC-PI-8

- FC-PI-8/128GFC (serial)
  - Project approved in April, 2018
  - backward compatible with 32GFC/64GFC
  - 100 m reach for OM5/OM4
  - Target technical stability date of 2021 and product availability of 2022
  - Key technical challenges:
    - technical feasibility of 100 Gb/s VCSELs within targeted project completion dates
    - meeting backplane loss budget and handling host PCB loss

Conclusions

- Bandwidth demands continue to grow, and application speeds are increasing to support those needs.
- OM5 standardization effort is complete.
- New 400 Gb/s multimode applications are being standardized
  - 400GBASE-SR8
  - 400GBASE-SR4.2
- 100Gb/s VCSEL based solutions are in the future!