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June 25-29, 2017 • Las Vegas, NV

High Speed Optics for Data Center Fabric & Optical Transport

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BRKOPT-2116

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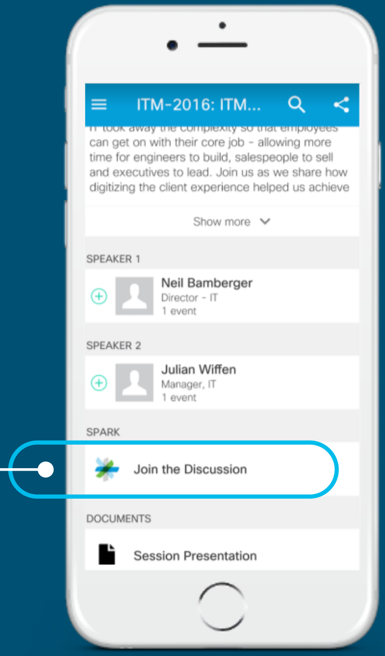

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Cisco Spark spaces will be available until July 3, 2017.

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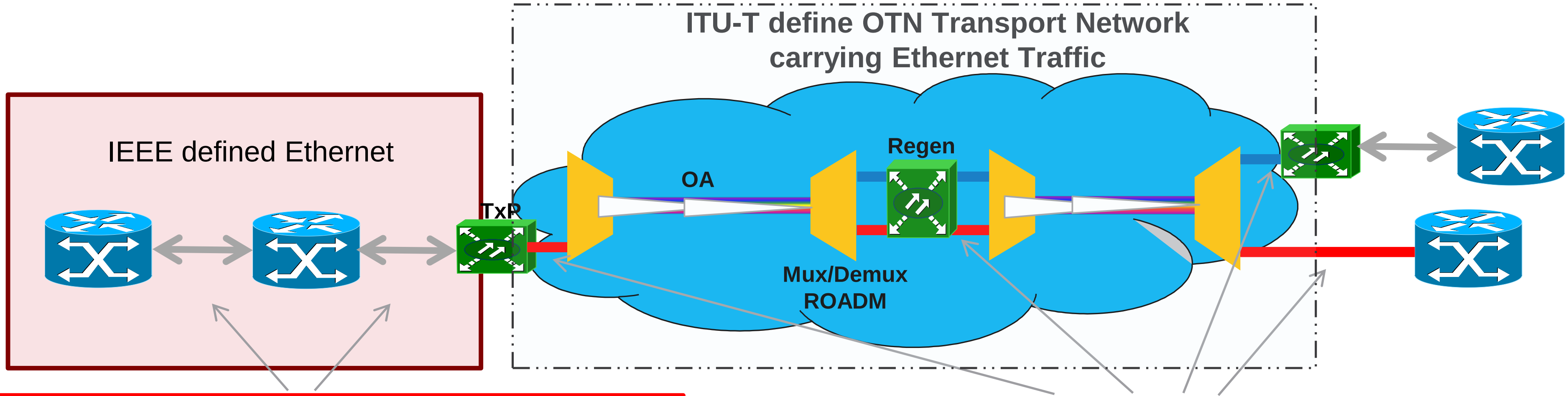
Agenda

- Introduction
- Industry and Market Trends
- Industry Standards
- Client Side Optics - Technologies
- Line Side Optics -Technologies
- Conclusion

Setting the stage......



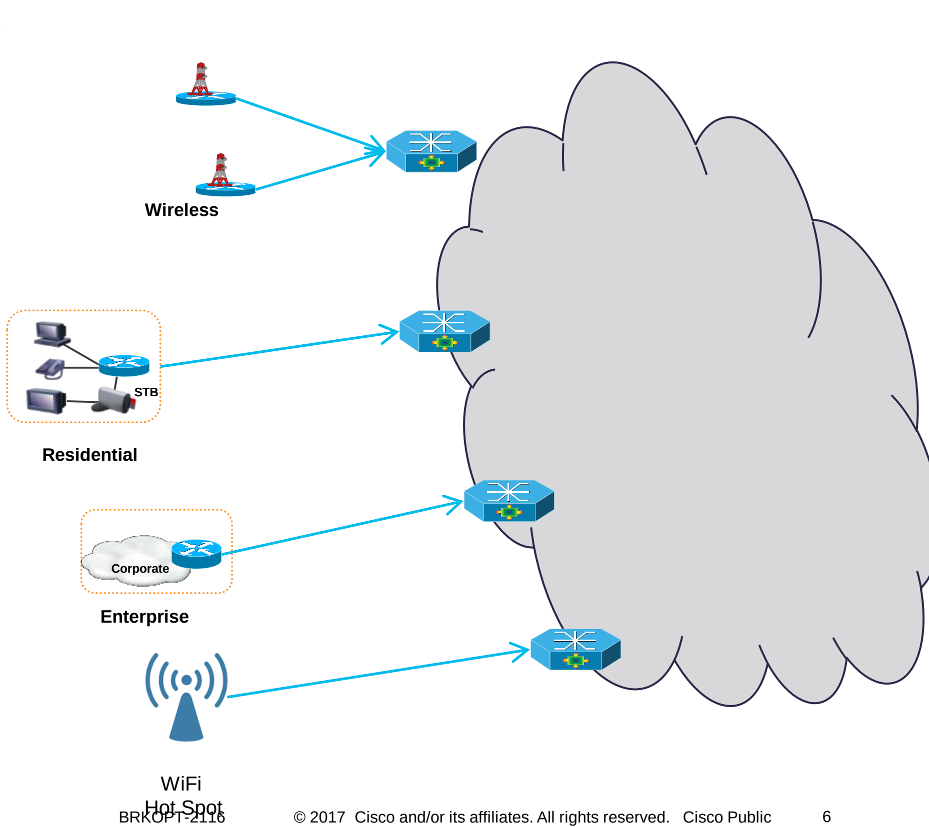
DC & Client Optics

- Within a building or campus or city
- Grey optics
- Ethernet
- **Solve for Cost, Power, Density**

Line Optics

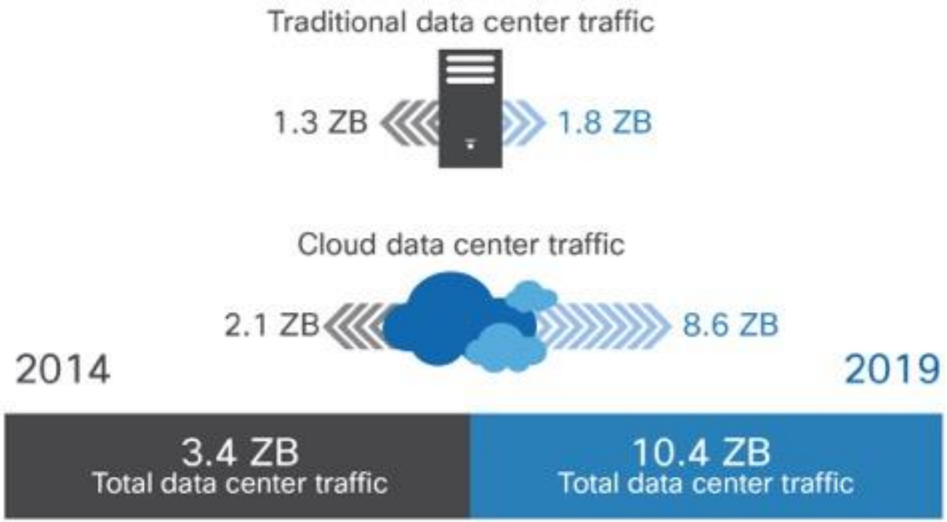
- Across country (a few hundred to 1000s km)
- Multiple channels / Fiber (DWDM)
- OTN
- **Solve for Spectral efficiency and Performance**

Last Mile Connectivity and Applications that Drive Traffic



Growth in the Cloud

By 2019, 83% of global data center traffic come from cloud services and applications



18% of traffic between datacenters & end users

9% between data centers for replication & inter-database links

73% will be coming from within the datacenter, storage, production, development and authentication traffic

1 zetabyte is trillion gigabytes

Industry Trends

Ethernet Roadmap

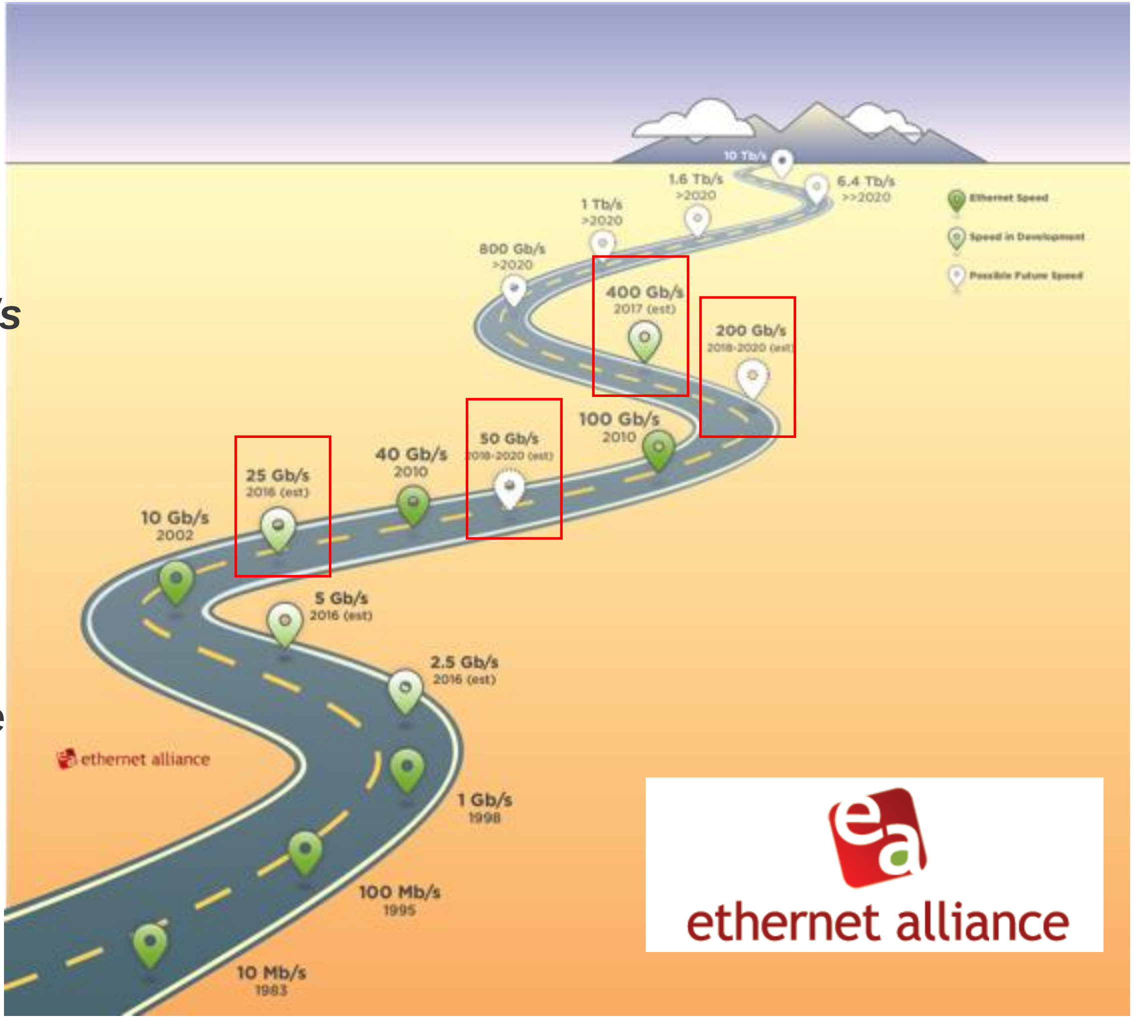
Evolution of New speeds:

25Gb/s, 50Gb/s, 200Gb/s, 400Gb/s

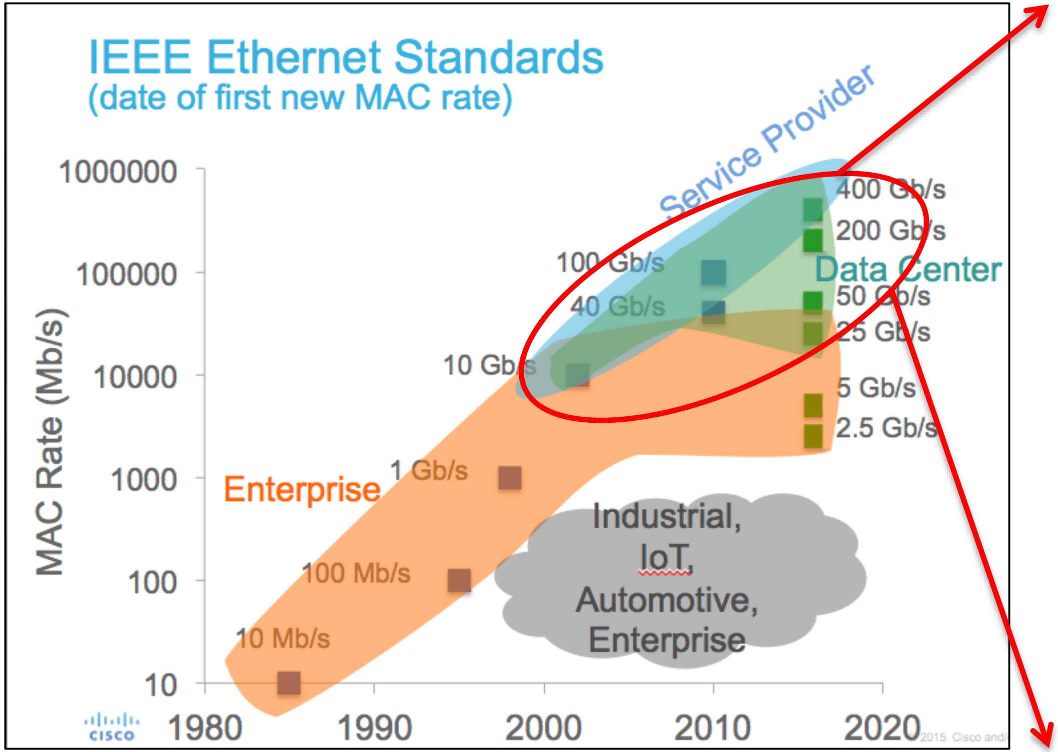
2.5Gb/s & 5Gb/s for wireless

Development and deployment at points all along the Ethernet value chain have exploded!!

6 Ethernet speeds in 5 years, same amount as the previous 40 years provided !!



The Impact of Cloud Data Center



Success of Ethernet protocol has shifted consumption to wider range of applications and markets

When market timing differences occur, different solutions emerge.

When market timing overlaps, common solutions emerge.

All markets benefit from economy of scale and converged technologies

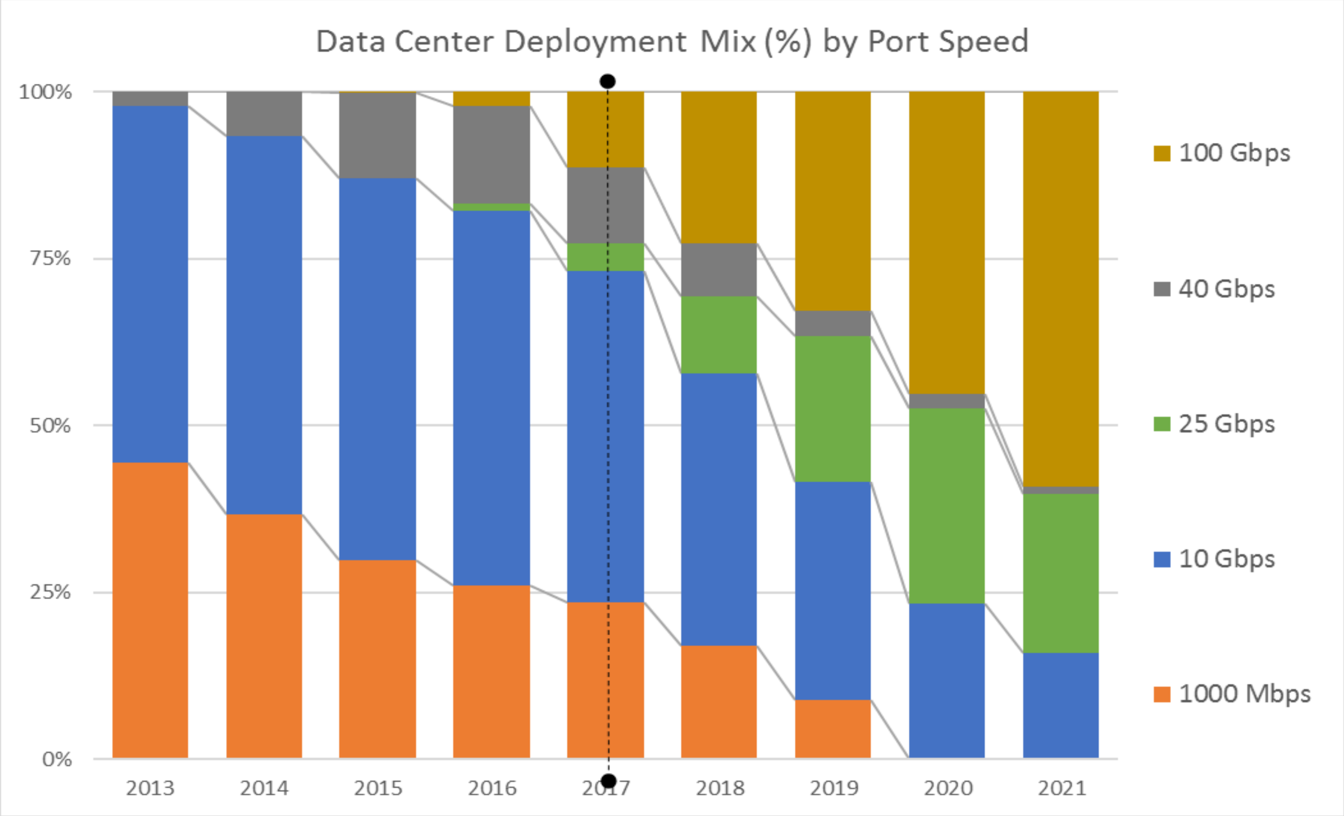
Network Migration Trends

Place in Network	2014/ 2015	2016/ 2017	2018/ 2019
Hyper scale Cloud server access	10G → 40G	10/40G → 25/50G*	25/50G* → 50/100G
Other Cloud server access	1G → 10G	10G → 25G	25G → 50G
Enterprise server access	1G → 10G	1G → 10G	10G → 25G
Enterprise Edge Routing	1G → 10G	10G → 100G	10G → 100G
SP/Cloud Core Routing	10G → 40/100G	10G → 100G	100G→ 200/400G

Each part of the network is migrating to a different speed

*2x25G

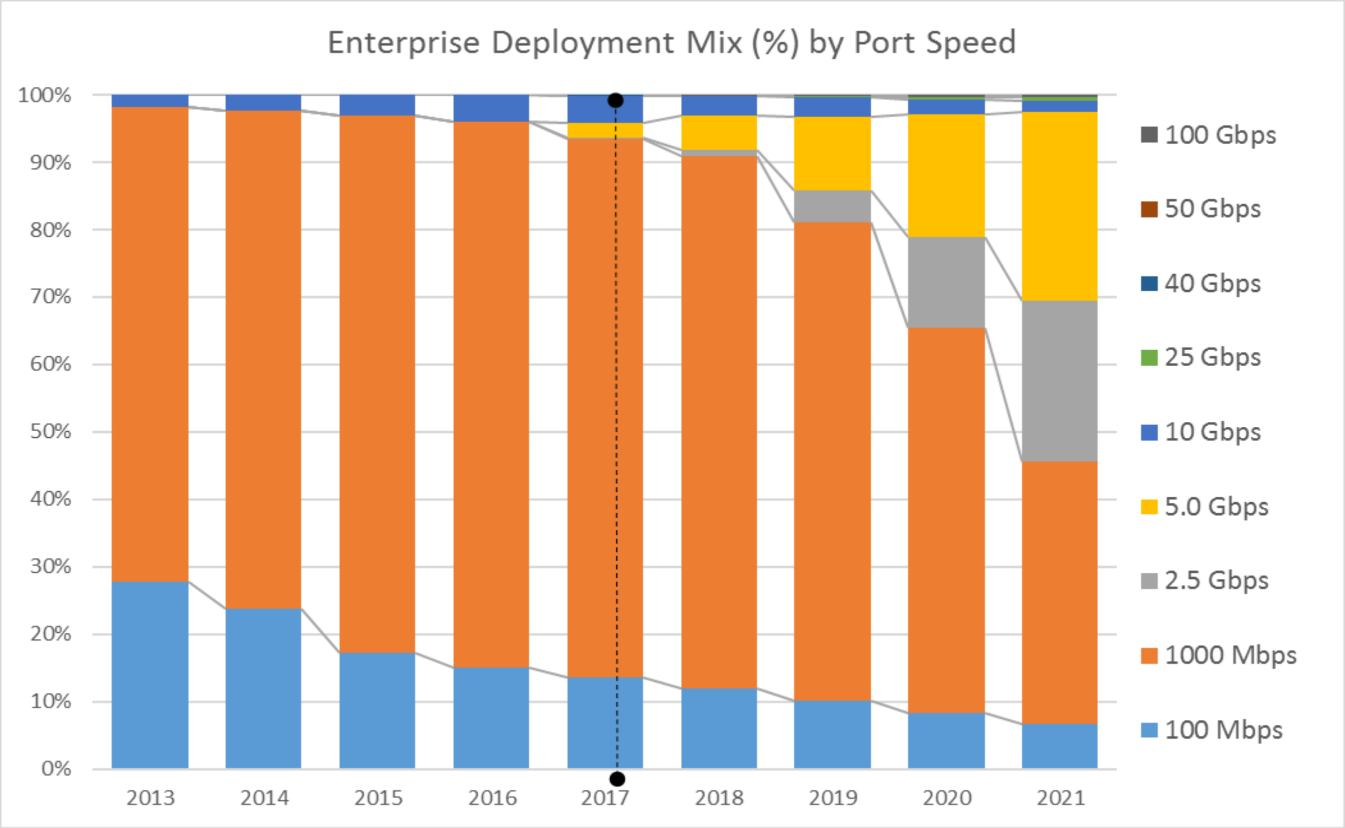
Data Center Switch Deployments



- **Data Centers**
  - *Cloud DC*
  - *Service Provider DC*
  - *Enterprise DC*
- **Growth Segment**:
  - *Cloud DC*
  - *Service Provider DC*
- **Growth Speeds**:
  - *100GbE*
  - *25GbE*

Source: DELL'ORO GROUP

Enterprise Switch Deployments



WLAN:

- 1GE to 2.5G/5G Access points

Uplinks:

- 10G to 25G+

Source: DELL'ORO GROUP INC ADVANCED RESEARCH REPORT ETHERNET SWITCH DEPLOYMENT LOCATION VOL. 6, NO.1 ARR95B

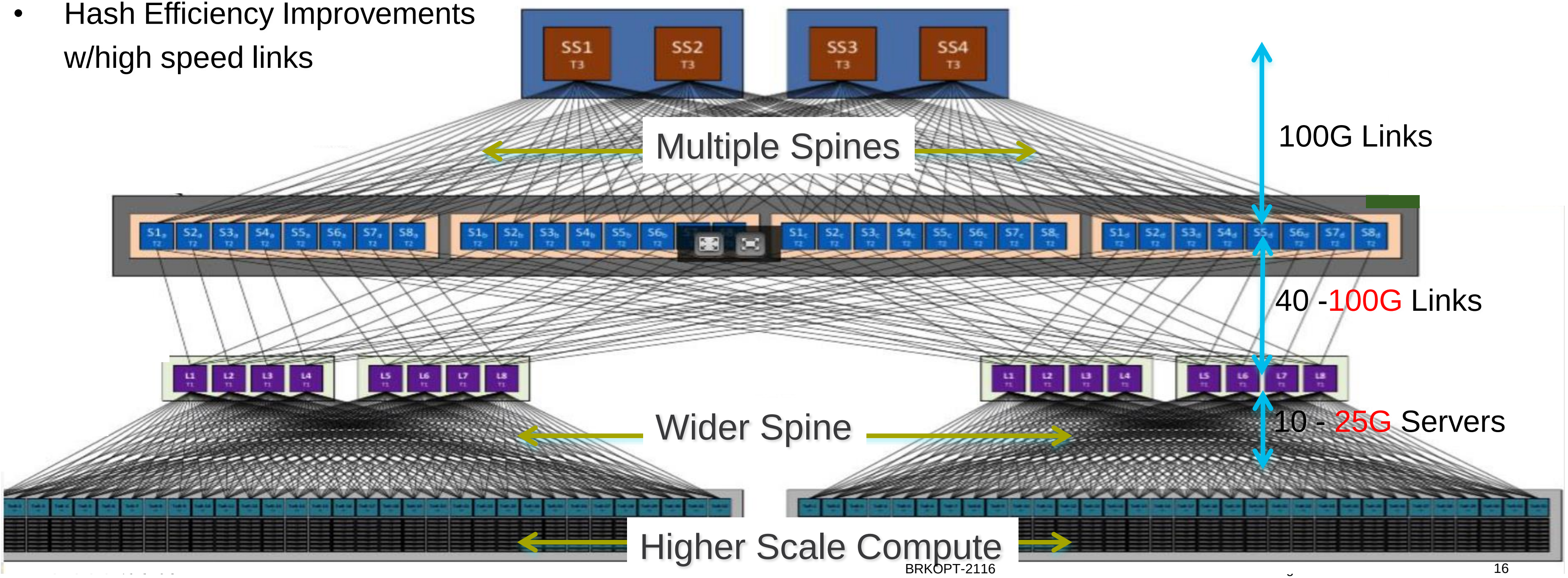
Pluggable transceivers Trends

- Cost, reach, size, power optimization continues
- QSFP28 form factor is the de-facto for high density 100G
  - Same port density as 40G QSFP
- SFP28 is the 25G form factor
  - Same port density as 10G SFP+
- QSFP-DD emerging as the 400G form factor
  - Same port density as QSFP 40G and QSFP 100G
- Advances in high order modulation techniques – electrical and optical.
- Market need for flexible interfaces on client devices
  - 4x10G breakout, 4x25G breakout …..

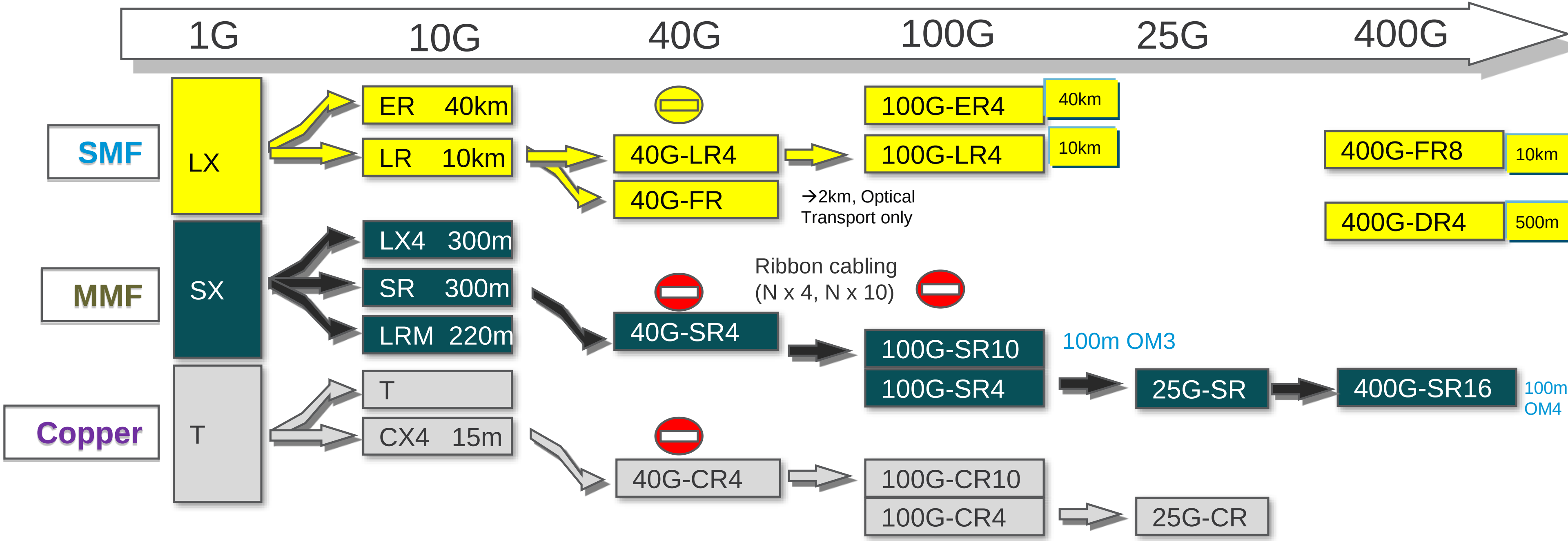
Data Center Fabric Trends

- High bandwidth Fabric
- Redundancy Model
- Physical Infrastructure
- Hash Efficiency Improvements w/high speed links

- Early Integration of 100G north-south focused DC edge



Ethernet Physical Interface Standards



IEEE continued to standardize a few reaches for each new speed……but these Standard PMDs do not sufficiently meet the requirements of new and emerging applications.

Additional Interface Options …….

	1G	10G	40G	100G	25G
SMF		10G DWDM 10G ZR	40G-LRL4/Lite 1-2km 40G-PLR4 1km 40G-UNIV 500m SMF	100G-ER4L 100G-CWDM4 100G-SM-SR 100G-PSM4	25G-LRL
MMF		FET10 100m SRL 100m	40G-CSR4 300m 40G-XSR4 300m Cisco BiDi 100m	SWDM4 BiDi	
AOC Cables		AOC <10m	AOC <30m	AOC <30m	AOC <10m

→ And more ‘non-standard interfaces to come….

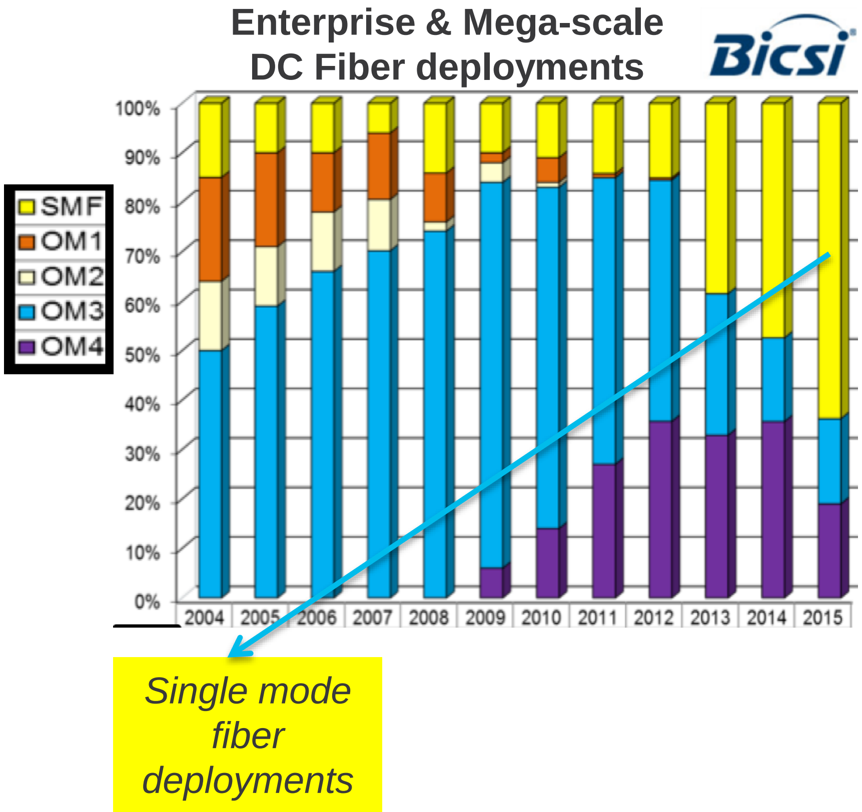
So what was Industry’s response?

- Create MSA (Multi-Source Agreements) targeted to specific applications (CWDM4, PSM4 etc)
- Release Non-Standard optics BiDi, UNIV, FET, SM-SR etc

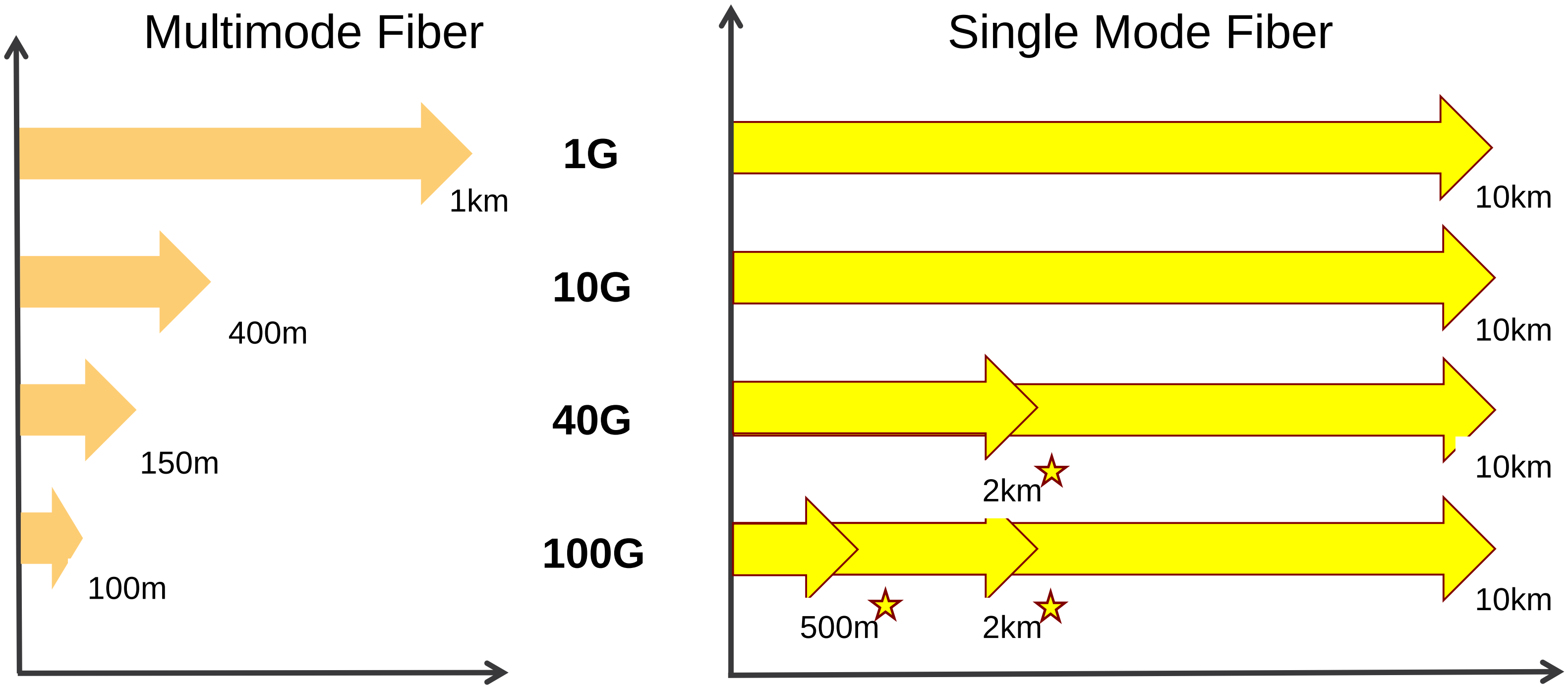
More choices, but also fragments the market…..

Datacenter Connectivity Trends

- Use of Multimode fiber for forward and backward compatibility in migration from 10GE->40GE->100G where possible
- Interconnect costs affect physical architecture
- DC Architecture is driving cost of short reach single mode optics down
- Single mode deployment for future-proofing fiber infrastructure .. Why?



Network fiber migration with increase in data rates

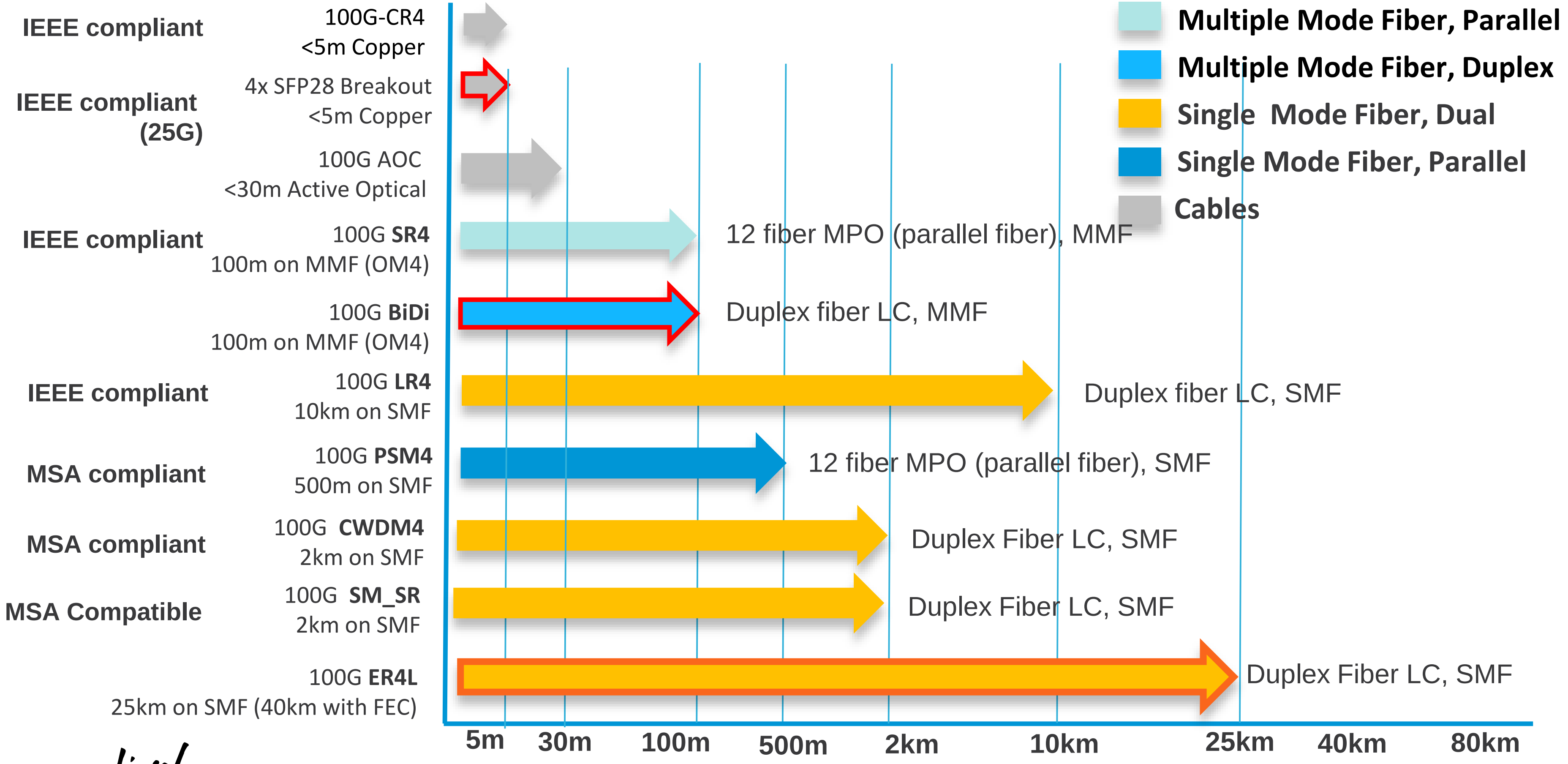


Shorter link distances with higher data rates on OM4 multimode fiber.

Short reach optics for single mode fiber at higher data rates.

Cisco QSFP28 100G Transceivers

For your reference

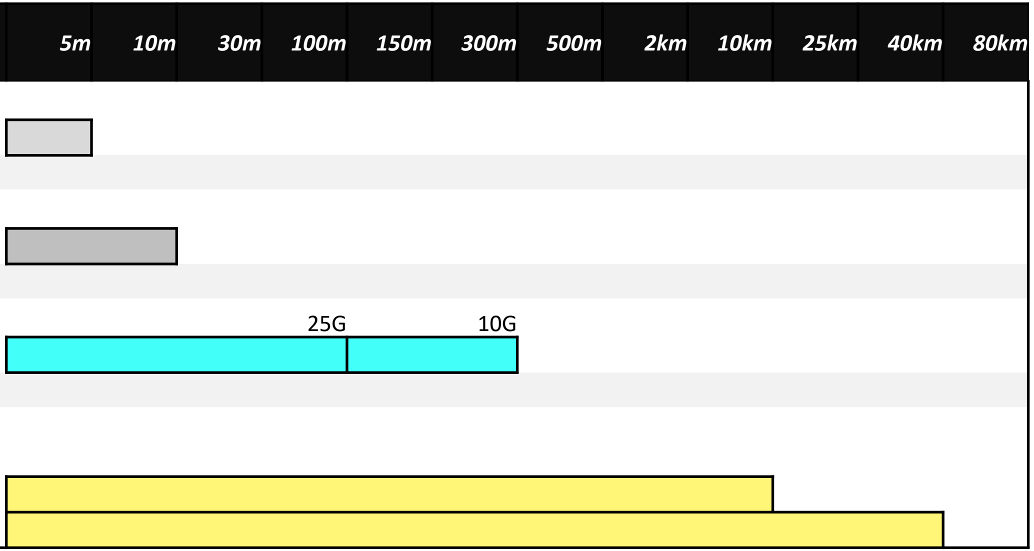


Transceiver Industry Trends
QSFP 40G to QSFP 100G Transition by reach

		QSFP 40G	QSFP 100G	5m	10m	30m	100m	150m	300m	500m	2km	10km	25km	40km	80km
1	**COPPER CABLES**														
	Direct Attach Copper cables	YES	YES												
	Breakout Copper Cables	YES	YES												
2	**OPTICAL CABLES**														
	Active Optical Cables	YES	YES												
	Breakout Active Optical Cables	YES	YES												
3	**PARALLEL FIBER MULTIMODE OPTICS**						100G	40G							
	SR4 (OM4)	YES	YES												
	CSR4 (OM4)	YES	YES												
4	**DUPLEX FIBER MULTIMODE OPTICS**						100G	40G							
	BiDi	YES	YES												
5	**PARALLEL FIBER SINGLEMODE OPTICS**									100G		40G			
		4x10G-LR	PSM4												
6	**DUPLEX FIBER SINGLEMODE OPTICS (SHORT REACH)**														
		LR4-Lite	CWDM4												
7	**DUPLEX FIBER SINGLEMODE OPTICS**												100G	40G	
	LR4	YES	YES												
	ER4	ER4	ER4L												

Transceiver Industry Trends
SFP 10G to SFP 25G Transition by reach

		SFP 10G	SFP 25G
1	**COPPER CABLES**		
	Direct Attach Copper cables	YES	YES
2	**OPTICAL CABLES**		
	Active Optical Cables	YES	YES
3	**DUPLEX FIBER MULTIMODE OPTICS**		
	SR	YES	YES
4	**DUPLEX FIBER SINGLEMODE OPTICS**		
	LR	YES	YES
	ER	YES	YES



100G QSFP Cables

100G Copper Cables
(upto 5m)
QSFP 100G to QSFP 100G

100G Copper Breakout Cables
(upto 5m)
QSFP 100G to 4 x SFP25G

100G Active Optical Cables (AOC)
(upto 30m)
QSFP 100G to QSFP 100G

- AOC cables are thinner than twinax Copper cables
- Enables improved air Flow
- No Electromagnetic Interference
- Reach upto 30m (while Copper cables have reach limitations with increasing speeds)
- Less weight and Flexible
- Significantly simplifies Cable management

Cable diameter

3mm

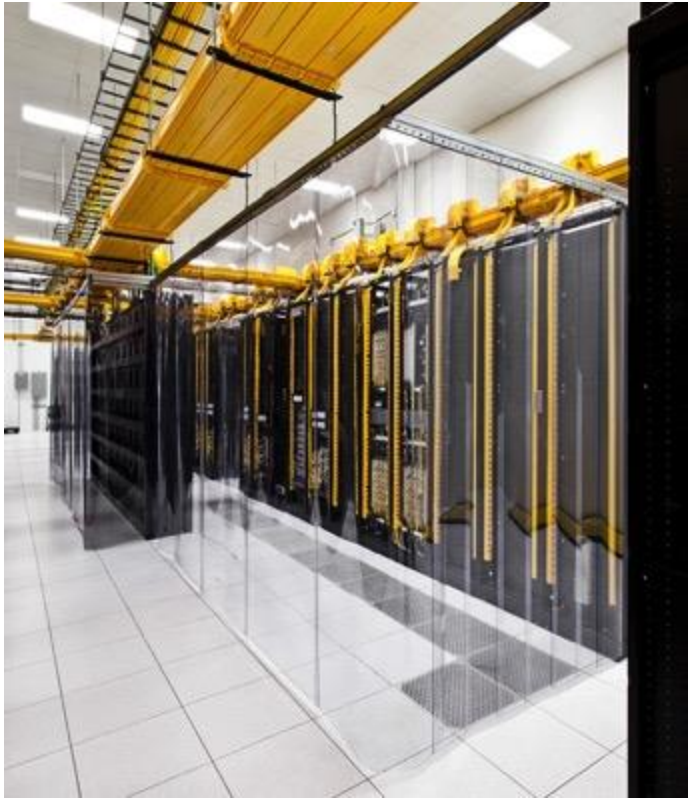
>10mm

Active Optical Cable

Twinax copper cable

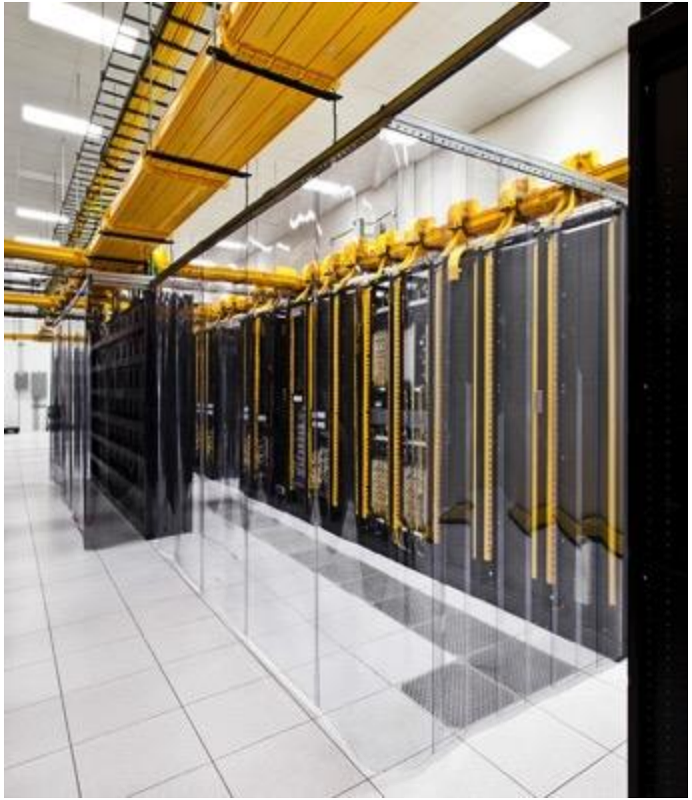
Hyperscale Datacenter Trends

- Continued evaluation of Multimode vs. Single mode for future bandwidth needs
- DC Campus can consume many acres and require significant amounts of fiber interconnect
- DC Architecture is driving cost of short reach Single mode optics down
- Interconnect costs affect DC physical architecture
- Increased choice of cabling options to address density, bandwidth and reach



Enterprise Datacenter Trends

- Use of Multimode fiber for forward and backward connectivity in migration from 10GE->40GE->100G where possible
- Continued evaluation of Multimode vs. Single mode for future bandwidth needs
- Interconnect costs affect DC physical architecture
- Increased choice of cabling options to address density, bandwidth and reach



For your reference

Data Center Cabling Architecture Considerations

- **Optics will drive physical architecture**
- Employ a main cross-connect at a MDA, for best management, scalability and growth
- Plan for future device optics density and reach;
  - Fiber density in the trunk cables – parallel vs duplex fiber optics support
  - Reach – multimode vs single mode
- Use low loss connectors to enable MDA
- Allocate rack space for orderly fiber count growth and network device interface scale
- Plan for future high density 10G/25G server access
  - Can also be addressed by 25/40/100GE break out cables
- Switch Architecture Type for Access – Modular or ToR

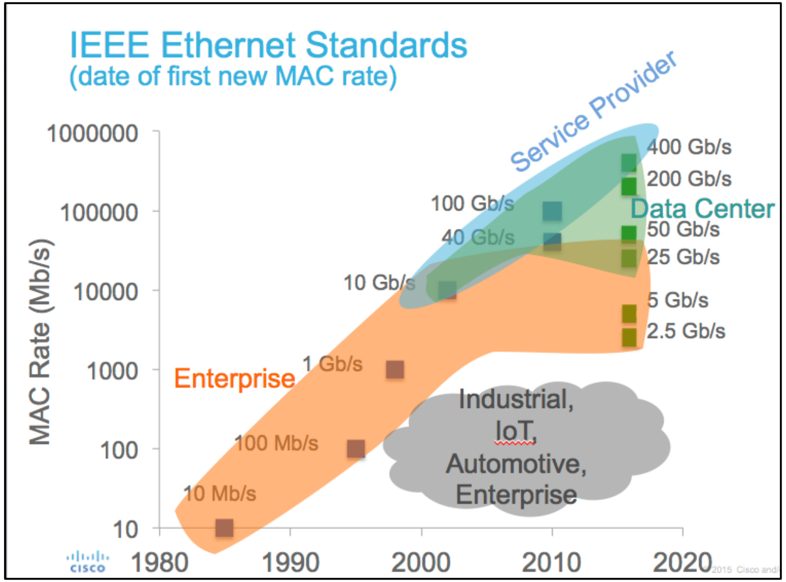
MDA: Main Distribution Area

Optical connectivity increasingly important for Performance, Scale, and Cost!

Need to optimize all
- cost, power, density -
simultaneously…

Design Choices will vary by network use-case!

Never ending balancing act!



Industry Standards

New Standards Leverage Previous Industry Investment

Technology	Nomenclature	Description	Status
Backplanes	100GBASE-KR4 100GBASE-KP4	4 x 25 Gb/s (NRZ) 4 x 25 Gb/s (PAM-4)	Deployed. Legacy 4x installed base requiring upgrade
Chip-to-Module	CDAUI-8	8 x 50 Gb/s PAM-4	IEEE P802.3bs in Task Force Review
Chip-to-Chip	CEI-56G-VSR-PAM	56 Gb/s PAM-4	Straw Ballot
SMF Optical	400GBASE-FR8 400GBASE-DR4	8 x 50 Gb/s PAM-4 4 x 100 Gb/s PAM-4	IEEE P802.3bs in Task Force Review
Module Form Factor	SFP56	1 x 50 Gb/s	Summary Document SFF-8402
	QSFP56	4 x 50 Gb/s	Summary Document SFF-8665

Client Side Optics - Technologies

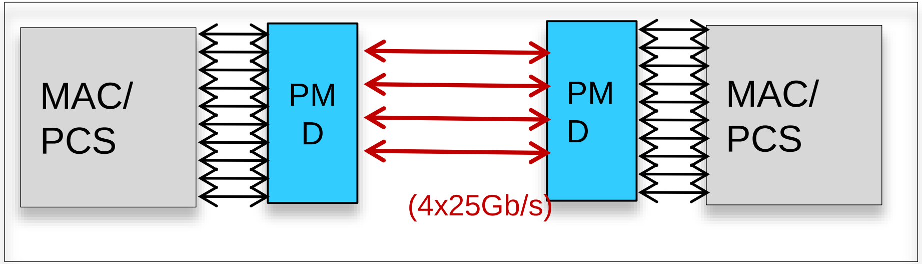
Optical Technology Trends

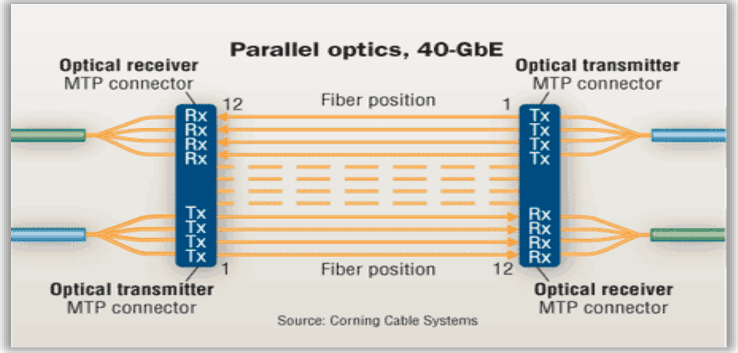
DC & Client optics

How can we go faster

- **Increase Signaling speed**
  - Evolution of Ethernet speed roadmap
- **Adopt advanced modulation formats**
  - carrying more bits/s, but keep the baud rate low
- **Increase number of fibers (Parallelize)**
  - Aggregating data over several number of fibers/ lanes
- **Increase number of wavelengths**
  - Combining data over multiple wavelengths (WDM)

Parallel Data Streams – Multi Layer Distribution (MLD)



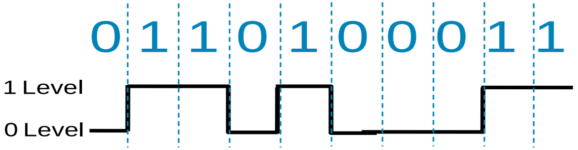


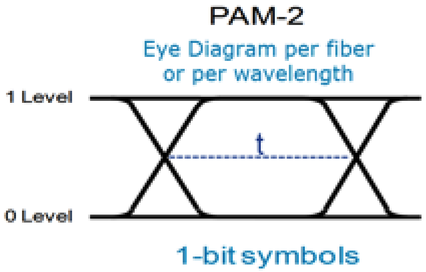
- Multi-lane Distribution (in the PCS layer) provides a simple way to map 40G/100G to physical interfaces of different lane widths – with Virtual lanes
- Data from any particular virtual lane will reside on the same electrical and optical lane across the link – No skew introduced between bits within the virtual lane

Higher Order Modulation

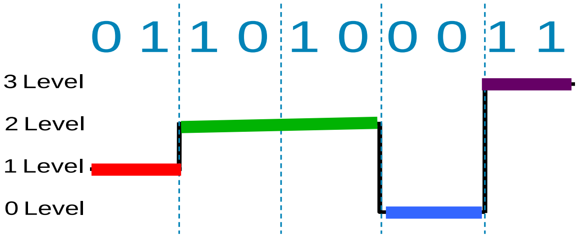
Same Data and Data Rate; but lower frequency (baud rate).

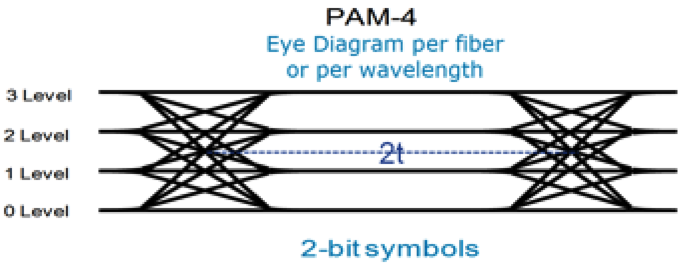
PAM-2
1-bit Symbols
- 1 (1 level)
- 0 (0 level)





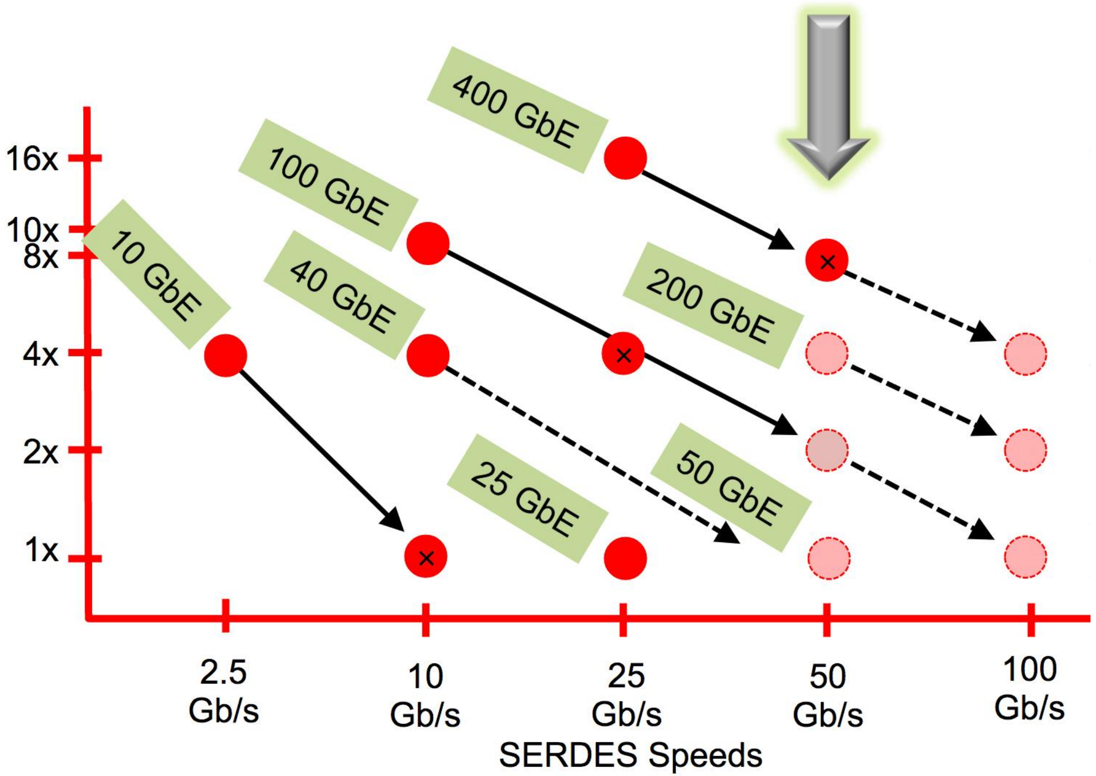
PAM-4
2-bit Symbols
But 4 levels
- 1 1 (3 level)
- 1 0 (2 level)
- 0 1 (1 level)
- 0 0 (0 level)





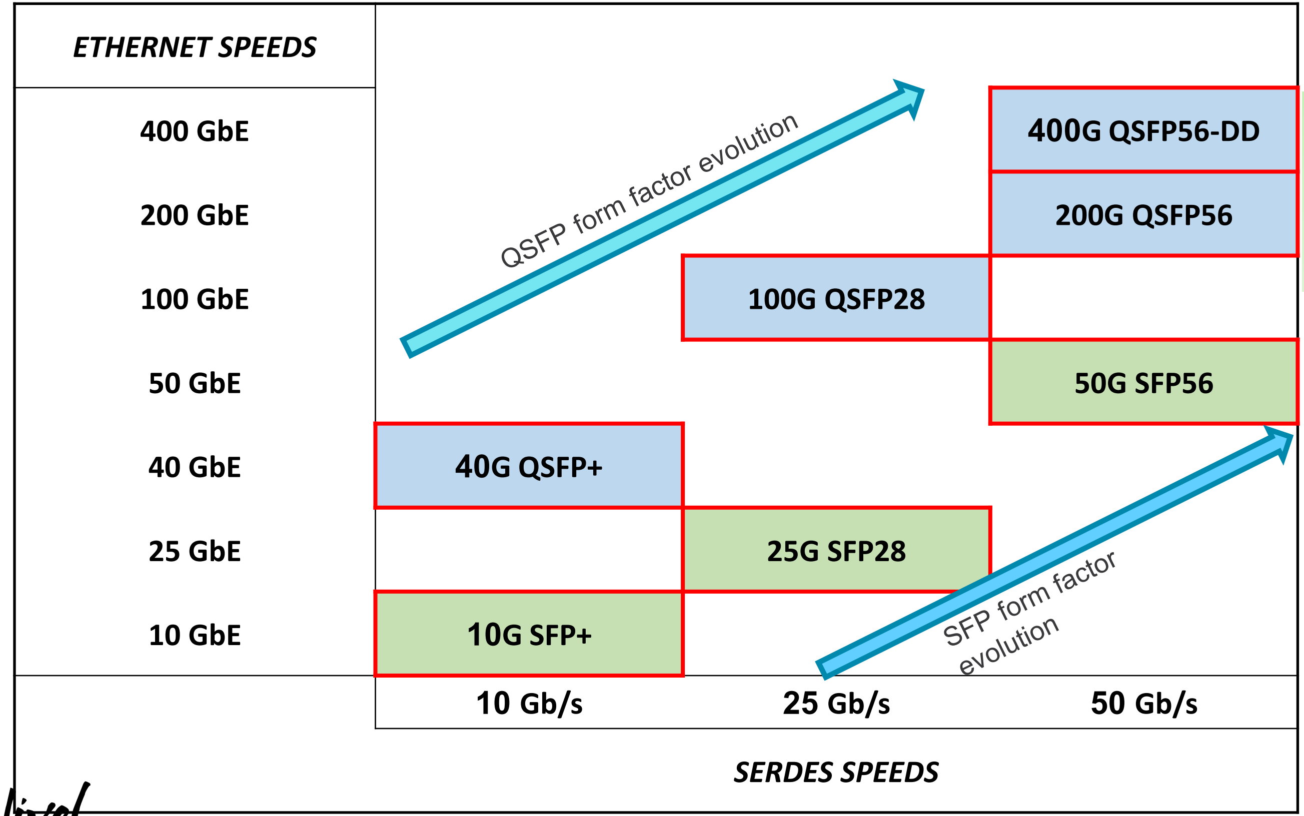
Why higher order modulation?
- Lessens many transmission penalties
- Enables lower bandwidth components and materials
- Reduces wavelengths & fibers compared to NRZ

The new Normal – Multi-lane & Reuse



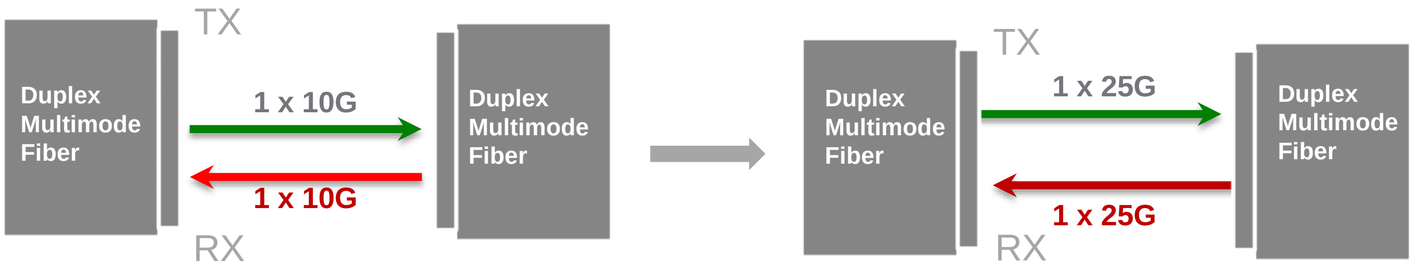
Since 10 GbE, Ethernet has progressed by defining pragmatic multi-lane solutions and fastest single lane technologies to produce cost-effective solutions.

Form factor evolution

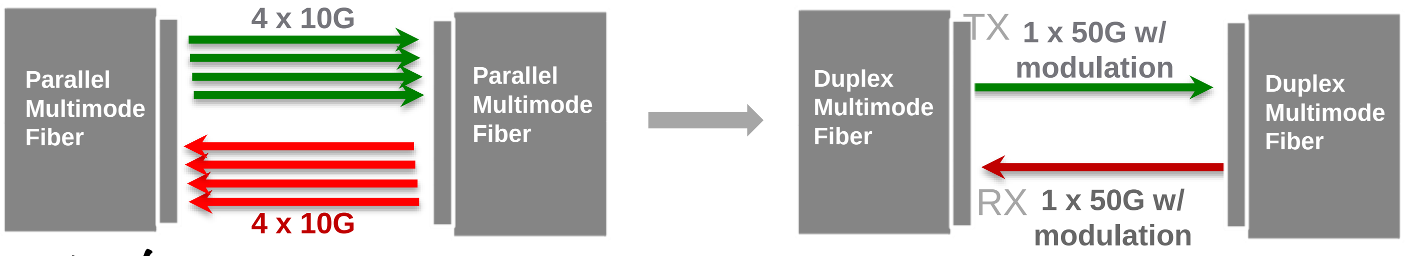


Form factor evolution follows multi-lane to single-lane serdes evolution

How can we go faster? Some examples….

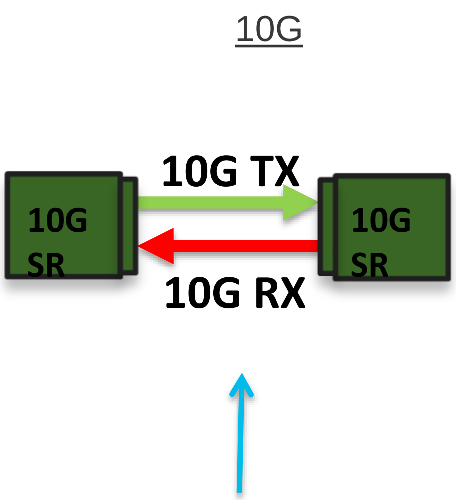


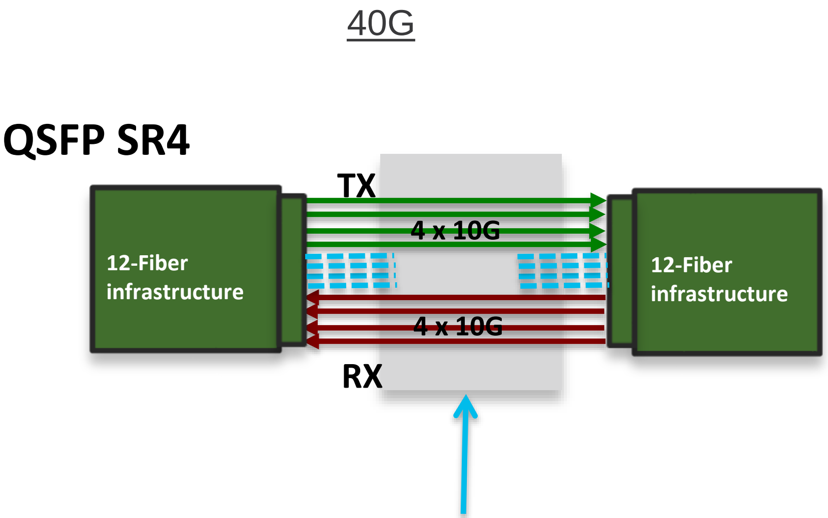
Toolkit:
Speed-up
WDM,
Modulation



Toolkit:
Speed-up,
WDM,
Modulation

The Challenge With Migration: Current 10G SR vs 40G QSFP SR4, 100G QSFP28 SR4

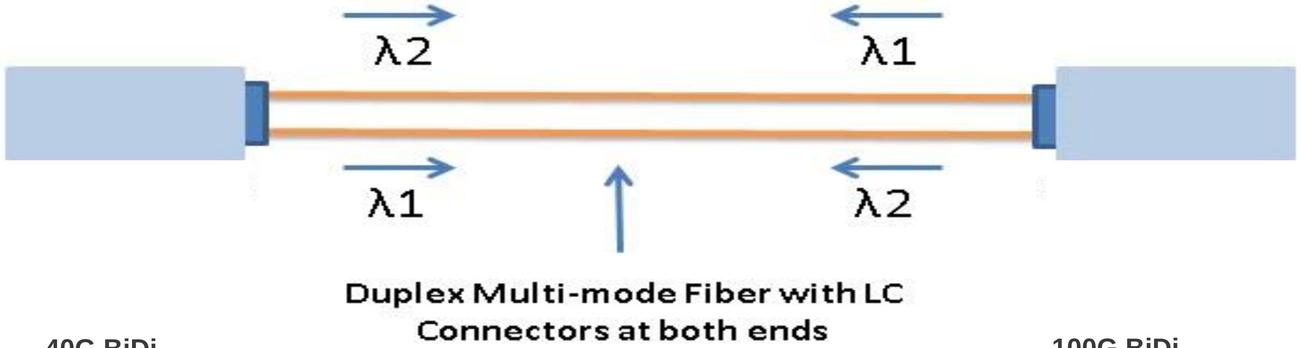




2 Fiber Strands

8 - 12 Fiber Strands

40G & 100G BiDi Technology



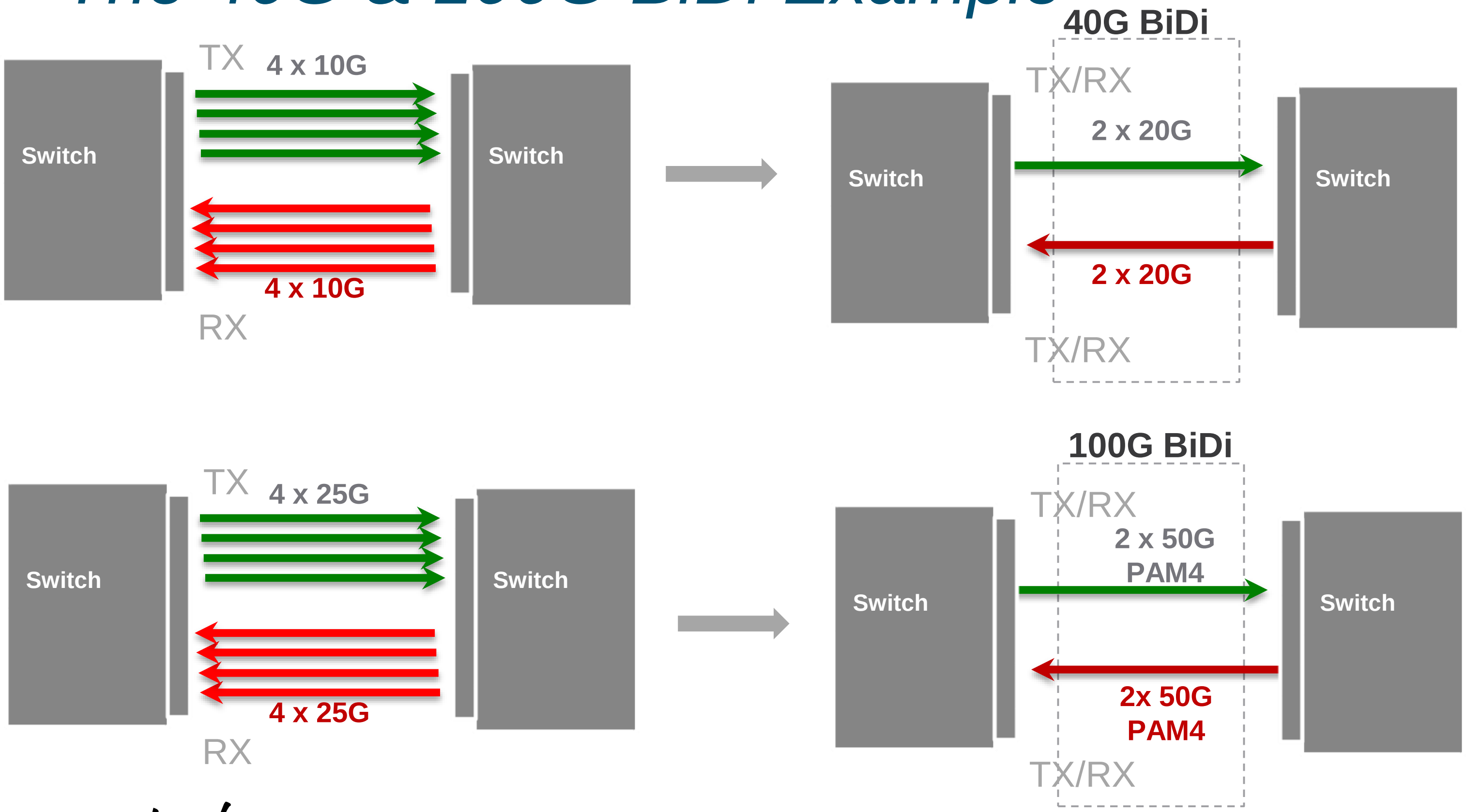
40G BiDi

- 4 electrical lanes of 10G from Host are converted to 20G electrical lanes by a Gearbox IC
- 20G electrical lanes are converted to 20G optical lanes and transmitted over 2 fibers
- The same fibers are used to receive 20G signals and the Gearbox coverts the 20G signals to 4 lanes of 10G before sending to Host
- The module uses Bi-directional Optical sub-assembly (BOSA) to transmit and receive 20G optical signals on the same fiber.

100G BiDi

- 4 electrical lanes of 25G from Host are converted to 50G-PAM4 electrical lanes by a Gearbox IC
- 50G PAM4 electrical lanes are converted to 50G PAM4 optical lanes and transmitted over 2 fibers
- The same fibers are used to receive 50G PAM4 signals and the Gearbox coverts the 50G PAM4 signals to 4 lanes of 25G before sending to Host
- The module uses Bi-directional Optical sub-assembly (BOSA) to transmit and receive 50G PAM4 optical signals on the same fiber.

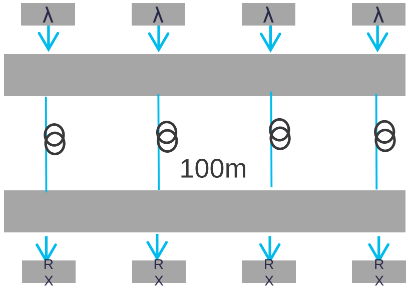
Single Lane .. Less Complexity
The 40G & 100G BiDi Example



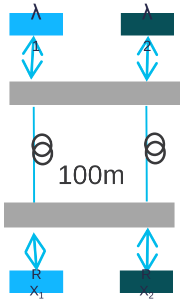
Toolkit:
Speed-up, ✓
WDM, ✓
Modulation

Toolkit:
Speed-up, ✓
WDM, ✓
Modulation ✓

100G QSFP28 Multimode Optics

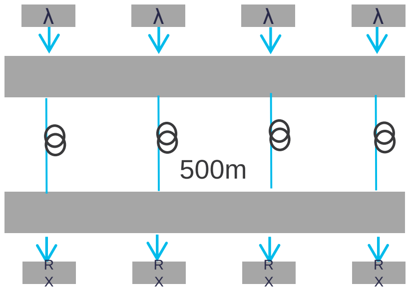


100G SR4
Parallel fiber (MPO)

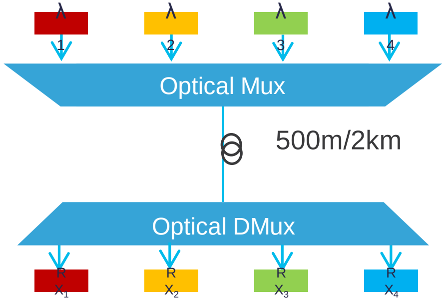


100G BiDi
Duplex Fiber (LC)
850/910nm wavelengths

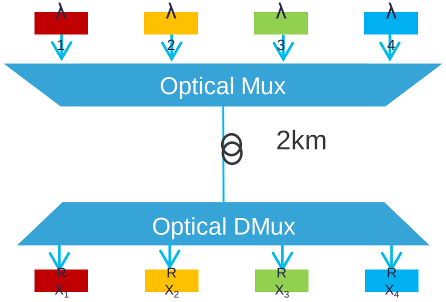
100G QSFP28 Single mode Optics



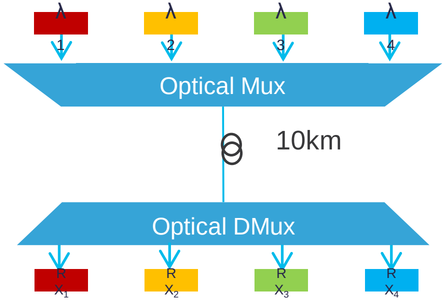
100G PSM4
Parallel fiber (MPO)



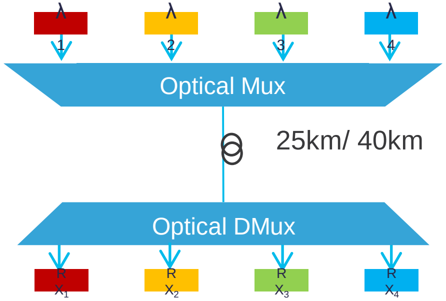
100G SM-SR
Duplex Fiber (LC)
Coarse WDM wavelengths



100G CWDM4
Duplex Fiber (LC)
Coarse WDM wavelengths



100G LR4
Duplex fiber (LC)
LAN WDM wavelengths

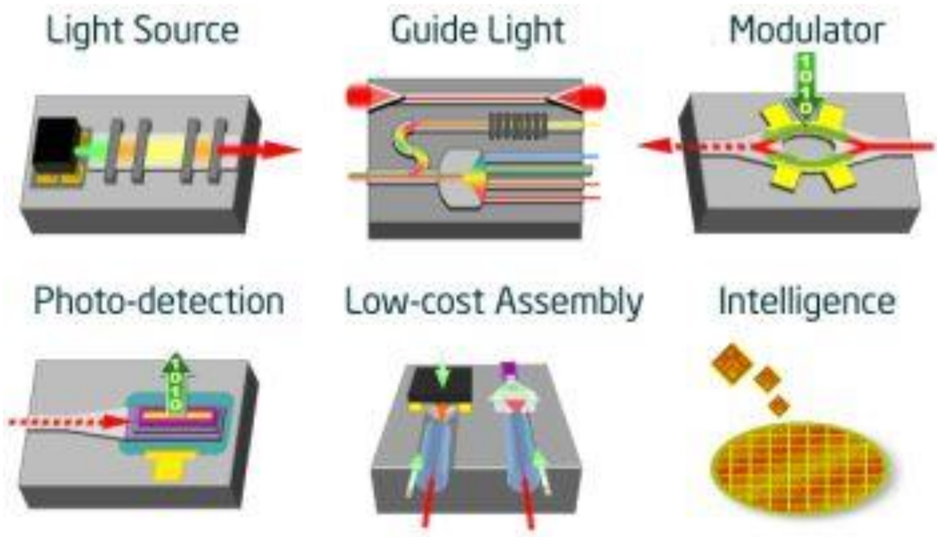


100G ER4L
Duplex fiber (LC)
LAN WDM4 wavelengths

Silicon Photonics

Potential for "transceiver on a chip"

- Optical devices can be made cheaply using standard semiconductor CMOS fabrication techniques
- Optics can be integrated with microelectronic chips.
- Silicon integrated optical chips that can generate, modulate, process and detect light signals



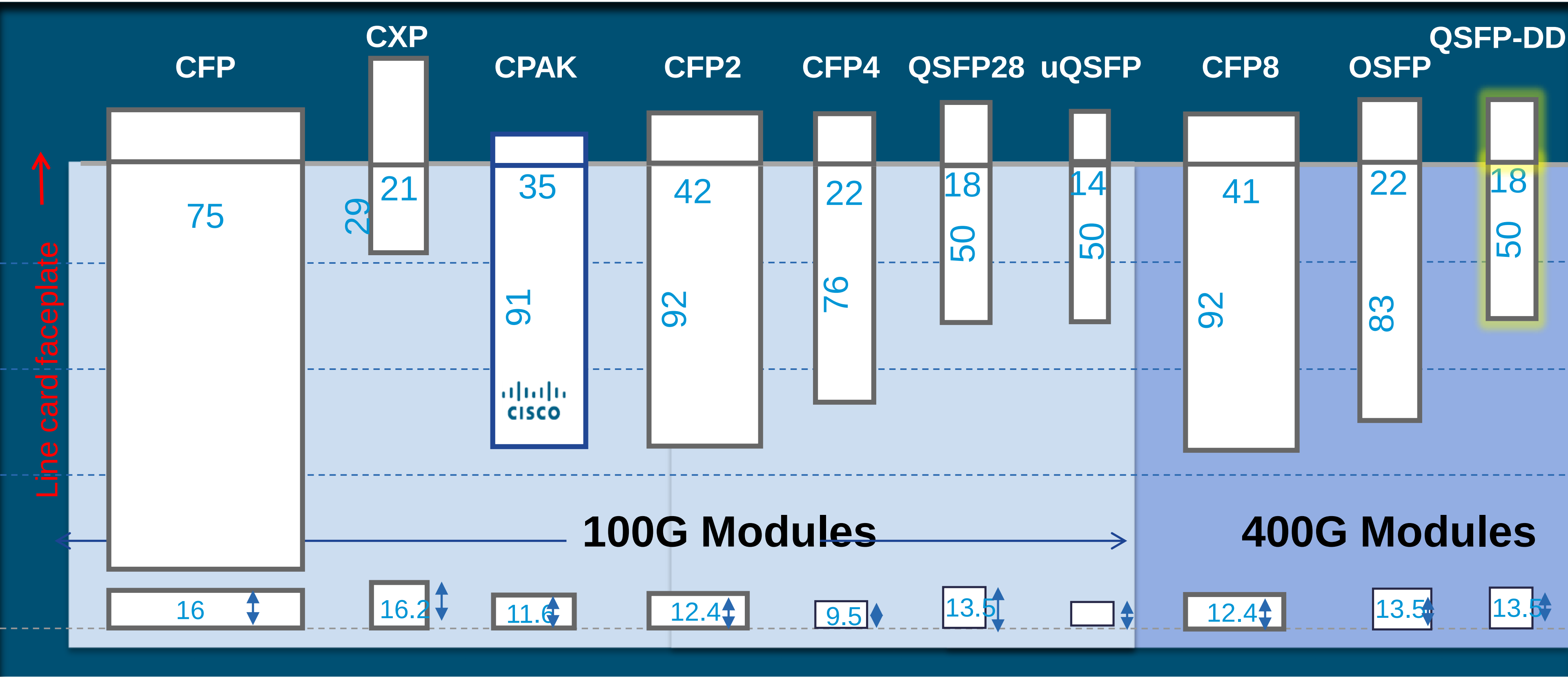
Silicon Photonics is the most promising optical technology for:

Solving for Cost, Power, Density for DC & Client optics

Solve for Spectral efficiency and Performance for DCI & Long Haul optics

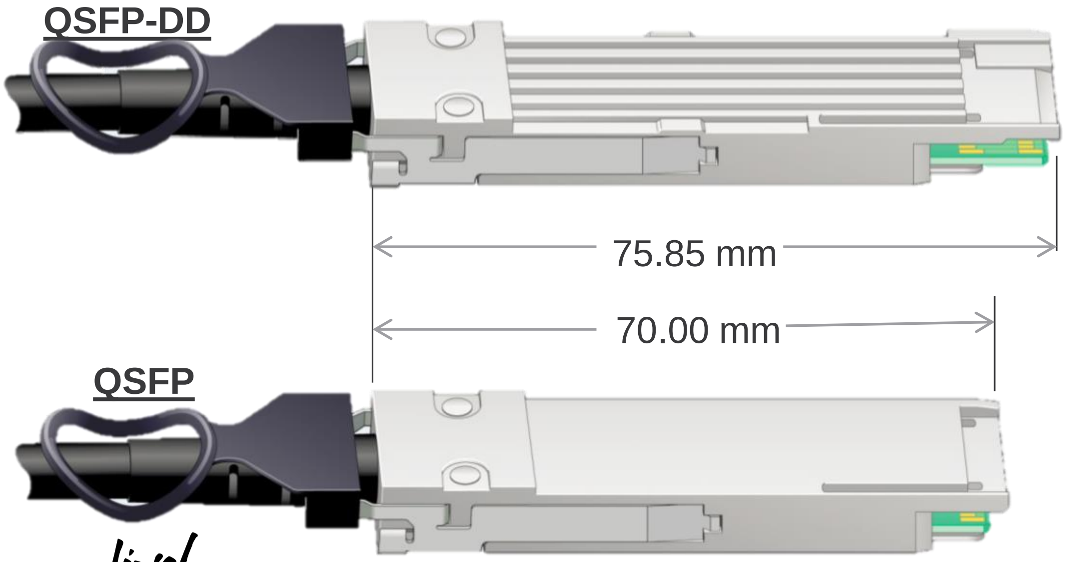
QSFP-DD 400G Module Comparison

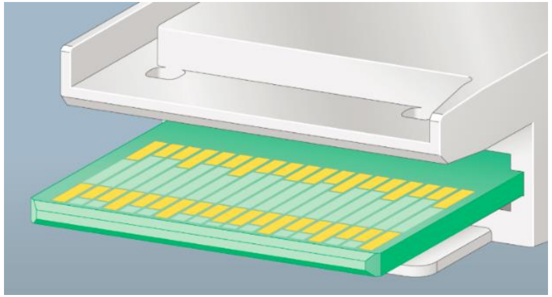
QSFP-DD Provides the Highest BW Density of Any Pluggable Module



Introducing QSFP-DD

Improved thermals supports
>2.5x QSFP power

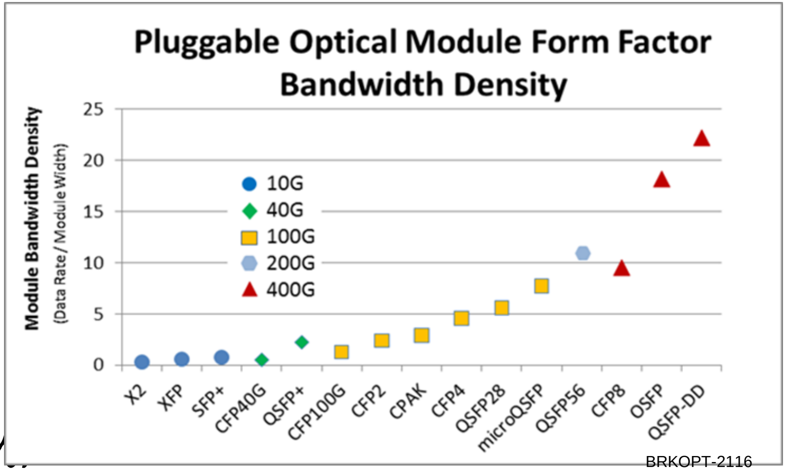


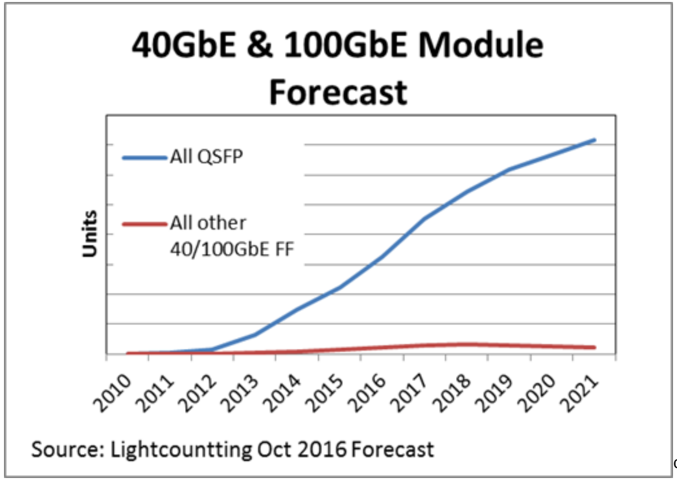


Essentially the same as QSFP but with extra row of contacts. Allows boards to be backwards compatible to both.

Why QSFP-DD for 400G?

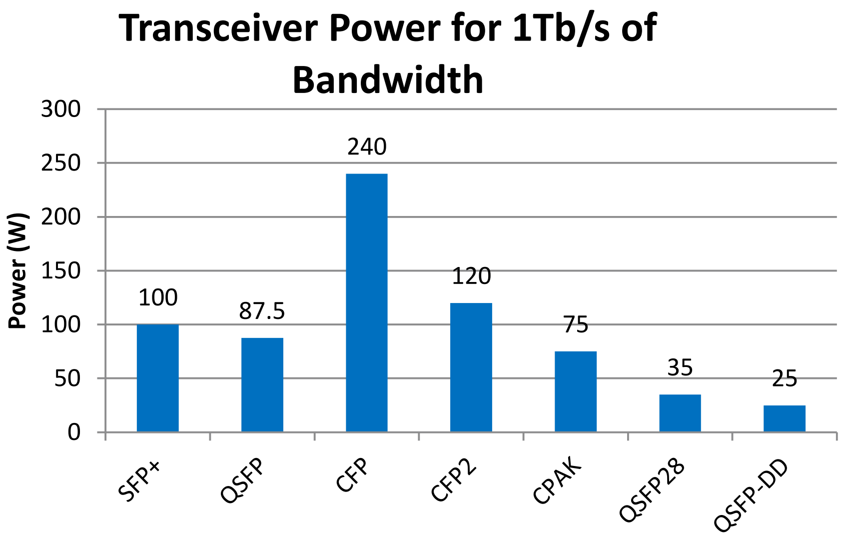
- The QSFP-DD module form factor has the highest BW density, enabling 14Tb/s in 1RU
- Avoids iteration of form factors for a particular speed, drives industry economy of scale
- **QSFP-DD port is backward compatible with all prior QSFP modules**
- This form factor leverages the industry's manufacturing capability and cost structure of QSFP+ and QSFP28, the de facto standards for 40GbE and 100GbE

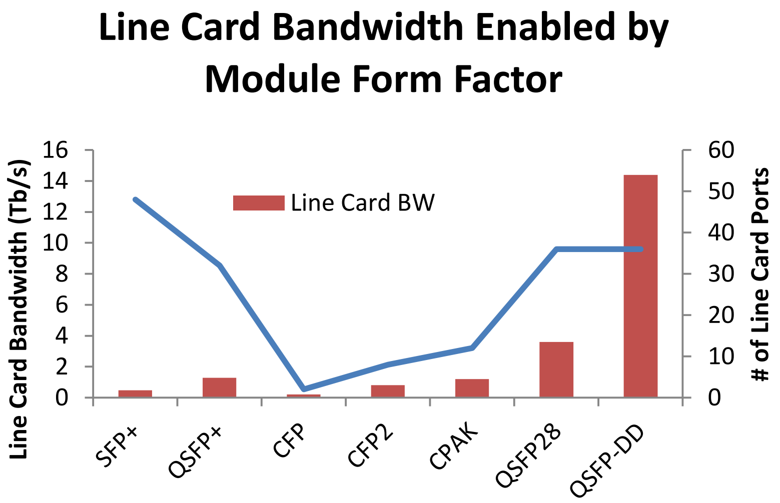




Transceivers Evolution Drive Efficiency

Modules use less power for the same bandwidth for density





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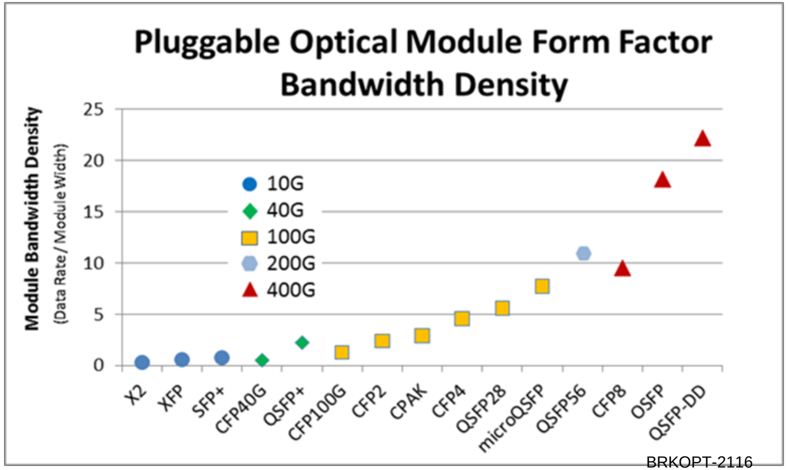
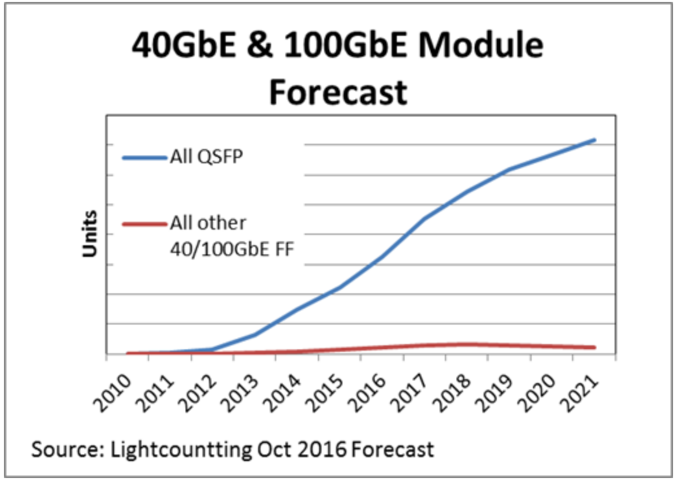
- This form factor leverages the industry's manufacturing capability and cost structure of QSFP+ and QSFP28, the de facto standards for 40GbE and 100GbE
  - Up to the end of 2016 over 7M QSFP (40G & 100G) have been deploy since their introduction

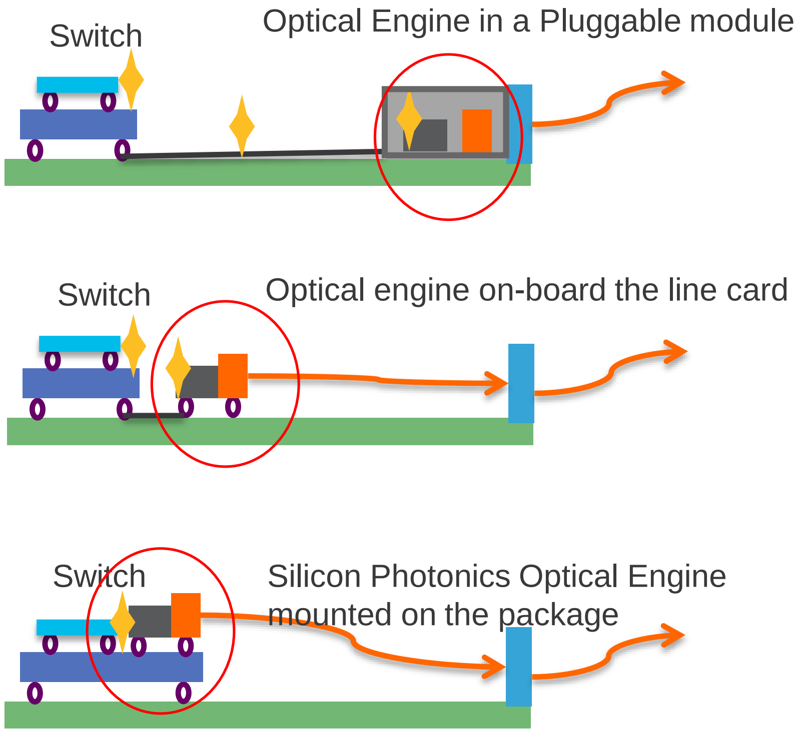




Other Future Industry Trends - Onboard optics

- How do we go beyond 12TB+ ?
- Will pluggables limit the faceplate density?
- >2020: board-level photonics
- **COBO** – Consortium On-board Optics [switch face-plate, bandwidth density..

> **"On-board optics permit greater switch radix with lower power consumption, which is really important as we continue to increase speed and bandwidth," - COBO**

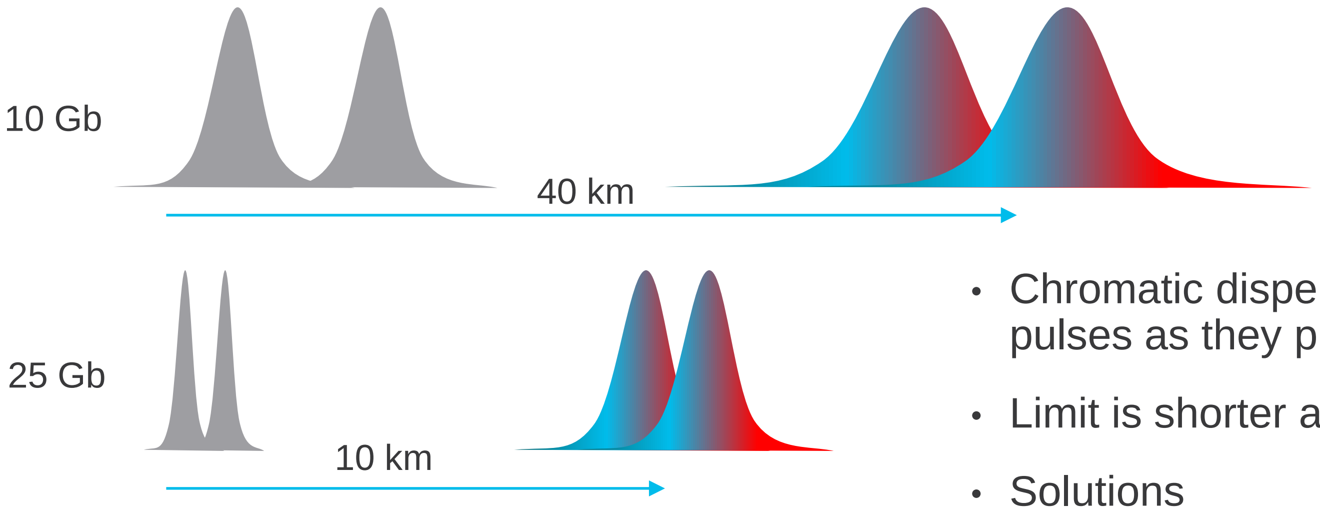


Optical technology…

…Is the key enabler for systems to maintain pace with the requirements of the bandwidth pressures

Challenge		Goal
Form Factor Size reduction	→	Port Density increase
Power reduction	→	Port Density increase
Reach	→	System/network scaling
Packaging simplification	→	Increased Yield, lowers cost
The next speed (400G/1T)	→	System Scale, lower costs

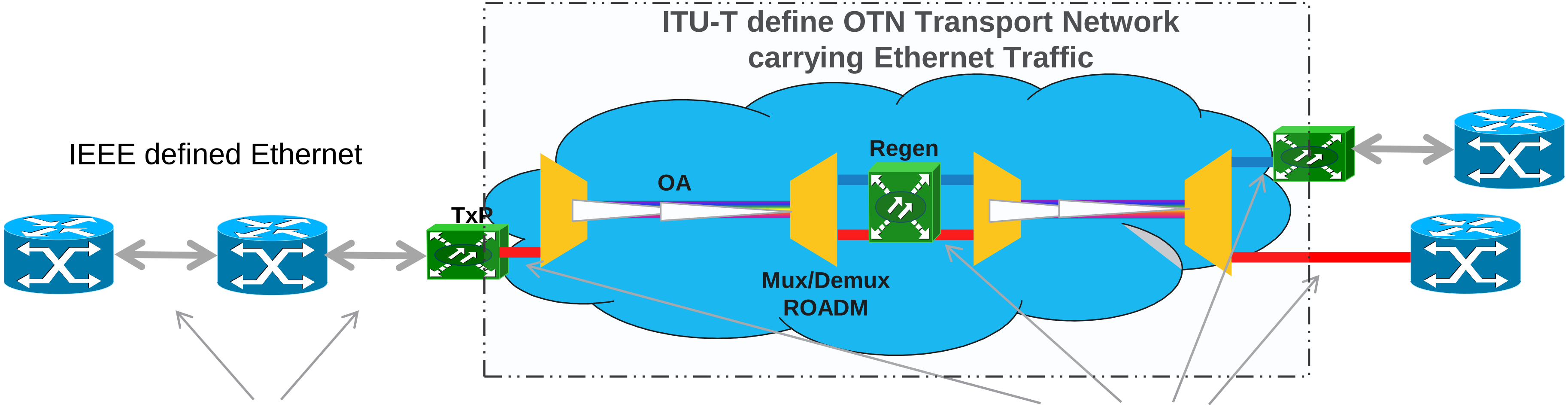
Beyond 40km at High Speeds



- Chromatic dispersion in SMF spreads pulses as they propagate, limit the distance
- Limit is shorter at higher data rates
- Solutions
  - 40km 40G in QSFP (40GBASE-ER4)
    - High quality laser and receiver
  - 40km 100G in QSFP
    - compatible with 100GBASE-ER4
    - “ER4-Lite”
    - High quality laser and receiver
    - Leverage FEC

Line Side Optics – Technoloigies

Setting the stage......



DC & Client Optics

- Within a building or campus or city
- Grey optics
- Ethernet
- **Solve for Cost, Power, Density**

Line Optics

- Across country (a few hundred to 1000s km)
- Multiple channels / Fiber (DWDM)
- OTN
- **Solve for Spectral efficiency and Performance**

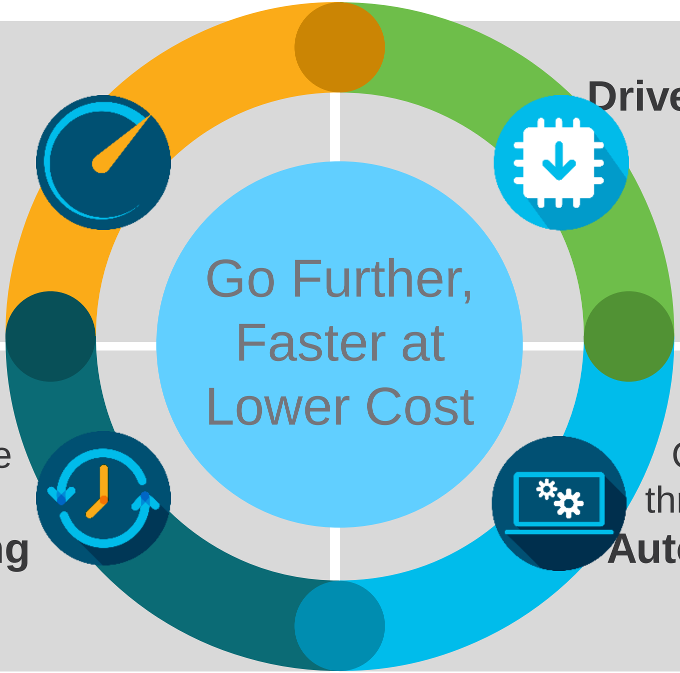
Goal: Enable Optical Networks go Farther and Faster at Lower Cost

Optimize Data Rate vs Distance vs Cost

Figure of Merit:
$$/Gb-Km

Drive to Next Gen Data Rates 600G, 800G, 1T, etc…

Increase bits per port to reduce cost per bit, leveraging Silicon advances



New approaches to increase fiber carrying capacity

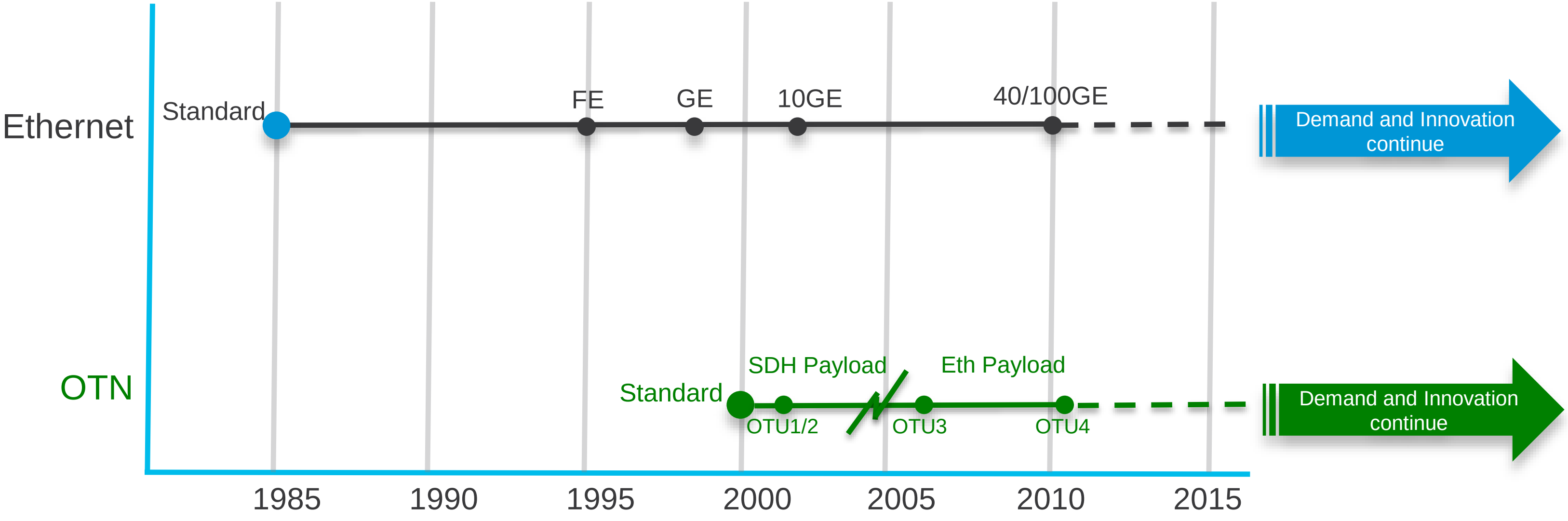
Gain more from existing Infrastructure

Reduce Operational Costs, Simplify through Automation
Optimize network continuously through Flexibility across Layers

Automation & Simplification via SW

Ethernet & OTN Evolution

- Ethernet has undergone continual innovation since standardization
- Transport systems evolving to 400G



OTN aligned with Ethernet speeds

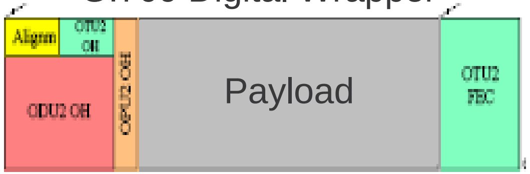
G.709 Hierarchy and Frame Structures

- G.709 defined a fixed “hierarchy” of payloads
- G.709 started as a digital wrapper around WDM client signals to improve reach and manageability.
- Recently it has developed into a complex multiplexing structure.
  - ODU-Flex allows flexible sub wavelength grooming.

G.709 Hierarchy

Frame	Payload (OPU)
ODU0	1,238,954 kbit/s
OTU1	2,488,320 kbit/s
OTU2	9,995,276 kbit/s
OTU3	40,150,519 kbit/s
OTU4	104,355,975 kbit/s
ODU-Flex	Flexible Data Rates

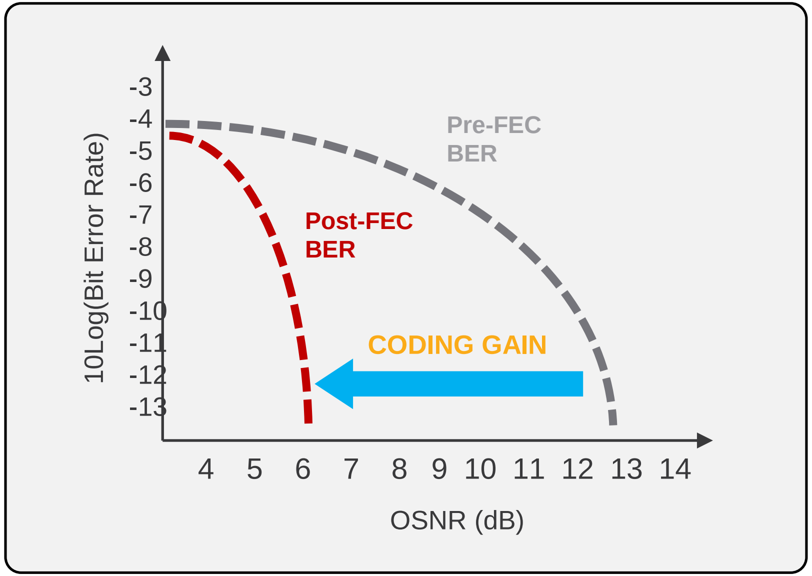
G.709 Digital Wrapper



MultiplexingStructure

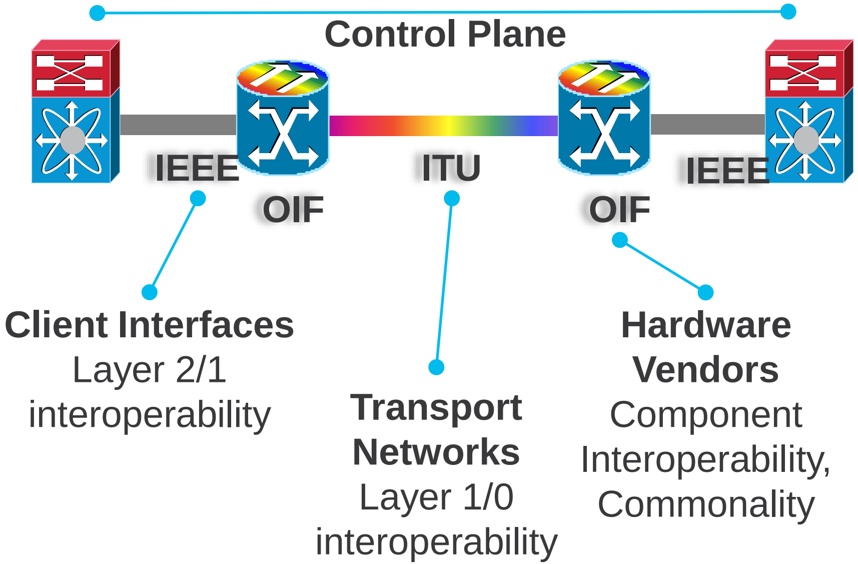
Improve OSNR Performance with G.709 FEC

- FEC extends reach and design flexibility, at "silicon cost"
- G.709 standard improves OSNR tolerance by 6.2 dB (at 10^{-15} BER)
- Higher gains (8.4dB) possible by enhanced FEC (with same G.709 overhead)
- Yet higher gains by soft decision (SD)FEC
- Offers intrinsic performance monitoring (pre and post-FEC error statitistics)



Industry Standards Groups

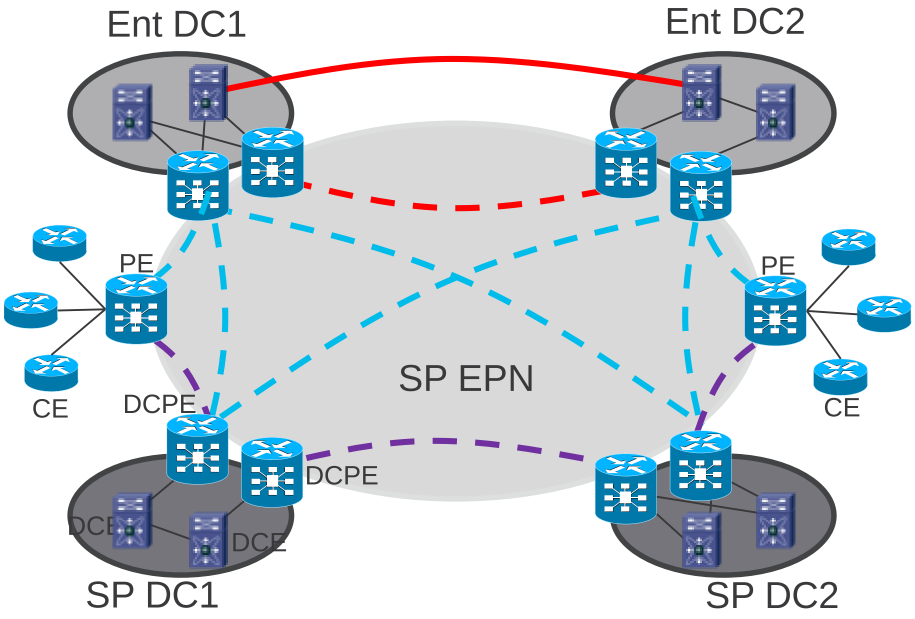
- **IEEE**
  - Physical interfaces for Backplane, Copper, Fiber PMDs
- **ITU** Study Group 15: Optical and Transport Networks
  - OTU4 frame format
  - Single mapping for 40GE/100GE into OTU3/OTU4 (e.g.)
  - OTL protocol enabling OTU3/4 over multi-lane optics
- **OIF**: 100G Long-distance DWDM Transmission
  - Industry consolidation around a single 100G DWDM solution



- 100G standardization coordinated among **ITU, IEEE,** and **OIF**
- Proactively eliminate interop issues encountered with 40G

Inter-DC connectivity in the Cloud-era

More than DCI



- Enterprise Data Center inter-connect
- Enterprise Data Center to Provider Data Center
- Provider Data Center to Provider Data Center

“DCI” with varying requirements:

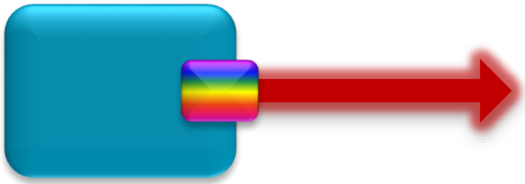
- Multiple data rates needs
- Higher Density Interconnect in metro
- Intra DC architecture extend beyond metro

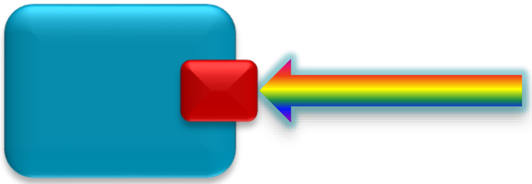
Tunable lasers and coherent receivers key enablers

Key enablers

Transmitter can tune its laser's frequency to any channel in the ITU grid.

Receiver can select any channel from of a composite (unfiltered) signal.



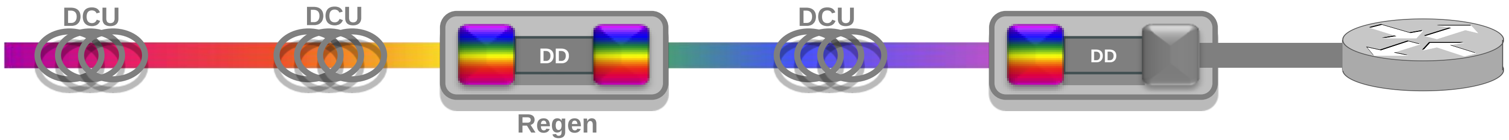


Tunable lasers work with colorless add/drop to enable touchless changes in the frequency of an optical signal. Coherent receivers simplify the construction of colorless and omni-directional ROADM nodes, by eliminating the need to de-multiplex a signal down to the individual wavelength.

100G Technology: Coherent Detection

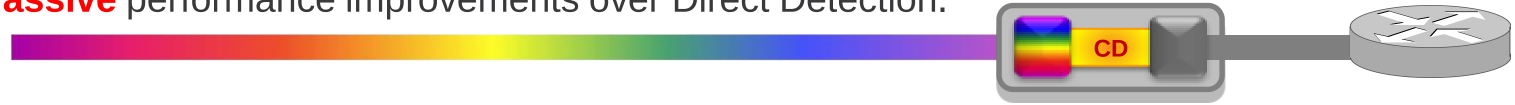
Direct Detection

- **Must correct for impairments in the physical domain** (insert DCU’s)
- Forced to live with non-correctable impairments via network design (limit distance, regenerate, adjust channel spacing)
- Dumb detection (OOK), no Digital Signal Processing, only FEC



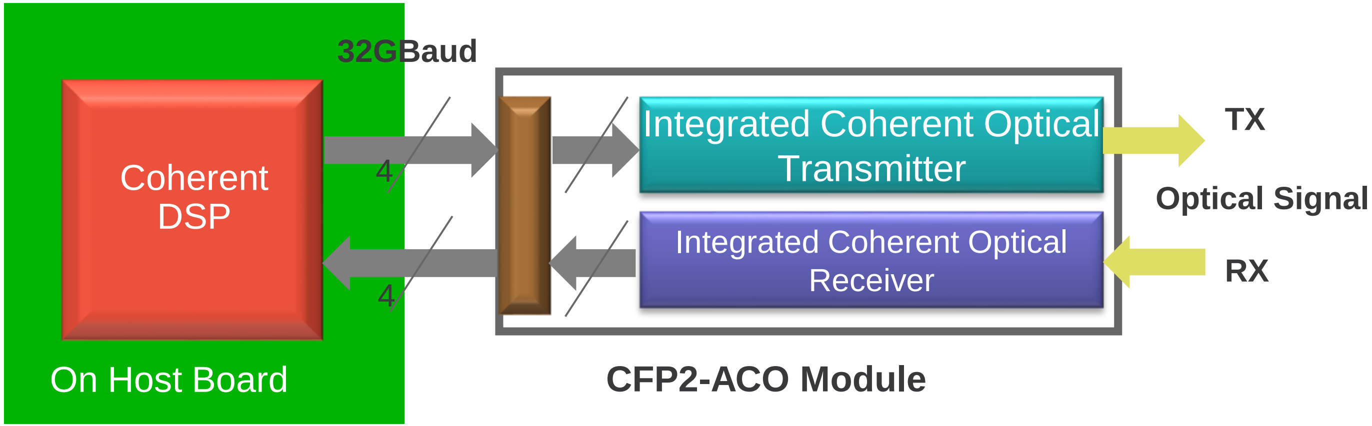
Coherent Detection

- **Moves impairment correction from the optical domain into the digital domain**
- Allows for digital correction of impairments (powerful DSP) vs. physical correction of impairments (DCU’s). Adds advanced FEC.
- **Massive** performance improvements over Direct Detection.



DCU – Dispersion Compensation Unit

Line Side Pluggable Optics- e.g. CFP2 ACO – Coherent Optics Pluggable



Optics in the pluggable CFP2, electronics on the line card

Reduces the components inside the module – improved power management

Only a CFP2-ACO can be used on the port; not gray optics

ACO → Analog Coherent Optics

Pluggable Optics

State of the art 28nm integrated ASIC

Multiple Line rates – Distance vs reach trade-off

Soft Decision FEC – Double the reach

Nyquist shaping – ~30% more capacity

Pluggable

Field replaceable

Deferrable

Thermal efficiency

100G — 9.6Tbps 4000Km +

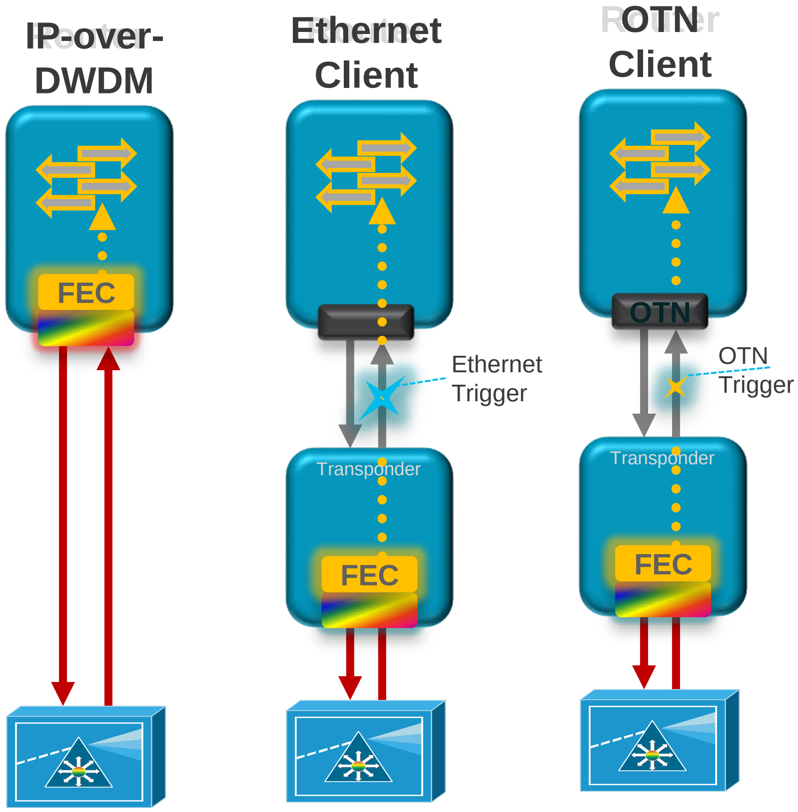
200G — 19.2Tbps 800Km

250G — 24Tbps 500Km

96 channel DWDM system

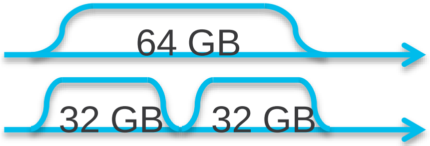
High Speed Client Implementations
Interface Independent Functionality

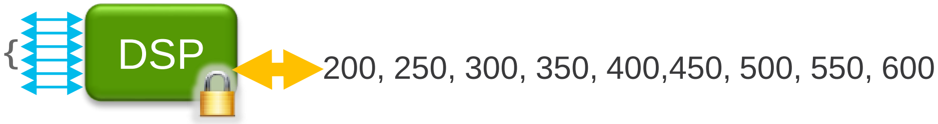
- **IP-over-DWDM**
  - Pre-FEC error threshold is monitored directly by router
  - RP initiates fast re-route based on internal trigger directly from PLIM
- **Gray Client - Ethernet**
  - Pre-FEC error threshold is monitored by transponder
  - Ethernet trigger is generated by transponder and sent to router which initiates fast re-route
- **Gray Client - OTN**
  - Pre-FEC error threshold is monitored by transponder
  - OTN PF-FDI trigger is generated by transponder and sent to router which initiates fast re-route
  - OTN interface monitors end-to-end path



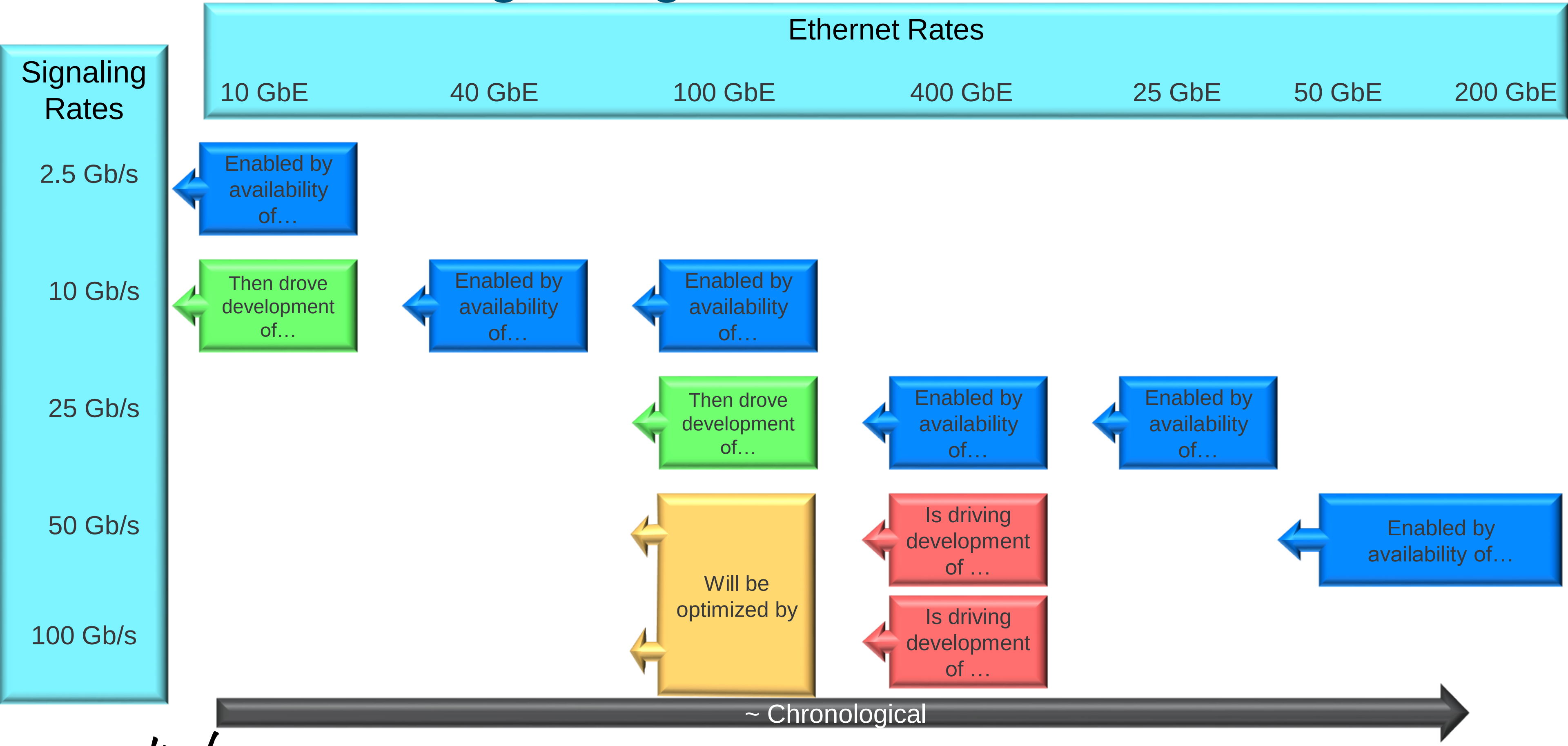
Line Interfaces – Developments

- **Doubling of baud rates**
- **Higher data rates**: 200G, 400G, 1T
- **Flex Ethernet ...**
- **Flex Spectrum**
- **Encryption**
- **Flexible modulation techniques**
  - PM-BPSK, PM-QPSK, PM-16QAM, PM-64QAM, ….
  - All come at the expense of reduced distance
- Hybrid Modulation for Improved capacity
- **Spectral Efficiency**
  - Nyquist Filtering
  - Dynamic bandwidth filters (Flex spectrum ROADM technology)



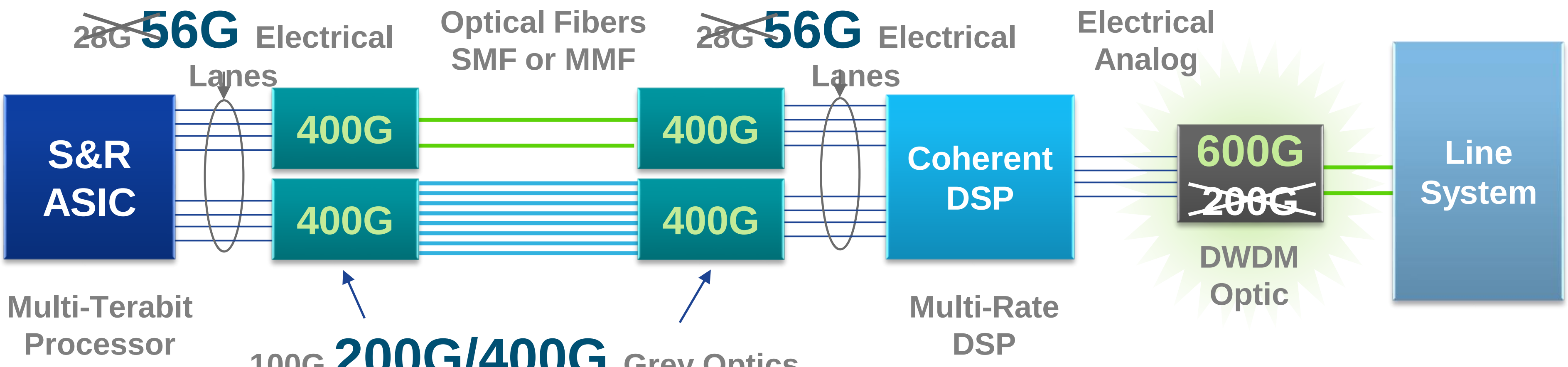


Ethernet and signaling rates



Cisco live!

What Will Change to Continue to Scale?



100G **200G/400G** Grey Optics

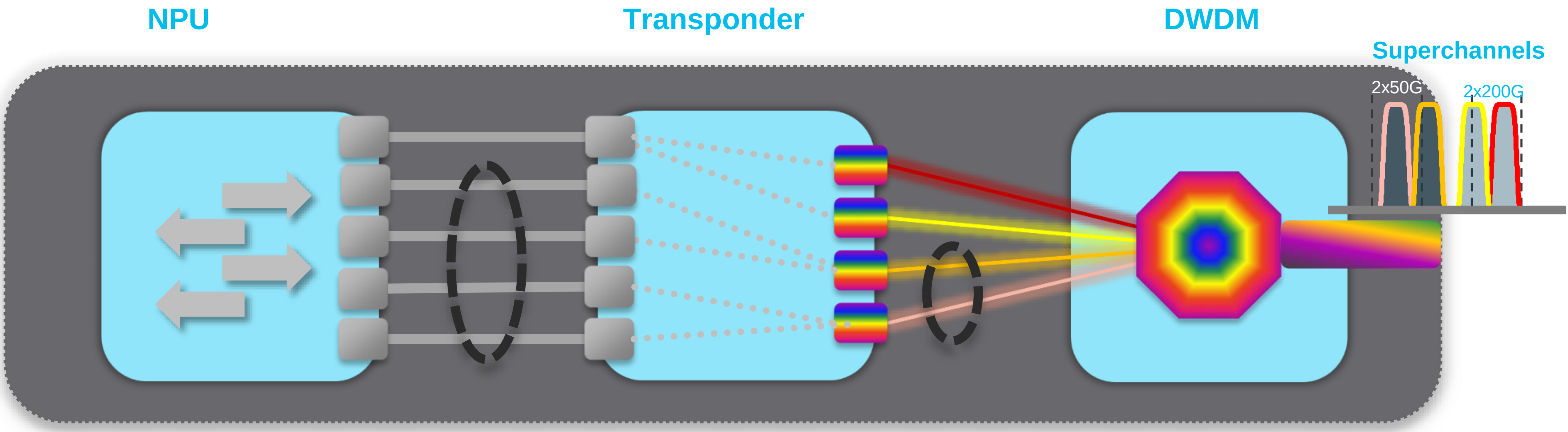
SR-10, SR-4, CWDM-4, LR-4 Lite, LR-4

+8QAM
+32QAM
+64QAM
Double Baud Rate

- **Client Side Optics:** QSFP28, QSFP56, QSFP28-DD, QSFP56-DD, COBO
- **Flexibility**: FlexE, FlexMod, and FlexRate

Network Optimizagtion ....

Flexible, efficient and dynamic mapping of packet services to optical transport



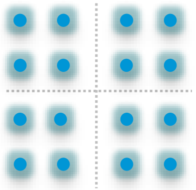
Flex FlexE
Flexible nx/25G
interconnects

Flex Mod
50G/100G/200/250G/+
DWDM interfaces

Flexspectrum
12.5/50Ghz/100Ghz
DWDM systems

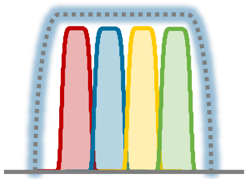
Tools to Increase and Optimize System Capacity

Speed up & WDM & Modulation



Multi-Modulation

Adjust spectral efficiency by transmitting more or less bits per symbol at a given baud rate

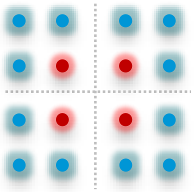


Superchannel Formation

Optimize spectral efficiency by tightly spacing sub-carriers using Flex-Spectrum ROADM

Flex Baud Rate

Increase the bit rate by increasing the rate at which symbols are transmitted

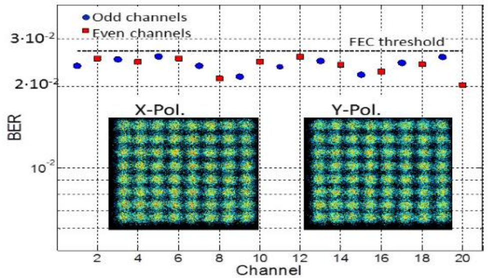


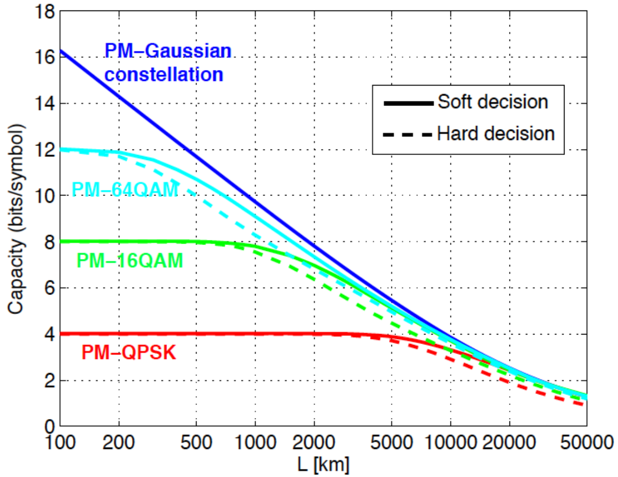
Hybrid Modulation

Mix different modulation formats in the time domain to achieve a greater bandwidth/distance granularity

Higher order modulation schemes

	BPSK	QPSK	8-QAM	16-QAM	64-QAM
Bits/ Symbol (2 pol.)	2	4	6	8	12
Capacity @32Gbaud	50G	100G	150G	200G	300G





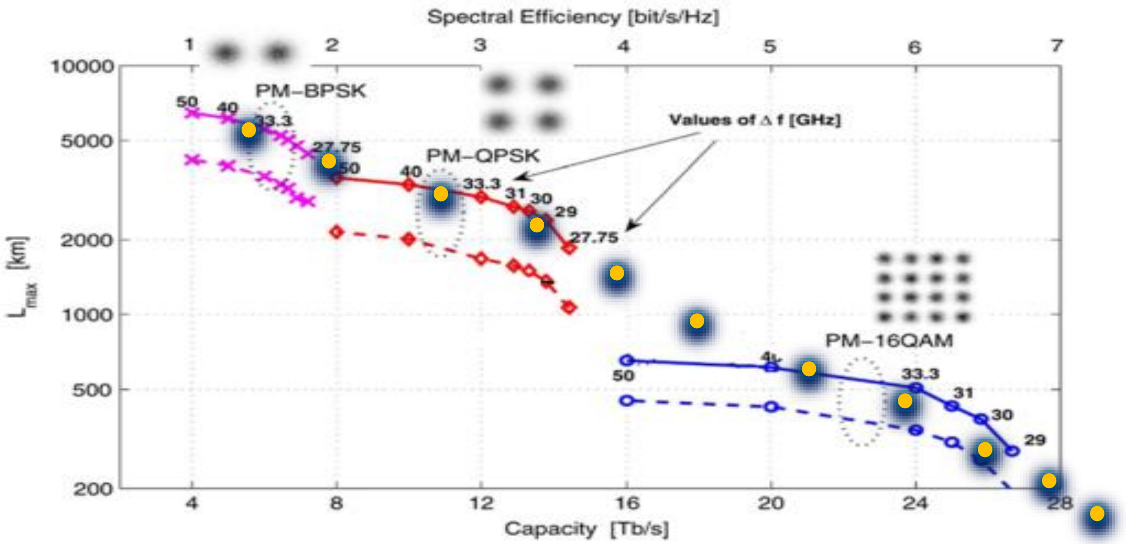
Increasing the capacity per WDM channel requires sending more complex signals; trading between spectral efficiency and reach

3x (64-QAM vs QPSK) gain

Optimize Data Rate vs Distance

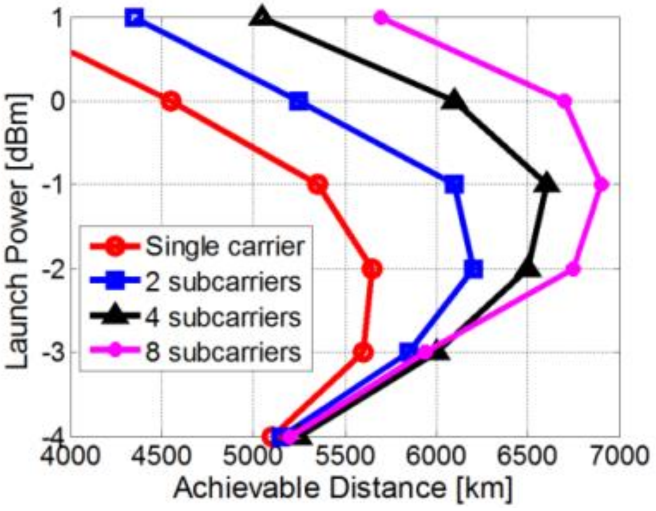
Flexible Modulation (FlexMod)

- Different modulations provide different capacity
- Different modulations provide different reach
- Chip sets provide the ability to SW config Capacity vs Reach
- Flex Mod will close the Gap and provide for 25Gig granularity



Baud rate increase

- Higher baud rates
  - 2x rate (1/2 carriers), but with Nyquist spectral density improvements only below 5%
  - While higher NLI and implementation impairment might indeed affect reach/bandwidth.

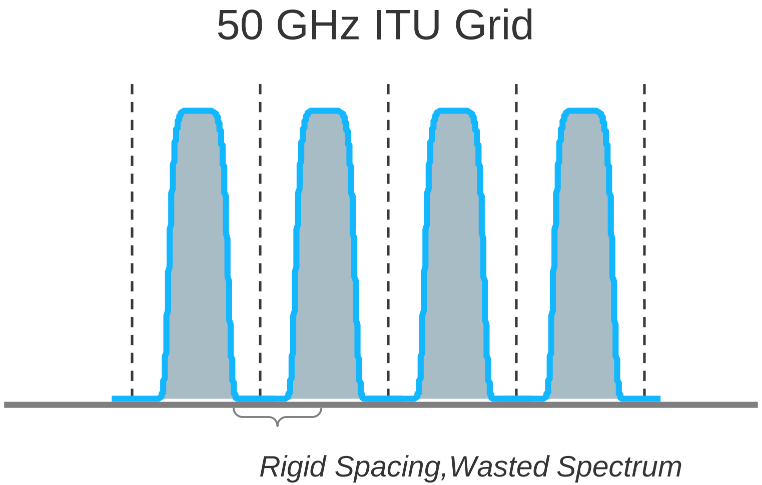


Meng Qiu, Qunbi Zhuge, Xian Xu, M. Chagnon, M. Morsy-Osman, and David V. Plant 'Subcarrier Multiplexing Using DACs for Fiber Nonlinearity Mitigation in Coherent Optical Communication Systems,' in
Proc. OFC 2014, paper Tu3J.2, San Francisco (CA), Mar. 2014.

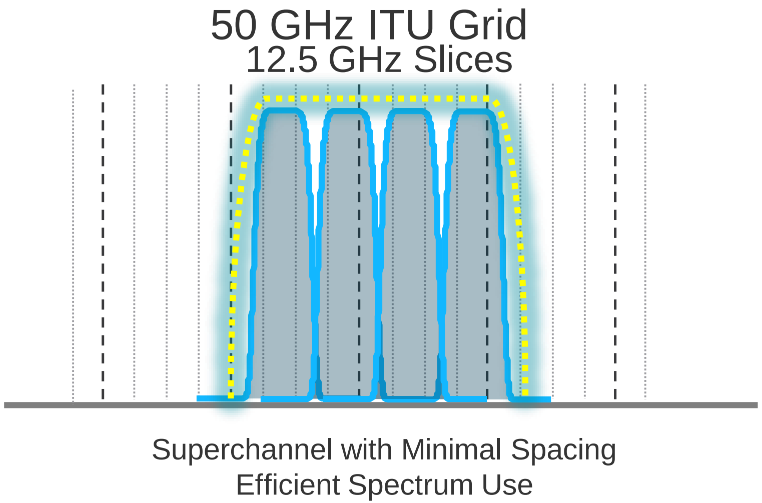
- Will higher baud rate be really required by bandwidth demand ?
  - No, transport over multiple wavelengths will be supported by new protocols (FlexE, OTUCn)
  - But cost and real estate reduction will justify it.

DWDM Network capacity limited by channel spacing imposed with fix ITU Grid

Superchannels require a new kind of ROADM, one that can switch chunks of bandwidth larger and yet more granular than 50GHz



Each 50GHz carrier provisioned and switched individually



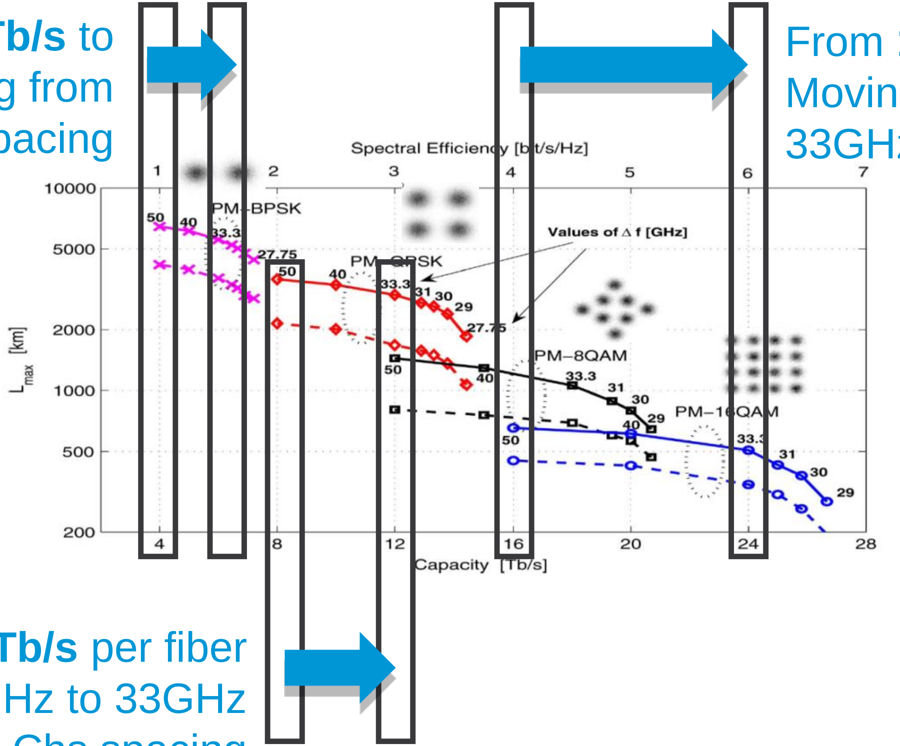
Superchannel switched through the ROADM network as a single entity

This requires Flexible Spectrum allocation – Flex Spectrum

FlexSpectrum & Capacity Relationships

80ch system: From **4Tb/s** to **6Tb/s** per fiber Moving from 50GHz to 33GHz Chs spacing

From **16Tb/s** to **24Tb/s** Moving from 50GHz to 33GHz Chs spacing

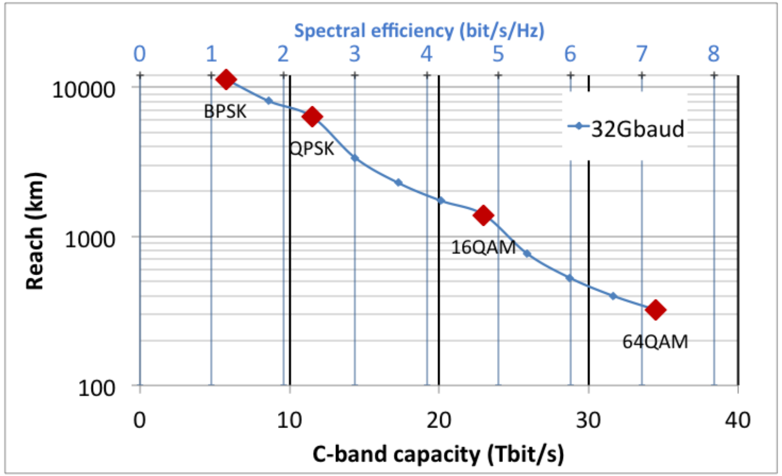


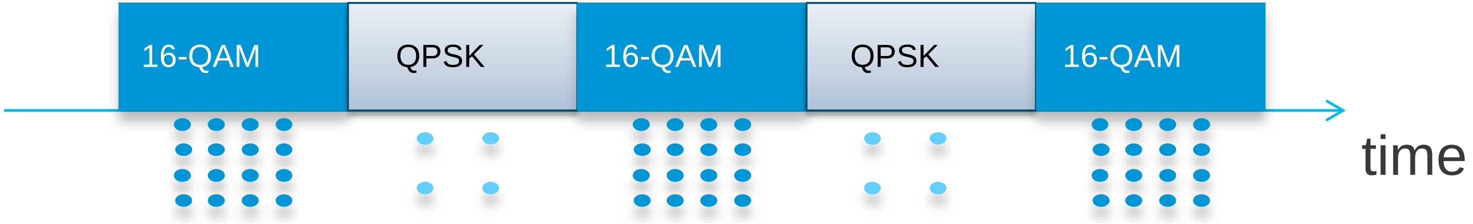
From **8Tb/s** to **12Tb/s** per fiber Moving from 50GHz to 33GHz Chs spacing

Adoption of hybrid modulation

Interleaving of different modulation schemes symbols enables continuous optimization of the capacity for every reach.

Flex Mod and Flex E allows for the mixing of different Constellations providing for 25GHz of Data Rate Granularity





Hybrid Modulation

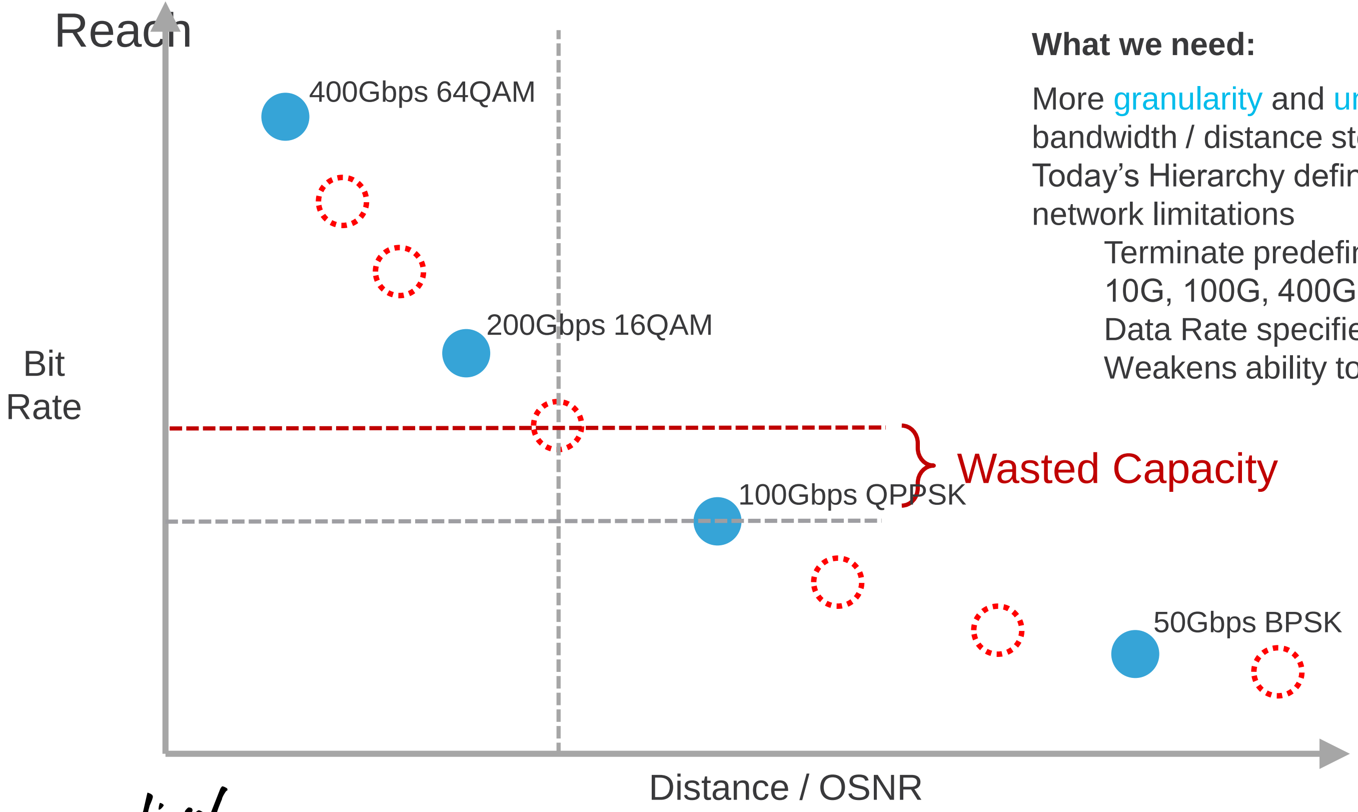
- Mix of constellations in the time domain
- Variable reach
- Signal processing needs only small changes
- Add one new modulation format

Time Domain →

32 GBaud	BPSK	BPSK	BPSK	BPSK	BPSK	BPSK	BPSK	50G
	BPSK	QPSK	BPSK	QPSK	BPSK	QPSK	BPSK	
	QPSK	QPSK	QPSK	QPSK	QPSK	QPSK	QPSK	
	QPSK	QPSK	QPSK	16QAM	QPSK	QPSK	QPSK	
	QPSK	16QAM	QPSK	16QAM	QPSK	16QAM	QPSK	
	16QAM	16QAM	QPSK	16QAM	16QAM	16QAM	QPSK	
	16QAM	16QAM	16QAM	16QAM	16QAM	16QAM	16QAM	200G
	16QAM	16QAM	16QAM	64QAM	16QAM	16QAM	16QAM	
	16QAM	64QAM	16QAM	64QAM	16QAM	64QAM	16QAM	
	64QAM	64QAM	16QAM	64QAM	64QAM	64QAM	16QAM	
	64QAM	64QAM	64QAM	64QAM	64QAM	64QAM	64QAM	300G
42 GBaud	16QAM	16QAM	16QAM	64QAM	16QAM	16QAM	16QAM	
	16QAM	64QAM	16QAM	64QAM	16QAM	64QAM	16QAM	
	64QAM	64QAM	16QAM	64QAM	64QAM	64QAM	16QAM	
	64QAM	64QAM	64QAM	64QAM	64QAM	64QAM	64QAM	400G
56 GBaud	16QAM	16QAM	16QAM	64QAM	16QAM	16QAM	16QAM	
	16QAM	64QAM	16QAM	64QAM	16QAM	64QAM	16QAM	
	64QAM	64QAM	16QAM	64QAM	64QAM	64QAM	16QAM	
	64QAM	64QAM	64QAM	64QAM	64QAM	64QAM	64QAM	600G

Dynamic Data Rates

Current Solutions are Still too Inflexible – FlexE and FlexMod optimize Capacity vs Reach



What we need:

More granularity and uniformity of bandwidth / distance steps

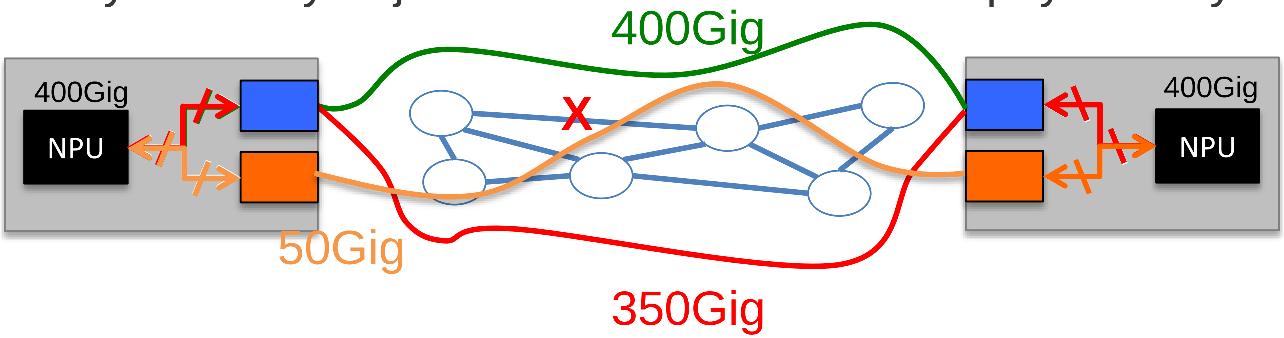
Today's Hierarchy defined in the IEEE and ITU provides network limitations

- Terminate predefined Standard Data Rates 10G, 100G, 400G, …. 1.6T?
- Data Rate specified by reach
- Weakens ability to optimaze DR vs. Reach

Optimize Data Rate vs Distance

Flex Ethernet (FlexE) – World's first Demo OFC 2016

- Ability to leverage the full capacity of the NPU
- Ability to specify any Data Rate with no Hashing inefficiencies
- Ability to grow the Data Rate in 25/50G granularity upto max NPU capacity independent of IEEE or ITU hierarchies
- Ability to dynamically adjust data rates to match the physical layer performance

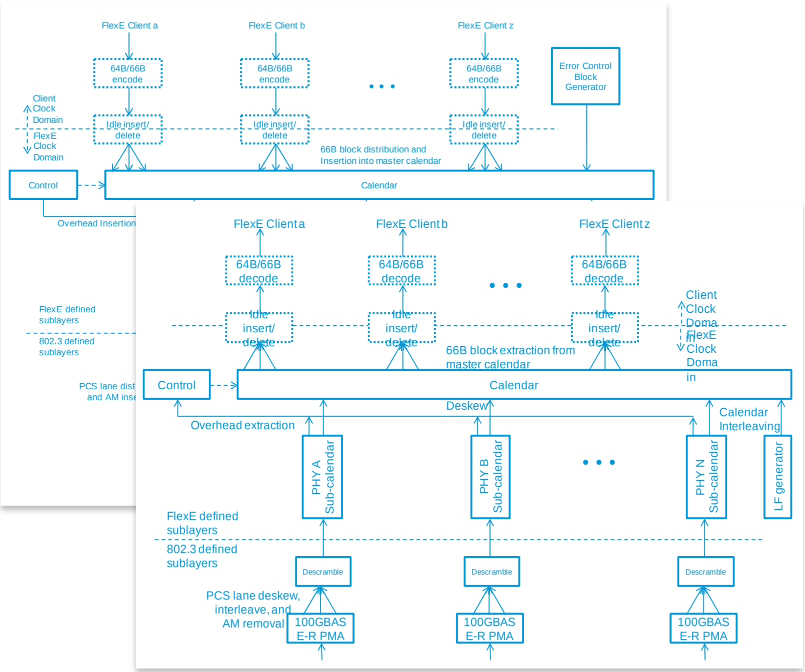


Truly Optimize Data Rate vs Reach

Optimize Data Rate vs Reach

Flex Ethernet – Beak existing dependencies

- Enable flexibility on Ethernet interface:
  - Eliminate existing Hierarchies - Custom rates
  - Eliminate LAG Inefficiencies
  - Match transport bandwidth
  - Break Ethernet and transport roadmap marriage
- Standardized under OIF
- Effort initially patented by Cisco
- Implementation led by Cisco, Google, Juniper and others



Above figures are copied from the OIF FlexE 1.0 Implementation agreement. Available on oiforum.com early in 2016.

Optimizing Transmission Efficiency

NPU	Friction	Ethernet	Friction	Transponder	Friction	DWDM
200G ↓ Terabits		10G 25G 40G 50G 100G 200G 400G		50G 100G 150G 200G 250G 300G 350G 400G 450G, 500G, 550G, 600G		ITU 50GHz Grid Flex Grid

NPU Capacity Growing **Interconnect Efficiency** **Spectrum Efficiency**

We need to reduce friction between different layers of the network to get the Client side, Line side optics, Flex modulation, FlexE, FlexGid innovations are the key to success

Summary

Agenda

- Introduction
- Industry and Market Trends
- Industry Standards
- Client Side Optics - Technologies
- Line Side Optics -Technologies
- Conclusion

Alignment Needed to Achieve TCO Goals

DC Network Infrastructure

ASIC BW & Port Speed

Cabling Infrastructure

Optics Speed and Size

- Innovation
- Standardization
- Open Ecosystems

Summary - Trends

- Transition infrastructure to duplex fiber for lower overall cost
- Balance choice of optics with cost, reach, power, density, performance and packaging
- Move to high speed optics in the DC fabric improves application performance
- CMOS photonics enables enable new generation of SMF optics (CPAK) and beyond
- Move to SMF backbone in DC will require low cost short reach SM optics
- Evolution of high speed optics will enable flexible bandwidth, increased system performance, drive network architecture and facilities consideration
- Cisco continues to invest and lead the industry in optics innovation to drive to lower cost structure.

Summary

- New Ethernet rates combined with line side DWDN advances will drive greater efficiency
- Higher cost sensitivity & shorter investment cycles at the edge
- Backward compatibility will de-couple investment cycles for server/ ToR & aggregation switching
- Flex Spectrum and Flex Modulation are a good start towards flexibility of trading off bandwidth vs. distance
- Hybrid Modulation plus Flex Ethernet will allow operators to squeeze every bit of bandwidth out of their networks.

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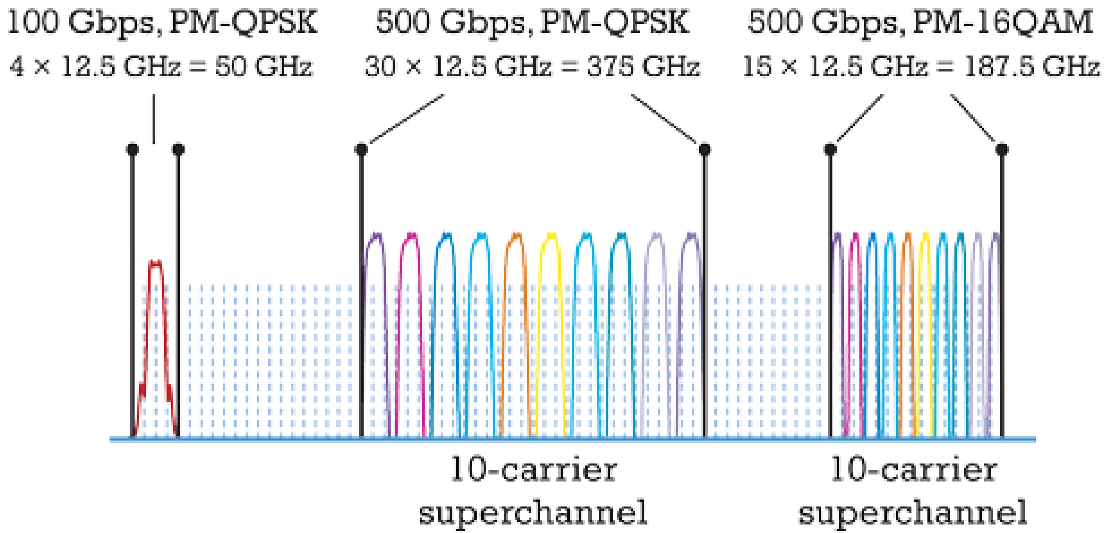
Reference / Backup Slides

For your reference

ITU-T Superchannels



WDM channels with a granularity of 12.5 GHz, and
Ability to define an aggregate superchannel spectral width of N × 12.5 GHz
Accommodates any combination of optical carriers, modulations, and data rate.