

IEEE 802.3 NEA Ad hoc 29 Oct 2020

IEEE 802.3 Call for Interest
CFI Consensus Presentation

“Beyond 400 Gb/s Ethernet”



OBJECTIVE FOR THE MEETING

- To measure the interest in starting a study group to address “Beyond 400 Gb/s Ethernet”
- We don't need to
 - Fully explore the problem
 - Debate strengths and weaknesses of solutions
 - Choose any one solution
 - Create PAR or five criteria
 - Create a standard or specification
- Anyone on the call may speak / vote
- RESPECT... give it, get it

Contributors

- John D'Ambrosia, Futurewei, U.S. Subsidiary of Huawei
- Matt Brown, Huawei Canada
- Joel Goergen, Cisco
- Mark Gustlin, Cisco
- Cedric Lam, Google
- Mike Li, Intel
- Ilya Lyubomirsky, Inphi
- Osa Mok, Innolight
- Gary Nicholl, Cisco
- Shawn Nicholl, Xilinx
- Mark Nowell, Cisco
- David Piehler, Dell Technologies
- Ted Sprague, Infinera
- Rob Stone, Facebook
- Jim Theodoras, HG Genuine
- Nathan Tracy, TE Connectivity
- Xinyuan Wang, Huawei
- George Zimmerman, CME Consulting
- Also
 - IEEE 802.3 2020 Ethernet Bandwidth Assessment
 - IEEE 802.3 NEA Ad hoc

Today's Panel

➤ **Speakers**

- **John D'Ambrosia, Futurewei (U.S. Subsidiary of Huawei)**
- **Ray Nering, Cisco**
- **Adam Healey, Broadcom**

➤ **Additional Panelists**

- **Cedric Lam, Google**
- **Rob Stone, Facebook**

AGENDA

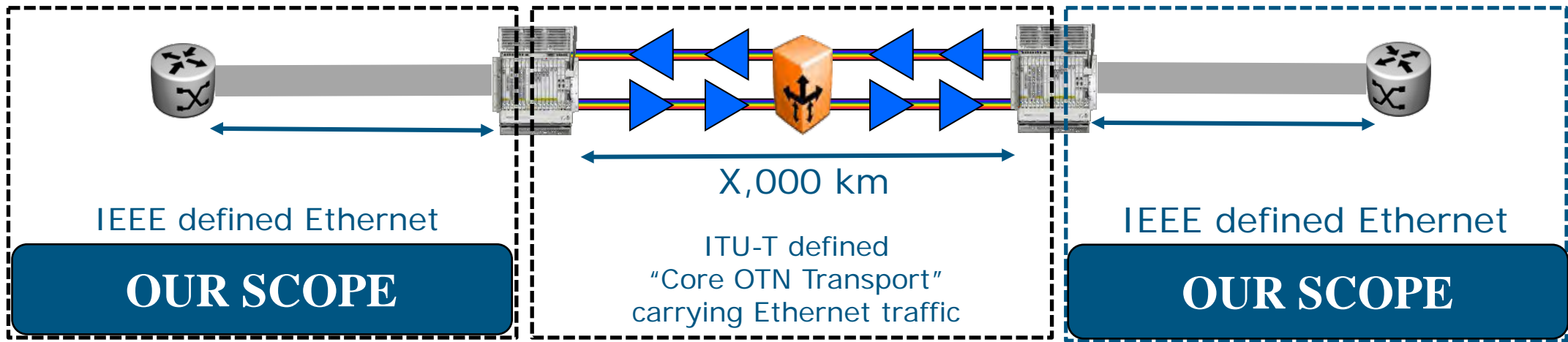
- **Introduction**
- **Presentations**
 - **Market Pressures for Beyond 400 GbE**
 - **The Technical Roadmap to Beyond 400 GbE**
 - **Beyond 400 GbE - Why Now?**
- **Straw Polls**
- **Future Work**

THE SCOPE OF ETHERNET TODAY

Scenario #1



Scenario #2



MARKET PRESSURES FOR BEYOND 400 GbE

Presented by
Ray Nering



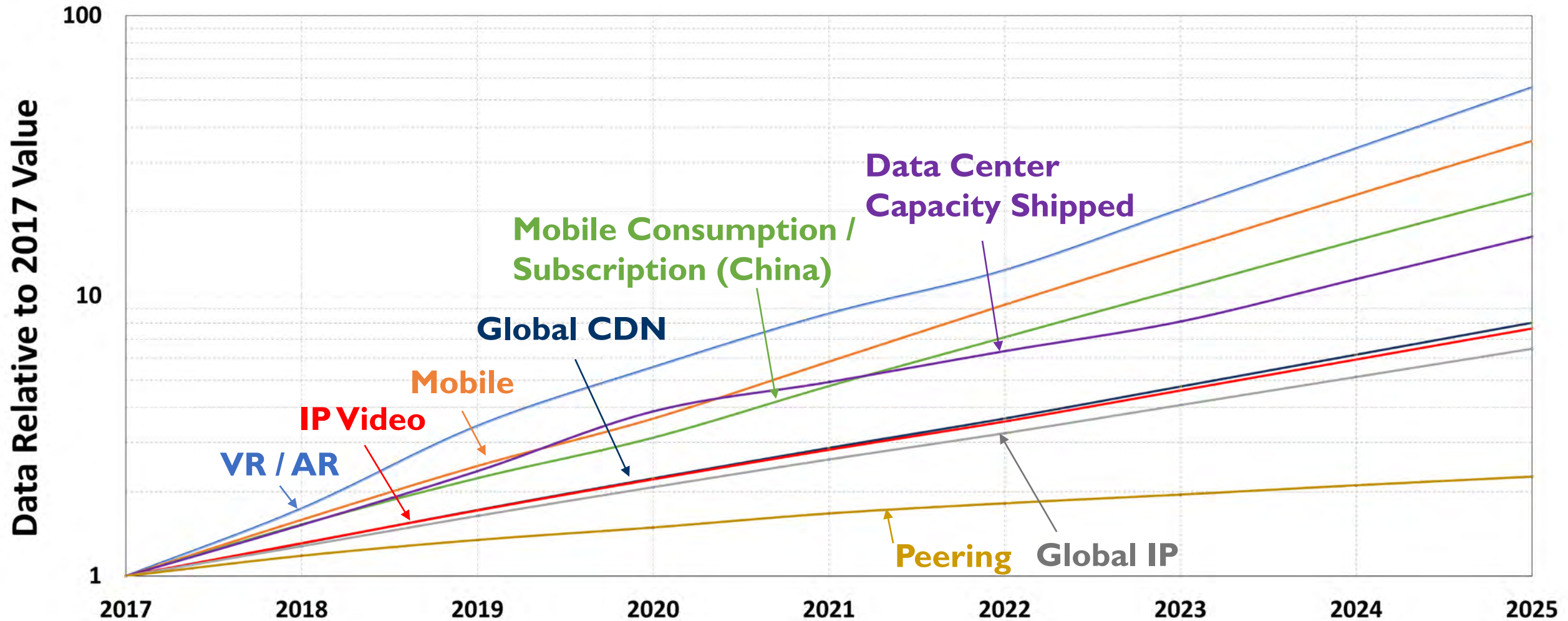
THE SONG REMAINS THE SAME

- **2020 Ethernet Bandwidth Assessment (BWA)** documented latest analysis of industry bandwidth needs and driving factors

Increased # of users x **Increased access methods and rates** x **Increased services** = **Bandwidth Explosion**

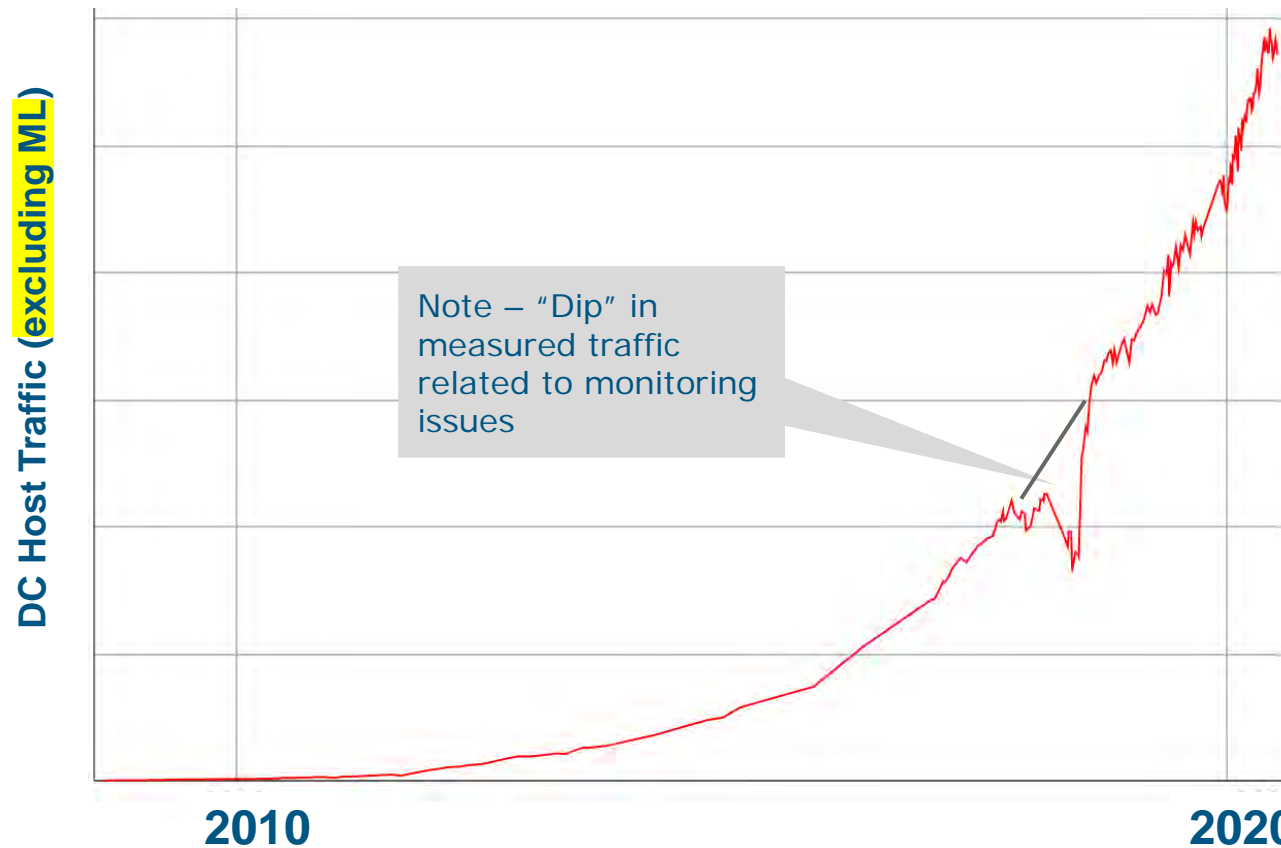
- **2020 Ethernet BWA**
 - Report - <https://bit.ly/802d3bwa2>
 - Tutorial – https://bit.ly/802d3bwa2_tut
- Reference slides in Appendix: Backup Slides

The 2020 Ethernet Bandwidth Assessment



DATA CENTERS CONTINUE AS A PRIMARY DRIVER

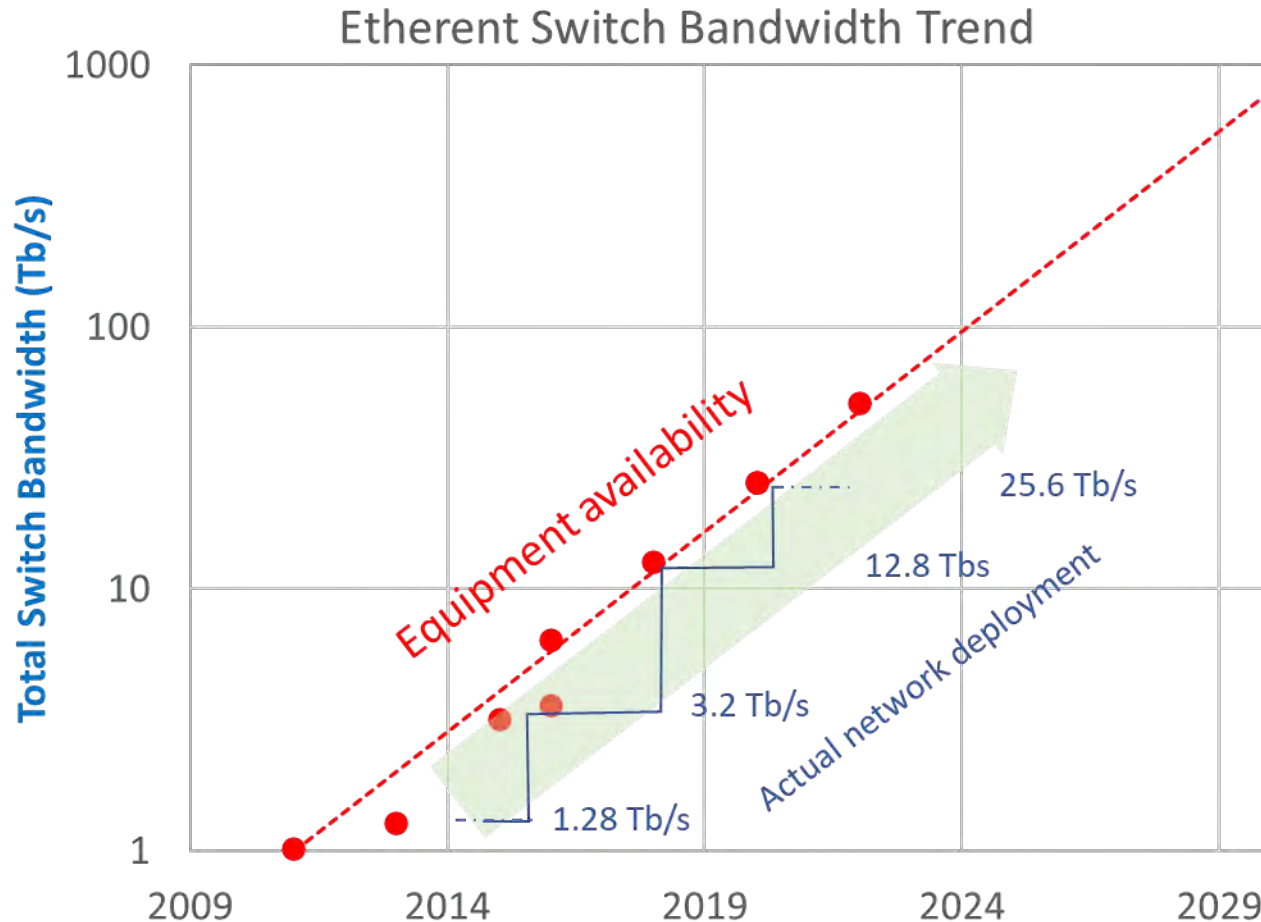
DC Traffic Continues to Grow Rapidly (Regular Servers)



Google

Courtesy - Cedric Lam, Google

Hyperscale Ethernet Deployment – Total Switch Bandwidth



Actual network deployment of higher capacity switches is driven by traffic demands as well as operational considerations:

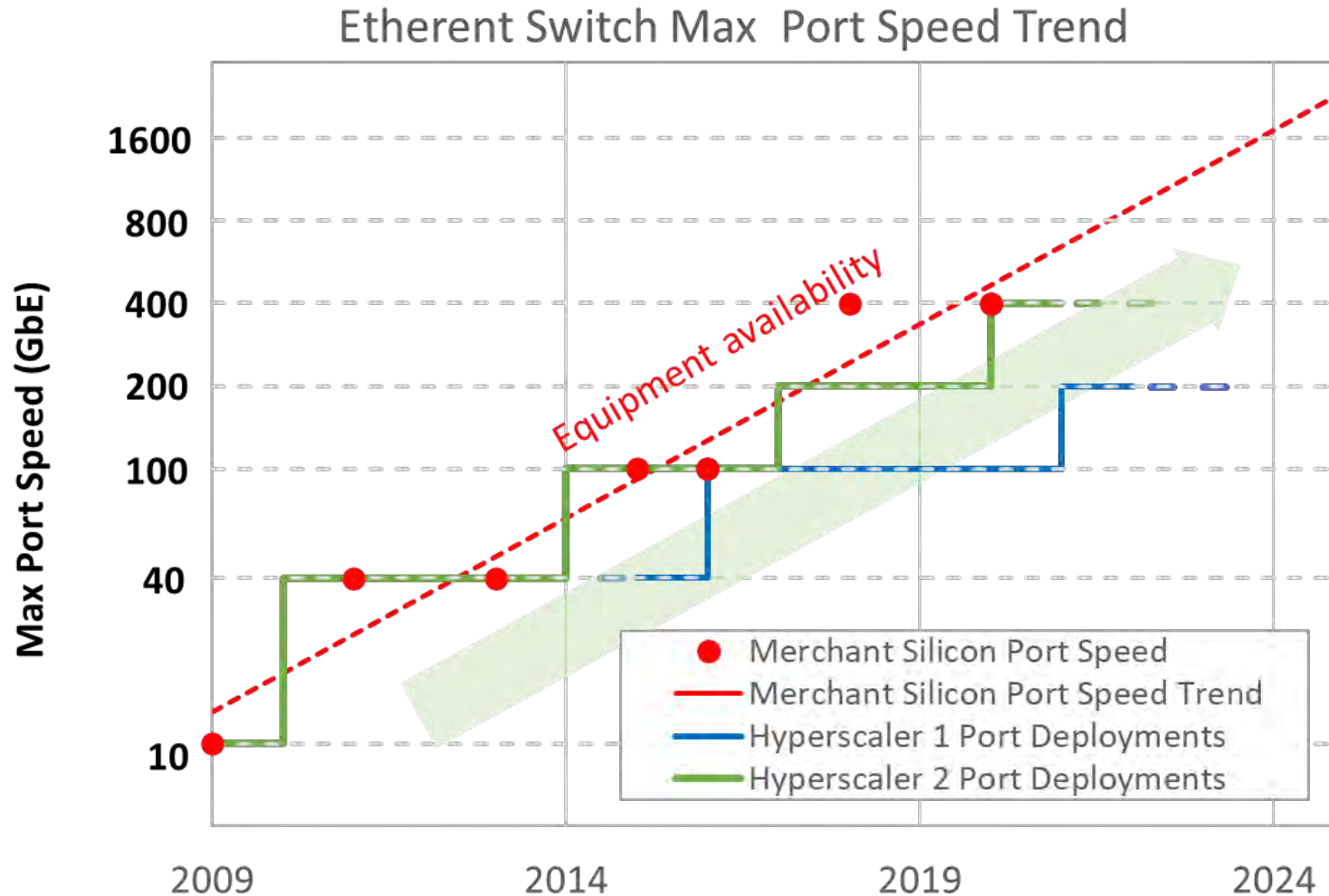
- Cost
- Power
- Network Architecture (e.g. Radix)

Deployment can occur quite quickly after availability

Key observation: Network needs are driving switch capacity developments

Courtesy of:
Rob Stone, Facebook
Cedric Lam, Google
Mark Nowell, Cisco

Hyperscale Ethernet Deployment – Port Speed



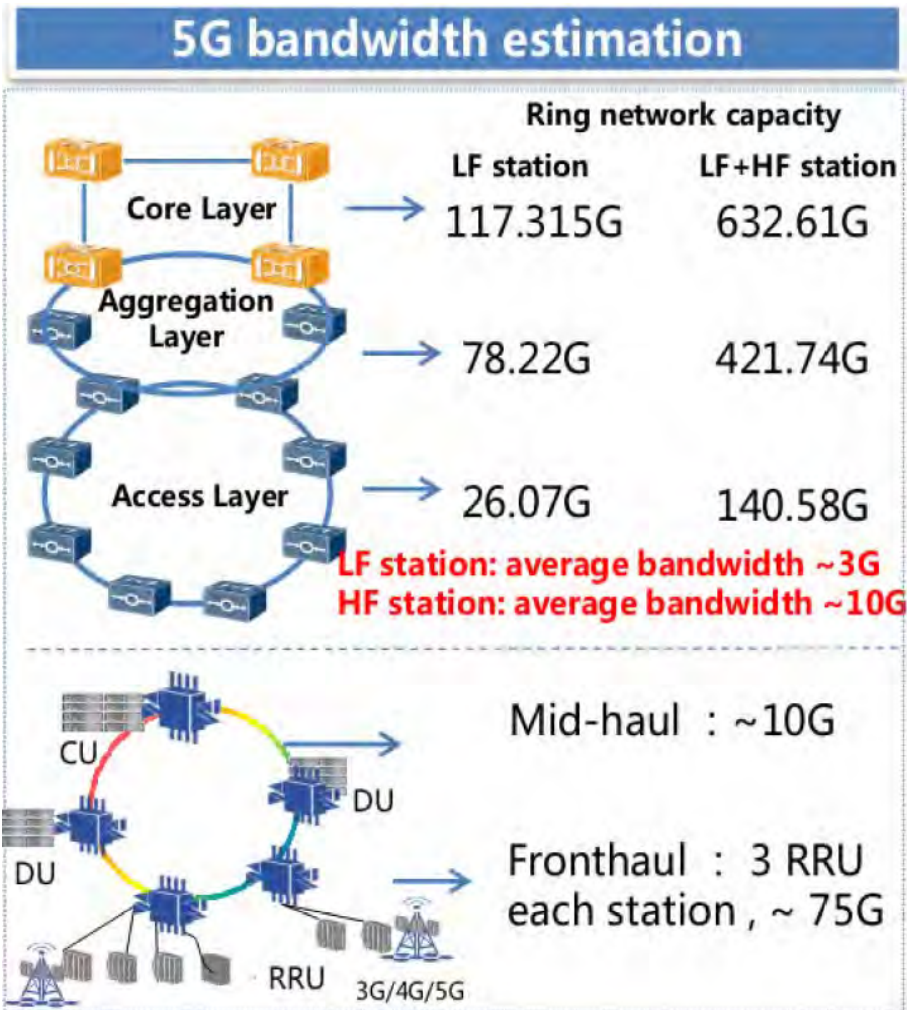
Key observation:

Network capacity needs are driving increased max port speeds.

Beyond 400 GbE port speed is required to support continued bandwidth demand

Courtesy of:
Rob Stone, Facebook
Cedric Lam, Google
Mark Nowell, Cisco

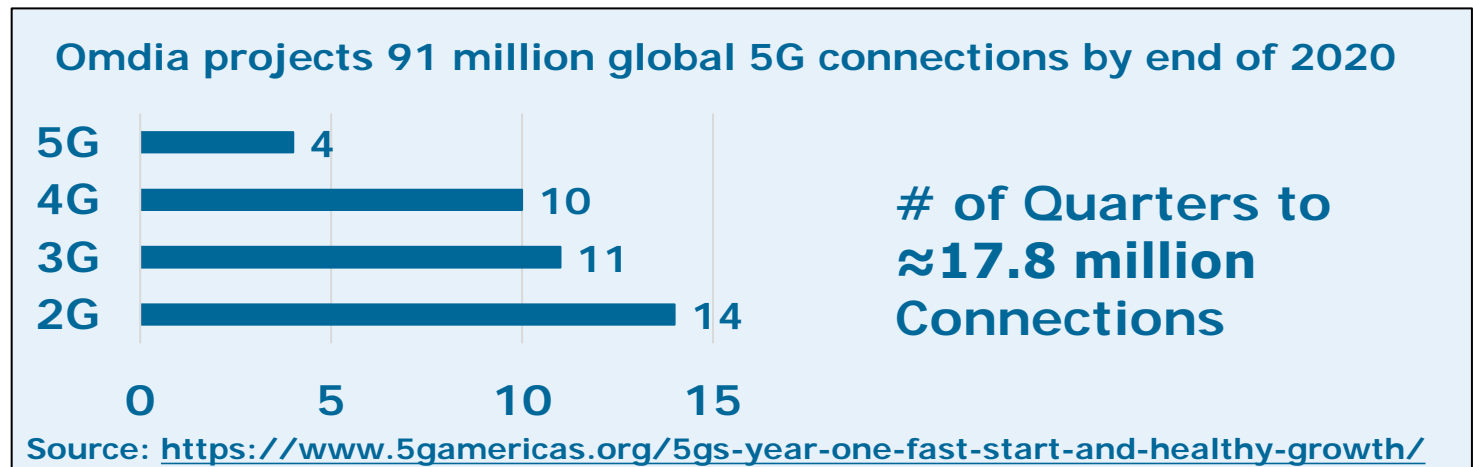
EXAMPLE EMERGING APPLICATION – 5G BACKHAUL



Source: http://www.ieee802.org/3/B10K/public/18_01/wang_b10k_01b_0118.pdf

# of Networks Deployed	LTE	LTE Advanced	5G
Africa	145	42	4
Asia & Pacific	162	74	29
Eastern Europe	93	59	14
Latin America & Caribbean	127	50	8
Middle East	44	29	12
U S & Canada	20	11	7
Western Europe	88	70	31
Global Totals	683	335	105

Source: as of 8/14/2020, <https://www.5gamericas.org/resources/deployments/>



ARTIFICIAL INTELLIGENCE & COMPUTE

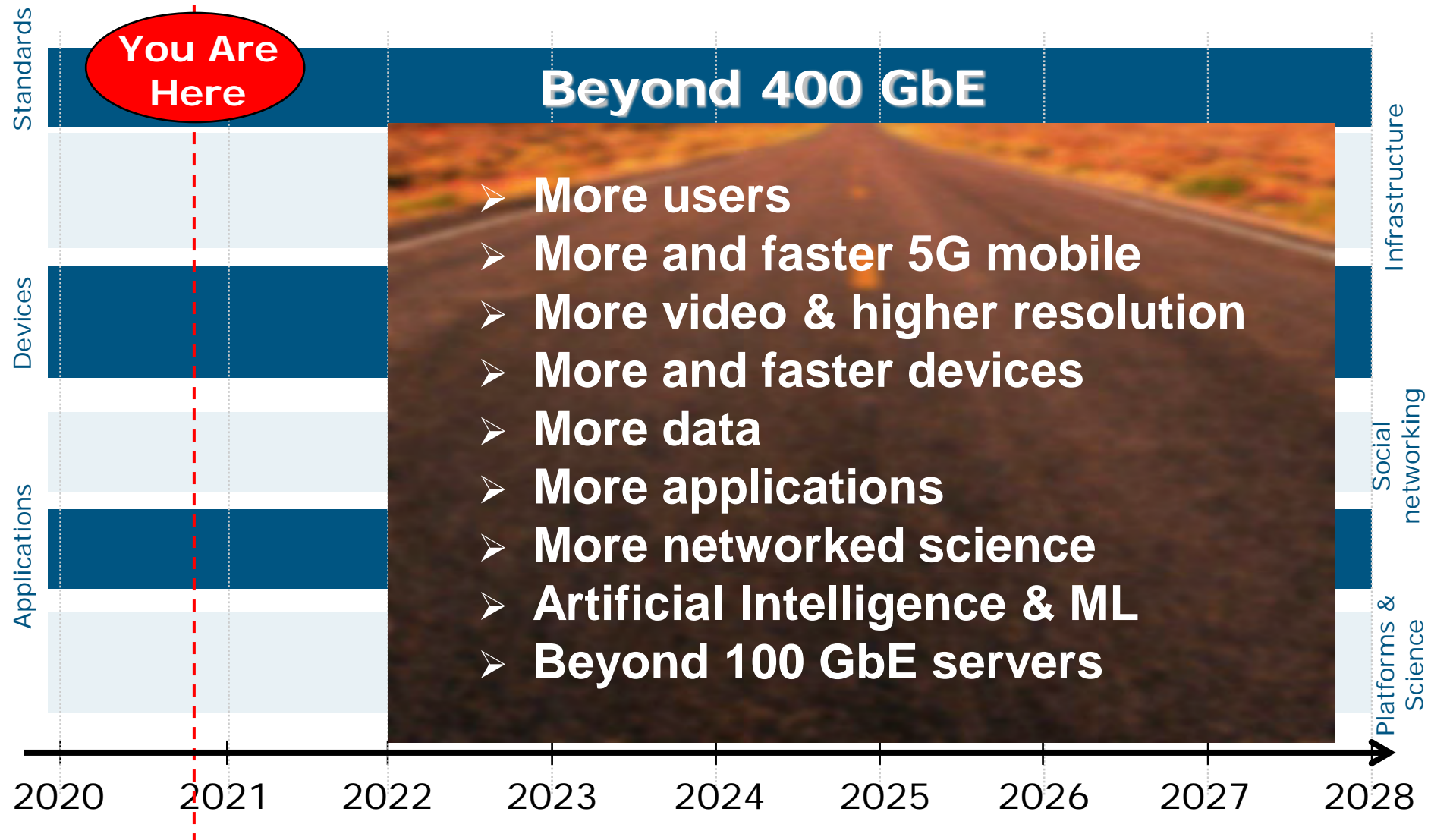
- **First Era (Before 2012)**
 - Moore's Law – 2-year doubling
 - Uncommon to use GPUs for machine learning
- **Modern Era (2012 and later)**
 - **2012 – 2014: most results used 1-8 GPUs rated at 1-2 TFLOPS**
 - **2014 – 2016: large-scale results used 10-100 GPUs rated at 5-10 TFLOPS**
 - **2016 – 2017: greater algorithmic parallelism (huge batch sizes, architecture search, expert iteration), specialized hardware (TPUs), faster interconnects**

Two Distinct Eras of Compute Usage in Training AI Systems



Source – OpenAI blog post ‘AI and Compute’ addendum ‘Compute used in older headline results’ posted 7th November 2019 by Girish Sastry, Jack Clark, Greg Brockman and Ilya Sutskever <<https://openai.com/blog/ai-and-compute/>>.

MORE OF THE SAME.....



COVID-19 TRENDS, APRIL 2020



CAGR data from various industry sources and Inphi estimates

Source - Inphi blog post 'Bandwidth in the Age of COVID-19' posted 22nd April 2020 by Ford Tamer, President and CEO, Inphi Corporation <<https://www.inphi.com/blog/>>

SUMMARY

- **Bandwidth growth continues and underlying factors indicate further bandwidth growth**
 - **Video (recorded and live) and mobile!**
 - **Increasing delta between “peak” and “average”**
- **New applications fueling bandwidth growth**
- **In today’s COVID-19 world**
 - **Connectivity has been critical!**
 - **“Instantaneous” growth in multiple application spaces**
 - **Moving to telepresence, i.e. streaming video**
- **“Up and to the right” continues**

THE TECHNICAL TOOLBOX TO BEYOND 400 GbE

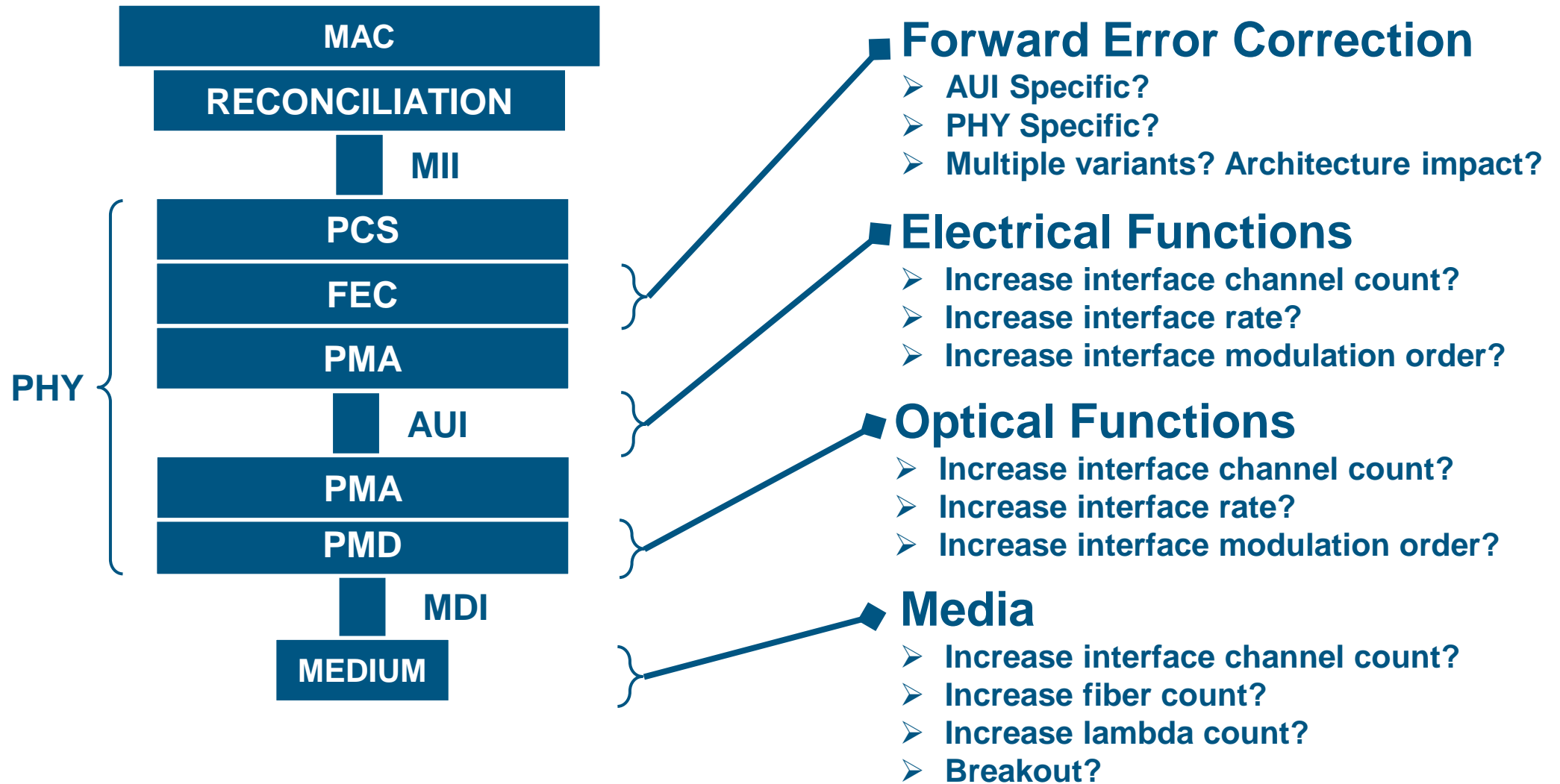
Presented by
Adam Healey



The Entire Ethernet Family Needs Considered



THE CHALLENGES TO BEYOND 400 GBE



MAC/PCS Technical Feasibility



- The options below are very feasible in near term technology (as an example, actual rate(s) are TBD)

MAC Rate	Technology Node	Device Type	Bus Width	Clock Rate
800 Gb/s	5 nm	ASIC	1024 b	800 MHz
	5 nm	ASIC	512 b	1.6 GHz
	7 nm	FPGA	1536 b	533 MHz
1.6 Tb/s	5 nm	ASIC	2048 b	800 MHz
	5 nm	ASIC	1024 b	1.6 GHz
	5 nm (or equiv)	FPGA	3072 b	533 MHz

Source – Mark Gustlin, Cisco; Mike Li, Intel; Shawn Nicholl, Xilinx

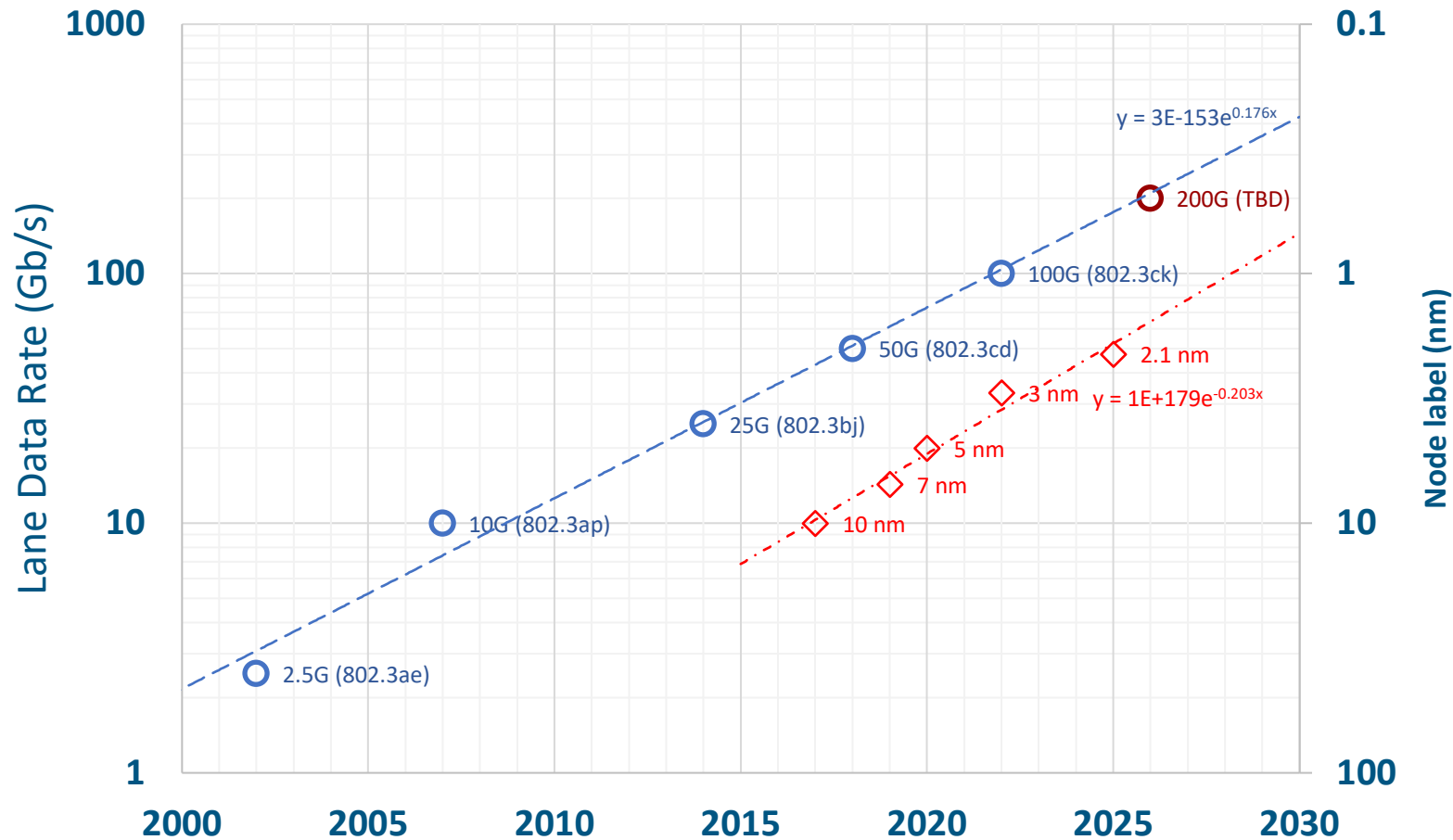
PCS/FEC

- **Previous PCS concepts could be re-used**
 - 64b/66b, transcoding, scrambling, AMs
- **Will likely want a new stronger FEC for 200 Gb/s lane (if the project chooses to define 200 Gb/s per lane)**
 - Multiple FEC options for direct detect, coherent light and longer reach coherent?
 - Still support end to end FEC for some options?
 - Optimize gain, latency, power and implementation burden for chosen FECs
 - While minimizing the overall number of FEC options

Source – Mark Gustlin, Cisco

CMOS Roadmap

Comparison of Lane Data Rate and Node Label Timelines



- The upper data (blue) shows evolution of electrical lane data rate over time.
- The lower data (red) shows the evolution of node label over time.
- Current designs for 100 Gb/s per lane are in 7 nm and are moving to 5 nm.
- 3 nm and 2.1 nm will be available when 200 Gb/s per lane is standardized.
- The node label (halving every 3.4 years) is progressing faster than the electrical lane rate (doubling every 3.9 years).

Source – Matt Brown, Huawei Canada

DSP Architecture Advances

Analog

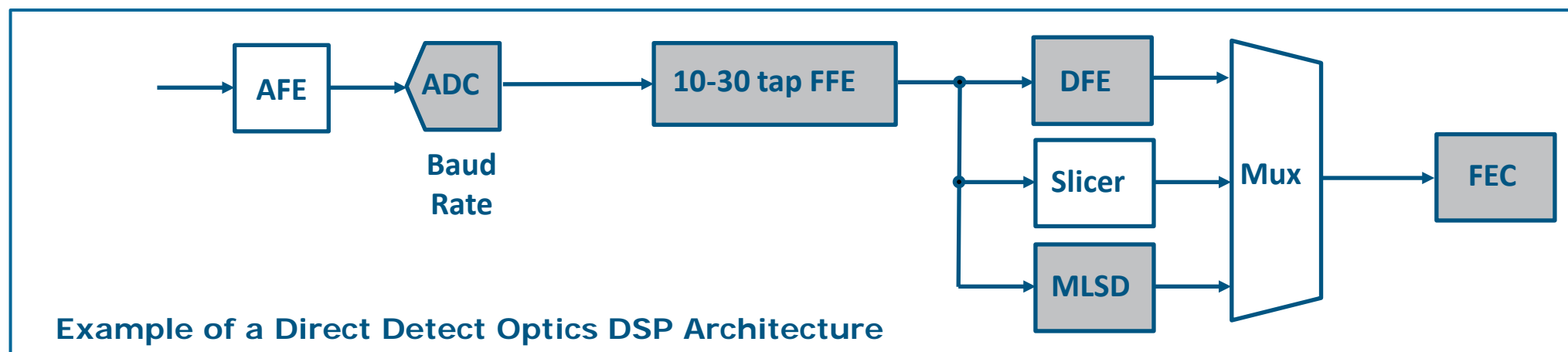
High Speed ADC enables
DSP Architectures

DSP

FFE, DFE, and MLSD for
stronger EQ

Coding

Leverage DSP soft
information for higher
coding gain FEC

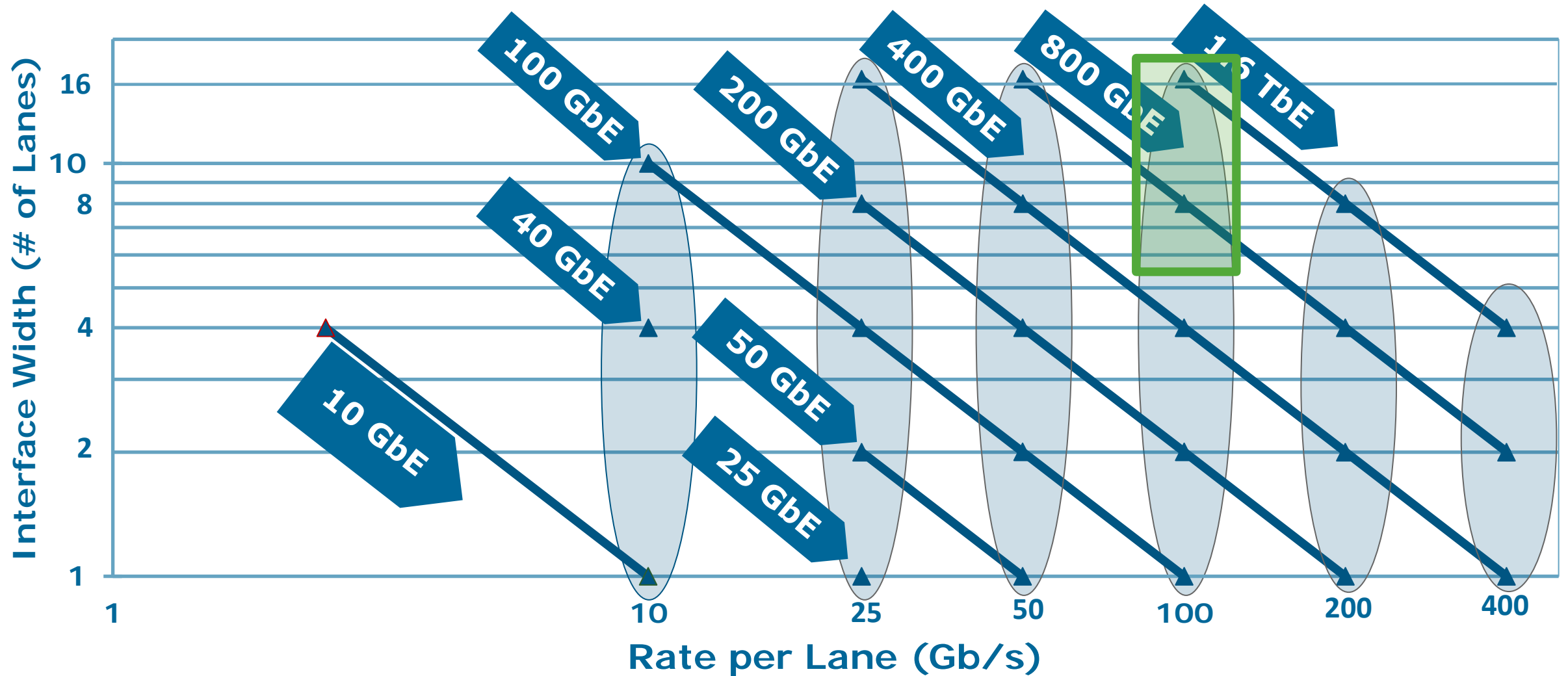


Reported implementations:

- "A 400 Gb/s Transceiver for PAM-4 Optical Direct-Detect Applications in 16nm FinFET," ISSCC, 2019
- "A 460mW 112 Gb/s DSP-Based Transceiver with 38 dB Loss Compensation for Next-Generation Data Center in 7nm FinFET Technology," ISSCC, 2020
- "FPGA Investigation on Error-Floor Performance of a Concatenated Staircase and Hamming Code for 400G-ZR Forward Error Correction," OFC, 2018

Courtesy of:
Ilya Lyubomirsky, Inphi
George Zimmerman, CME Consulting
John D'Ambrosia, Futurewei Technologies

Beyond 400 GbE - Leveraging 100 Gb/s Signaling



Industry Efforts - 100 Gb/s Signaling

- **IEEE 802.3**
 - **Standards –**
 - IEEE P802.3bs – 400GBASE-DR4 (4 x 100 Gb/s)
 - IEEE P802.3cd – 100GBASE-DR (1 X 100 Gb/s)
 - **In Development**
 - IEEE P802.3ck 100 Gb/s, 200 Gb/s, and 400 Gb/s Electrical Interfaces Task Force
 - IEEE P802.3cu 100 Gb/s and 400 Gb/s over SMF at 100 Gb/s per Wavelength Task Force
 - IEEE P802.3db 100 Gb/s, 200 Gb/s, and 400 Gb/s Short Reach Fiber Task Force
 - IEEE P802.3ct 100 Gb/s over DWDM Systems Task Force
- **Other Industry Efforts**
 - INCITS T11 (Fibre Channel) FC-PI-8, 128GFC (112 Gb/s electrical and optical interface specifications)
 - OIF Common Electrical Interface 112 Gb/s Efforts
 - 100G Lambda MSA (100 Gb/s optical interfaces specifications)

800 Gb/s Industry Activities

➤ Ethernet Technology Consortium

- <https://ethernettechnologyconsortium.org/>
- "The 800 GbE specification introduces a new media access control (MAC) and Physical Coding Sublayer (PCS)"

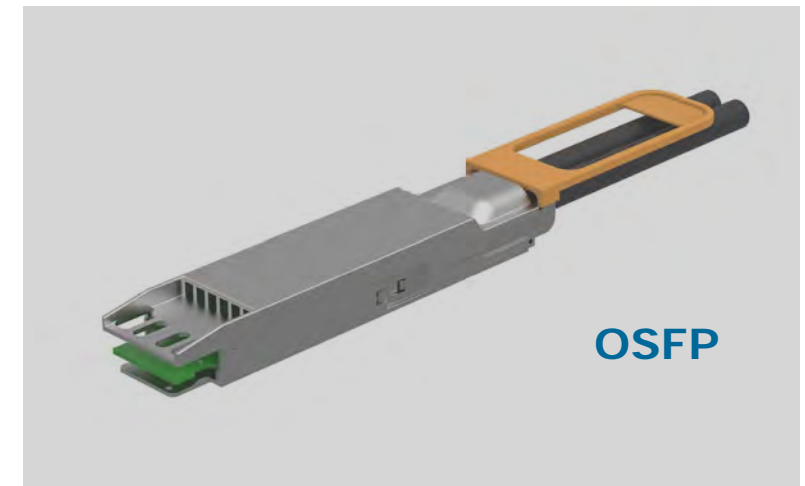
➤ QSFP-DD800 MSA

- <http://www.qsfp-dd800.net/>
- Rev 1.0 released Mar 6 2020

➤ OSFP

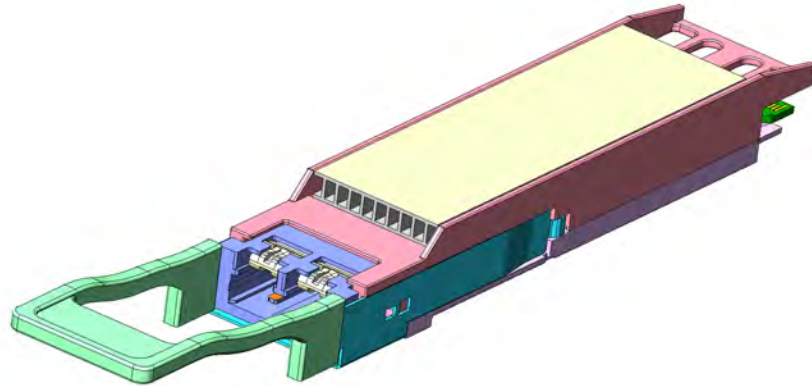
➤ 800G Pluggable MSA

- <https://www.800gmsa.com/>
- 800G PSM8 specification (Draft 1.0) - Specification covering cost effective 8x100G transmission over at least 100m



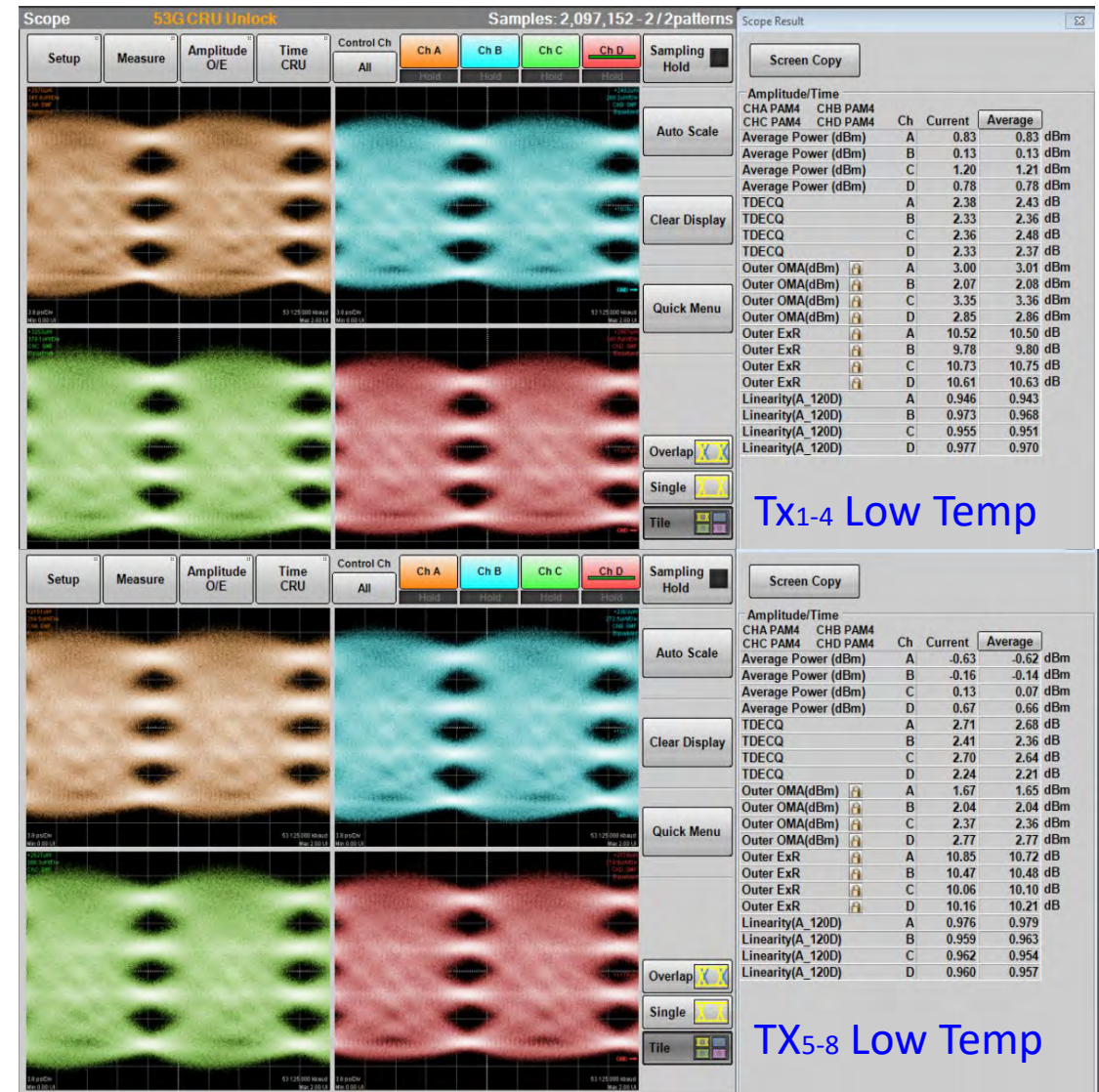
Source– Nathan Tracy, TE Connectivity

Example: 800 Gb/s OSFP Capacity Module

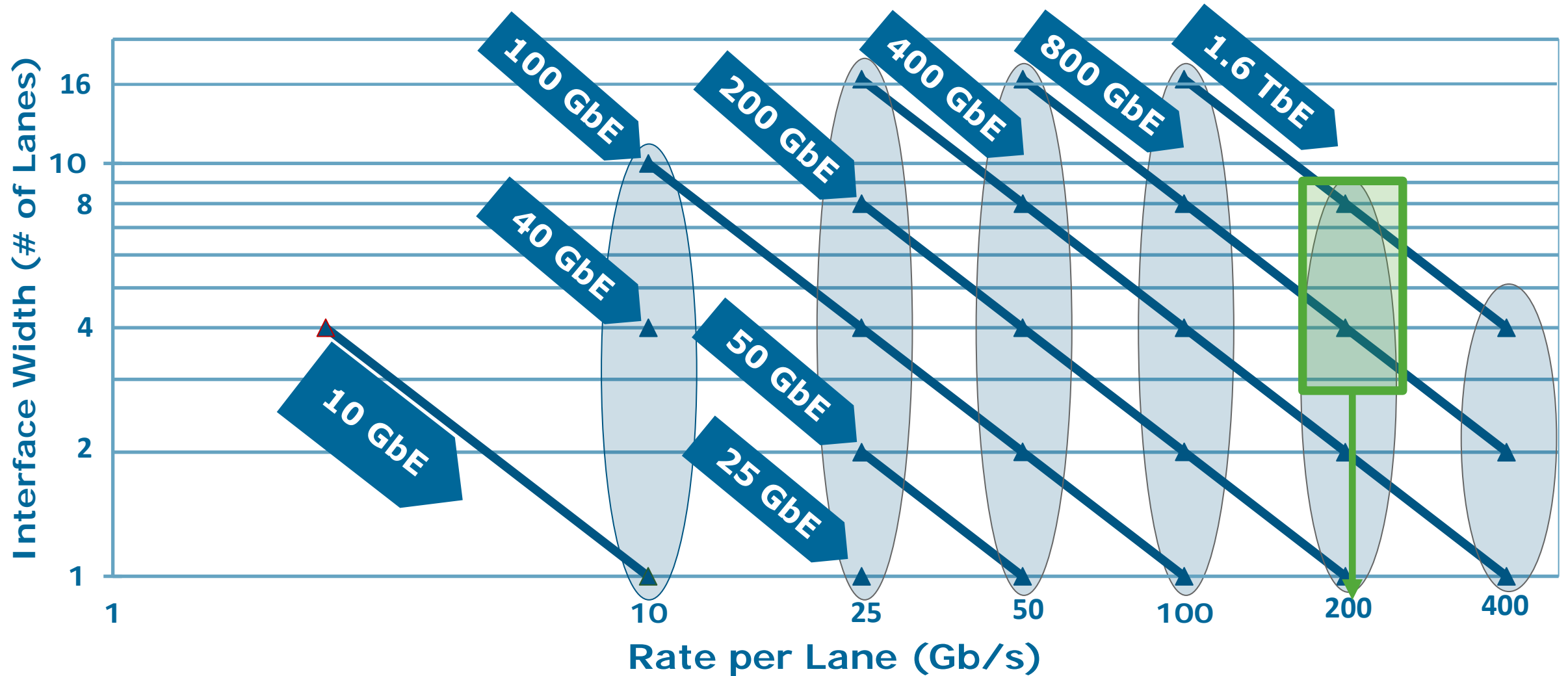


- OSFP Form Factor
- Targeting 2km:
 - 8 x 100 GbE with MPO-16
 - 2 x 400 GbE with CS connector
- OIF CEI-112G-VSR interface
- 0~70degC 18W, 10~60C 17W
- 7nm DSP inside

Source – Osa Mok, Innolight



Beyond 400 GbE - Leveraging 200 Gb/s Signaling



Potential for Technology Reuse

Reuse of signaling rate technologies developed for higher Ethernet rates enables existing lower speed Ethernet rate specifications (AUI, -KR, -CR, -SR, -DR, -FR, -LR, -ER)

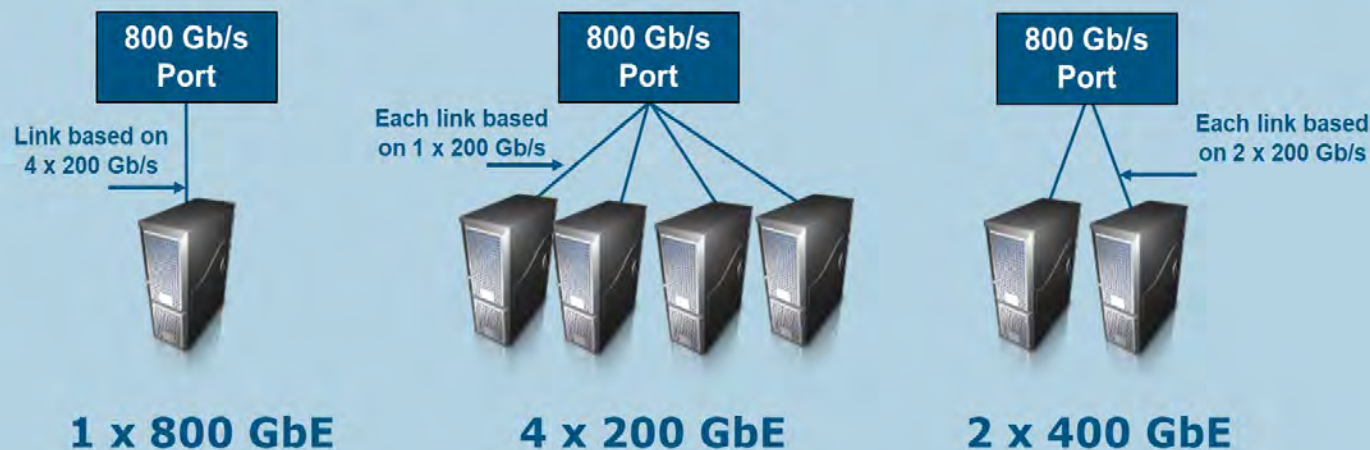


Image courtesy of David Piehler, Dell Technologies

- 32 - 400 Gb/s capacity ports
- Can be configured to support 32 - 400 GbE ports
- Can be configured to support 128 - 100 GbE ports

Possible Scenario – 800 GbE is developed based on 4 x 200 Gb/s

The 200 Gb/s signaling rate technology could be reused to support development of 200 GbE and 400 GbE physical layer specifications



Reuse of 200 Gb/s signaling rate technology could be applicable to:
AUIs, -KR, -CR, -SR, -DR, -FR, -LR, -ER, others?

“It has been my experience at Google that we have used optical and copper modules to support different configurations of a given port, including applications that require the maximum capacity of the single port.”

Cedric Lam, Google

Beyond 100 Gb/s Research is Underway

- S. Yamaoka et al., "239.3-Gbit/s net rate PAM-4 transmission using directly modulated membrane lasers on high-thermal-conductivity SiC" in Proceedings of European Conference on Optical Communication (ECOC), 2019/9.
- X. Pang et al., 200 Gbps/lane IM/DD Technologies for Short Reach Optical Interconnects, <https://core.ac.uk/download/pdf/289286726.pdf>, 2019/04/24.
- W. Heni et al., Ultra-High-Speed 2:1 Digital Selector and Plasmonic Modulator IM/DD Transmitter Operating at 222 GBaud for Intra-Datacenter Applications, <https://www.osapublishing.org/jlt/abstract.cfm?URI=jlt-38-9-2734>, 2020/9.
- S Lange et al., 100 GBd Intensity Modulation and Direct Detection with an InP-based Monolithic DFB Laser Mach-Zehnder Modulator, Journal of Lightwave Technology, https://www.researchgate.net/publication/319259046_100_GBd_Intensity_Modulation_and_Direct_Detection_with_an_InP-based_Monolithic_DFB_Laser_Mach-Zehnder_Modulator, 2017/8.
- E. Sentieri et al., "12.2 A 4-Channel 200Gb/s PAM-4 BiCMOS Transceiver with Silicon Photonics Front-Ends for Gigabit Ethernet Applications," 2020 IEEE International Solid-State Circuits Conference - (ISSCC), San Francisco, CA, USA, 2020, pp. 210-212, doi: 10.1109/ISSCC19947.2020.9062992.
- T. Wettlin et al., "Beyond 200 Gb/s PAM4 transmission using Tomlinson-Harashima precoding," 45th European Conference on Optical Communication (ECOC 2019), Dublin, Ireland, 2019, pp. 1-4, doi: 10.1049/cp.2019.0834.
- Net 212.5 Gbit/s Transmission in O-band With a SiP MZM, One Driver and Linear Equalization, Maxime Jacques¹, Zhenping Xing¹, Alireza Samani¹, Xueyang Li¹, Eslam El-Fiky¹, Samiul Alam¹, Olivier Carpentier¹, Ping-Chiek Koh², David Plant¹; ¹McGill Univ., Canada; ²Lumentum, USA. OFC-2020, Post deadline paper Th4A.3

Industry Efforts Targeting Signaling Beyond 100 Gb/s

- **IEEE 802.3**

- IEEE P802.3cw 400 Gb/s over DWDM Systems

- **ITU-T**

- Recommendation ITU-T G.698.2, to include 200 Gb/s and 400 Gb/s application codes

- **OIF**

- **400ZR**

- https://www.oiforum.com/wp-content/uploads/OIF-400ZR-01.0_reduced2.pdf

- **CEI 224G Development Project**

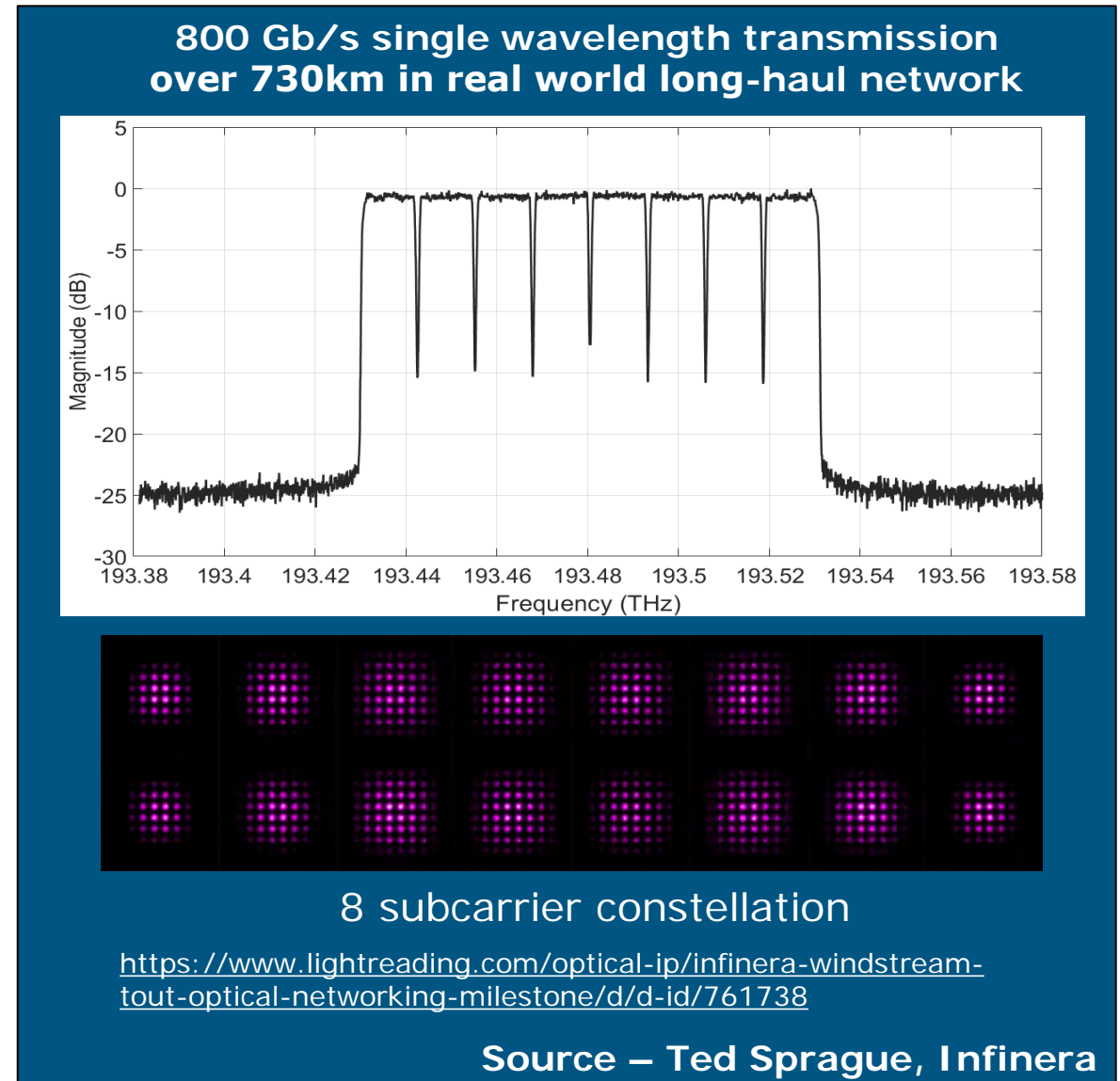
- <https://www.businesswire.com/news/home/20200826005437/en/OIF-Approves-CEI-224G-Development-Project-Reviews-Co-packaging>

800 Gb/s Single Wavelength Transmission

The Future of Coherent is emerging

- Successful trial of 800 Gb/s single-wave transmission over 950 km - <https://bit.ly/2Wdkh8e>
- Platform supporting 200 Gb/s to 800 Gb/s single-carrier - <https://bit.ly/2KLpW05>
- "Industry's first 800G tunable ultra-high-speed optical module" <https://bit.ly/2yTYNFK>
- "Verizon says it has successfully transmitted an 800-Gb/s wavelength on its live network" - <https://bit.ly/3d2GX1M>

Potentially applicable to Duplex SMF and DWDM systems!



SUMMARY

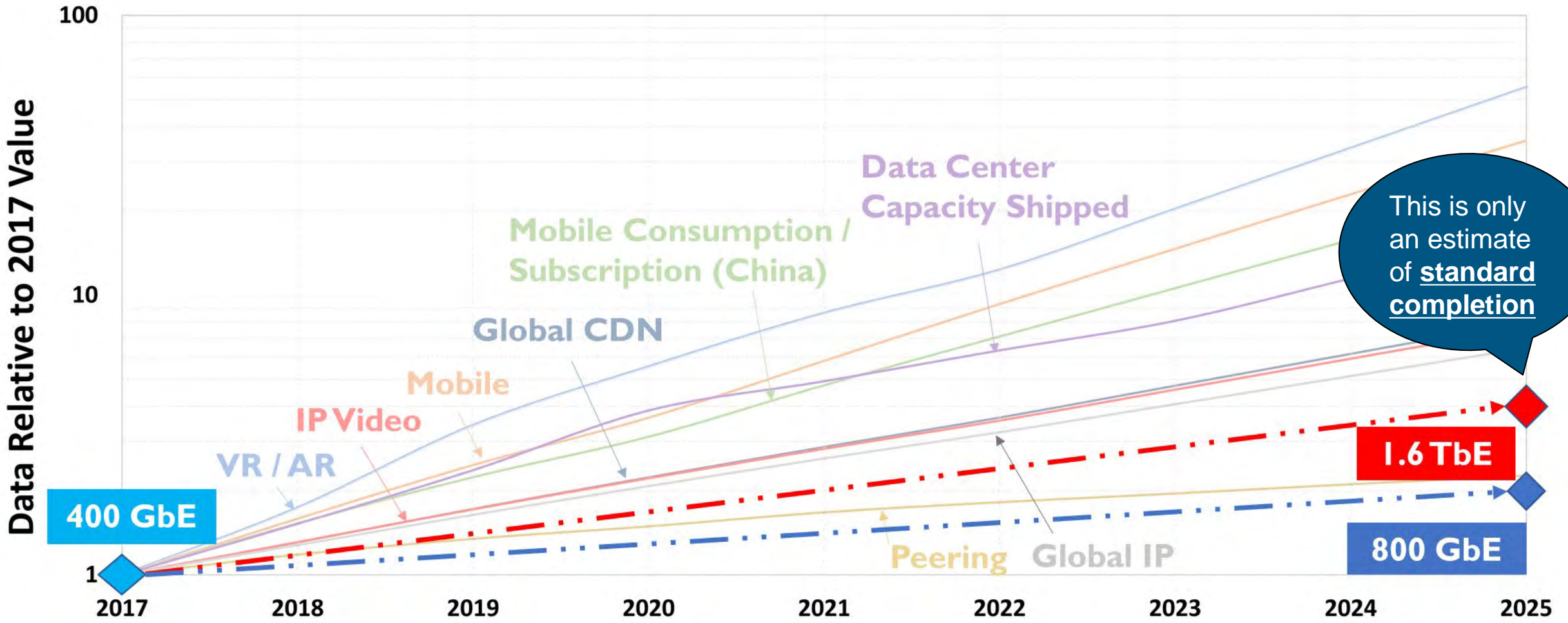
- **Path to Beyond 400 GbE exists**
- **Leverage 100 Gb/s building blocks**
- **800 GbE building blocks and example available now**
- **Plausible implementations for today and next generation**
- **800 Gb/s over a single wavelength for duplex SMF and DWDM systems is emerging now**

BEYOND 400 GbE WHY NOW?

**Presented by
John D'Ambrosia**



CONSIDERING THE NEXT ETHERNET RATE STANDARD



This is only an estimate of standard completion

Source: <https://bit.ly/802d3bwa2>

The Work Needs to Begin...



SUMMARY

- **Bandwidth –**
 - Underlying factors all indicate continued growth
 - Exponential growth continues!
- **New bandwidth generating applications constantly being introduced**
 - Mobile (5G) / Video
 - Artificial Intelligence
 - Virtual / Augmented Reality
- **Today's world stressing the need for connectivity and bandwidth**
- **Last two "Higher Speed" efforts (from CFI to standard ratification)**
 - 40 / 100 GbE – 3 years, 11 months
 - 200 / 400 GbE – 4 years, 9 months
- **There is some time between standard ratification and product introduction**
 - The bandwidth problem will only continue to grow
- **We need to begin the process to study the problem!**
- **Big questions to consider**
 - Next speed or speeds?
 - What physical layer specifications?

Proposed Study Group Chartering Motion

Approve the formation of a Beyond 400 Gb/s Ethernet Study Group to consider development of a Project Authorization Request (PAR) and Criteria for Standards Development (CSD) responses for:

- 1. Beyond 400 Gb/s Ethernet;**
- 2. Physical Layers specifications for existing Ethernet rates based on any signaling rate used for (1).**

Supporters (Page 1 of 3)

John Venu	Abbott	Corning Incorporated	Claudio Mike	DeSanti	Dell Technologies
Thananya	Balasubramonian	Marvell	Dave	Dudek	Marvell
Davinder	Baldwin	Keysight Technologies	John	Estes	Spirent
Vipul	Basuita	Glenair	Vince	Ewen	Marvell
Mark	Bhatt	II-VI Incorporated	Ali	Ferretti	Corning Incorporated
Ralf-Peter	Bordogna	Intel	Joel	Ghiasi	Ghaisi Quantum LLC
Paul	Braun	DEUTSCHE TELEKOM AG	Steve	Goergen	Cisco
Matt	Brooks	VIAVI Solutions	Bob	Gorshe	Microchip Technology
Leon	Brown	Huawei Technologies Canada	Chin	Grow	RMG Consulting
John	Bruckman	Huawei	Mark	Guok	Esnet
Steve	Calvin	Keysight	Rubio	Gustlin	Cisco
Derek	Carlson	High Speed Design	Xiang	Han	China Mobile
Frank	Cassidy	IET / ICRG	Adam	He	Huawei
Ayla	Chang	Source Photonics	Howard	Healey	Broadcom
Jacky	Chang	Huawei	Briah	Heck	Intel
David	Chang	Hewlett Packard Enterprise	Tom	Holden	Kandou
Gang	Chen	AOI	Jeff	Huber	Nokia
Weiqiang	Chen	Baidu	Kazuhiko	Hutchins	Ranovus
Mabud	Cheng	China Mobile	Hideki	Ishibe	Anritsu
Robert	Choudhury	OFS	Tom	Isono	Fujitsu Optical Components
John	Coenen	InterOptic	Ken	Issenhuth	Huawei
Eli	D'Ambrosia	Futurewei, U.S. Subsidiary of Huawei	John	Jackson	Sumitomo Electric Device Innovations USA
John	Dart	ESnet	Lokesh	Johnson	Broadcom
	DeAndrea	II-VI Inc		Kabra	Synopsys

Supporters (Page 2 of 3)

Mark	Kimber	Semtech	Guangcan	Mi	Huawei
Mike	Klempa	Amphenol-TCS	Mario	Milicevic	MaxLinear
Beth	Kochuparambil	Cisco	Osa	Mok	Innolight
Kishore	Kota	Inphi	Inder	Monga	Esnet
Cedric	Lam	Google	Andy	Moorwood	Keysight Technologies
Dominic	Lapierre	EXFO	Shimon	Muller	Enfabrica Corp. / Axalume Inc.
Ryan	Latchman	MACOM	Dale	Murray	LightCounting
Greg	Le Cheminant	Keysight Technologies	Ray	Nering	Cisco
David	Lewis	Lumentum	Shawn	Nicholl	Xilinx
Jon	Lewis	Dell Technologies	Gary	Nicholl	Cisco
Junjie	Li	China Telecom	Paul	Nikolich	Independent
Mike	Li	Intel	Mark	Nowell	Cisco
Robert	Lingle	OFS	David	Ofelt	Juniper
Hai-Feng	Liu	HG Genuine	Kumi	Omori	NEC
Kent	Lusted	Intel	Tom	Palkert	Samtec
Ilya	Lyubomirsky	Inphi	Earl	Parsons	CommScope
Valerie	Maguire	Siemon	Vasu	Parthasarathy	Broadcom
Jeff	Maki	Juniper	Jerry	Pepper	Keysight Technologies
David	Malicoat	Malicoat Networking Solutions	Phong	Pham	EPCOMM Inc.
Eric	Maniloff	Ciena	David	Piehler	Dell Technologies
Flavio	Marques	Furukawa Electric	Rick	Pimpinella	Panduit
Brett	McClellan	Marvell	Rick	Rabinovich	Keysight Technologies
Larry	McMillan	Western Digital	Sridhar	Ramesh	Maxlinear
Rich	Mellitz	Samtec	Adee	Ran	Intel

Supporters (Page 3 of 3)

Francisco	Rodrigues	PICadvanced	Jeff	Twombly	Credo Semiconductor
Olindo	Savi	Hubbell	Ed	Ulrichs	Intel
Ed	Sayre	North East Systems Associates, Inc.	Paul	Vanderlaan	UL LLC
Steve	Sekel	Keysight Technologies	Prasad	Venugopal	Arista Networks
Steve	Shellhammer	QualComm	Xinyuan	Wang	Huawei
Kapil	Shrikhande	Innovium	Winston	Way	Neophotonics
Priyank	Shukla	Synopsys	Markus	Weber	Acacia Communications
Scott	Sommers	Molex	Tom	Williams	Acacia Communications
Yoshiaki	Sone	NTT	James	Withey	Fluke
Massimo	Sorbara	GlobalFoundries	Chongjin	Xie	Alibaba
Ted	Sprague	Infinera	Shuto	Yamamoto	NTT
Henk	Steenman	AMS-IX	Zhiwei	Yang	ZTE
Rob	Stone	Facebook	Wen	Yangling	Futurewei
Steve	Swanson	Corning Incorporated	James	Young	Commscope
John	Swanson	Synopsys	Xu	Yu	Huawei
Bharat	Tailor	Semtech	Hua	Zhang	Hisense Broadband
Tomoo	Takahara	Fujitsu	Bo	Zhang	Inphi
Jack	Tang	Guangdong Ruigu Optical Network Communications Co.,Ltd.	Wenyu	Zhao	CAICT
Jim	Theodoras	HG Genuine USA	Xiang	Zhou	Google
Nathan	Tracy	TE Connectivity	Yan	Zhuang	Huawei
Viet	Tran	Keysight Technologies	George	Zimmerman	CME Consulting
Steve	Trowbridgge	Nokia	Pavel	Zivny	Tektronix

STRAW POLLS



Call-for-interest

- **Should a Study Group be formed for “Beyond 400 Gb/s Ethernet”**
 - **YES**
 - **No**
 - **Abstain**

- **Call Count**

Participation

- **I would participate in the “Beyond 400 Gb/s Ethernet” Study Group in IEEE 802.3**
 - **Tally:**
- **I believe my affiliation would support my participation in the “Beyond 400 Gb/s Ethernet” Study Group in IEEE 802.3**
 - **Tally: (Results to be processed after call)**

Future work

- **Ask 802.3 WG for approval**
- **If approved, request formation of “Beyond 400 Gb/s Ethernet” Study Group by 802 EC**
- **If approved,**
 - **Creation of Study Group page /reflector**
 - **First Study Group meeting [teleconference?] anticipated for Jan 21 Interim**

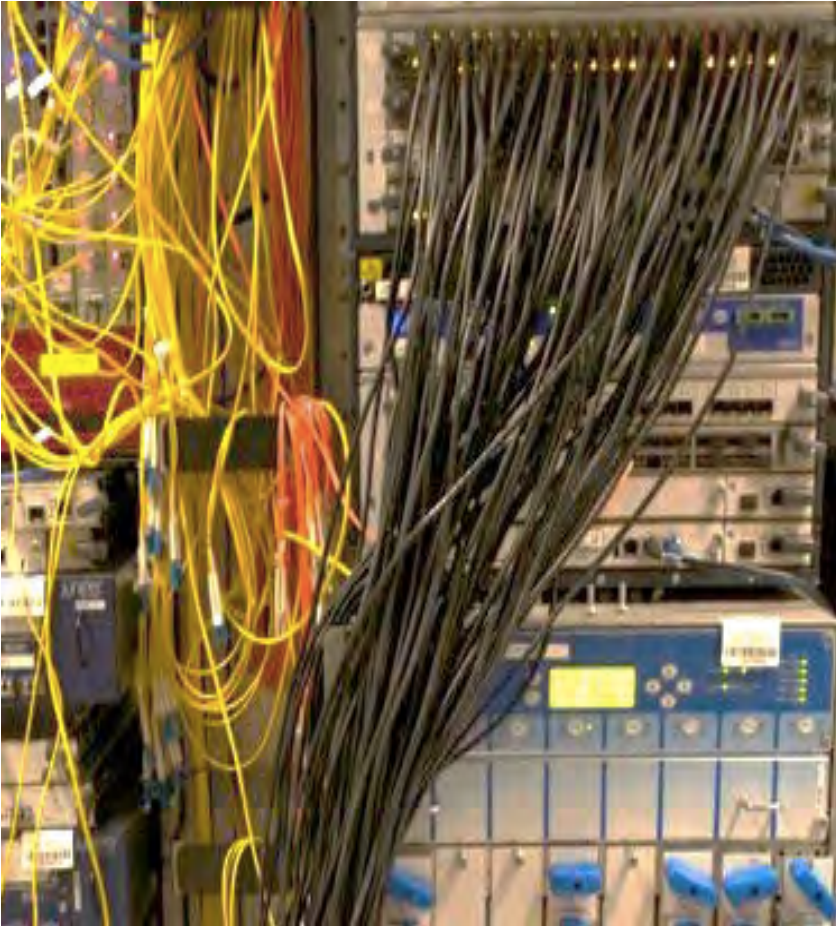
THANK YOU!



APPENDIX: BACKUP SLIDES



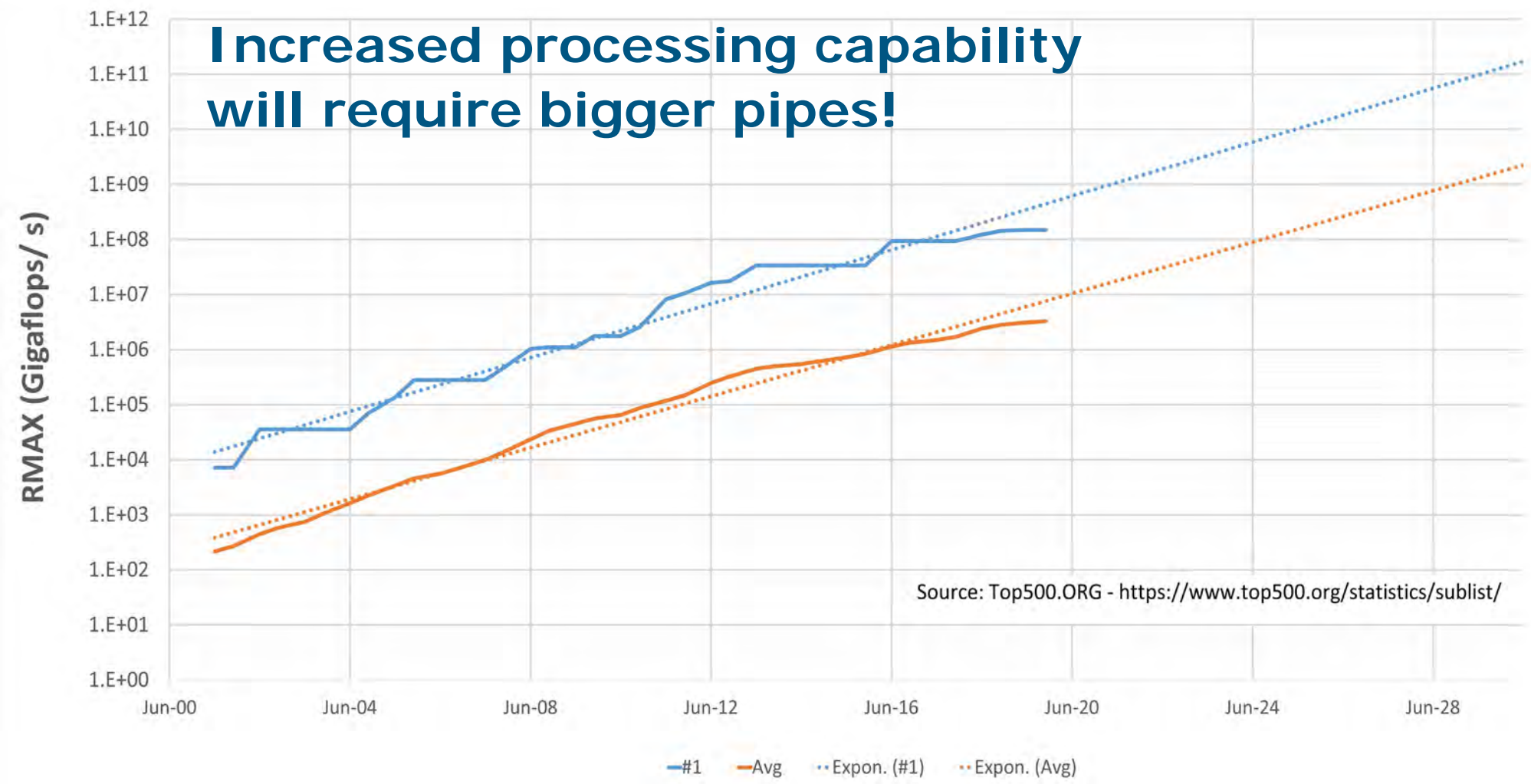
LINK AGGREGATION WILL NOT SUFFICE



Courtesy, David Ofelt, Juniper.

- Problem: Need to scale the Network (density & cost)
- Temporary Solution: Link Aggregation
- Pros:
 - Addresses bandwidth requirements between releases of faster links
- Cons:
 - Non-deterministic performance
 - Fastest flow limited to individual link speed
 - Growth in operational & management issues
- Other bonding mechanisms, e.g. FlexE, fixes performance limitations but not density issues
- Faster links address these issues and they will be LAGGed or bonded!

HIGH PERFORMANCE COMPUTING

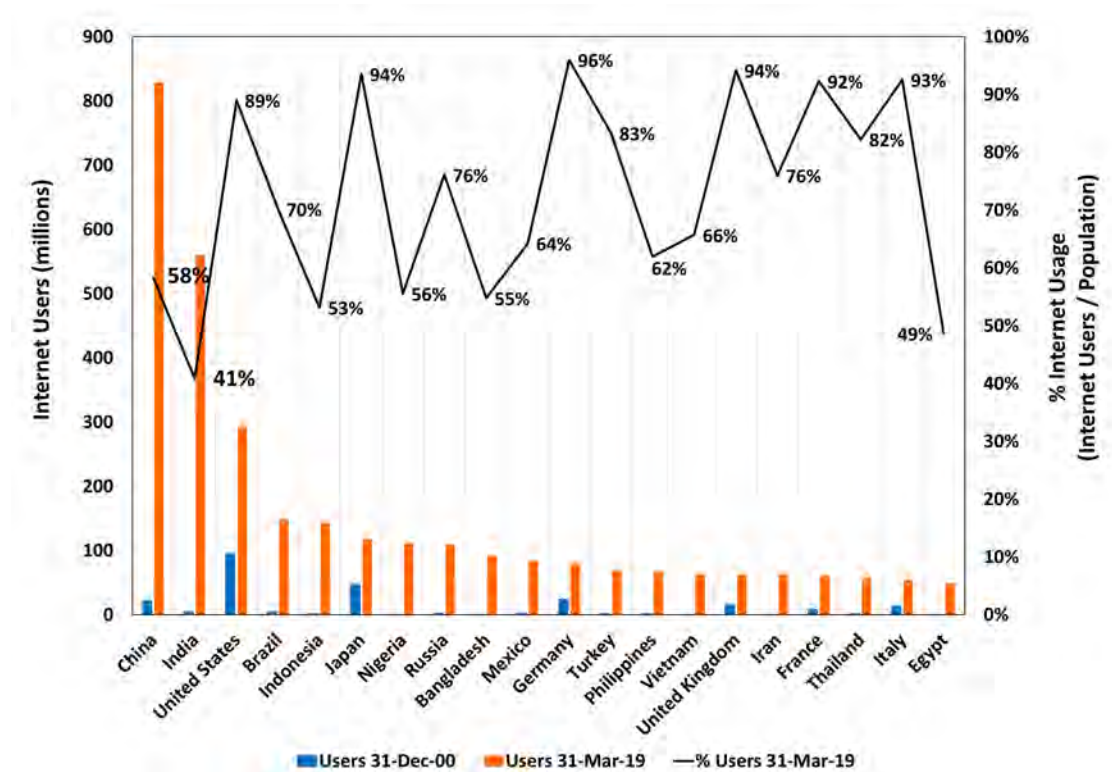


WORLD INTERNET USAGE

Total World	As of 3/31/19 ¹	As of 12/31/19 ³	Increase	As of 7/20/20 ²	Increase
Population	7,716,223,209	7,796,615,710	80,392,501	7,796,949,710	80,726,501
Internet Users	4,383,810,342	4,574,150,134	190,339,792	4,833,521,806	449,711,464
Internet Penetration	57%	59%	2%	62%	5%

Top 20 Countries	As of 3/31/19 ¹	As of 12/31/19 ³	Increase
Population	5,187,499,066	5,233,377,837	45,878,771
Internet Users	3,117,533,898	3,241,273,512	123,739,614
Internet Penetration	60%	62%	2%

Rest of World	As of 3/31/19 ¹	As of 12/31/19 ³	Increase
Population	2,565,984,143	2,563,237,873	-2,746,270
Internet Users	1,229,027,955	1,332,876,622	103,848,667
Internet Penetration	48%	52%	4%



Observations

- ❖ Only 8 countries had at least 80% connectivity
- ❖ ≈ 450 million users increase
- ❖ 5% increase in Total World Internet Penetration since Mar 31 2019

1. IEEE 802.3 BWA, PART II
 2. [HTTPS://WWW.INTERNETWORLDSTATS.COM/STATS.HTM](https://www.internetworldstats.com/stats.htm)
 3. [HTTPS://WWW.INTERNETWORLDSTATS.COM/TOP20.HTM](https://www.internetworldstats.com/top20.htm)

GLOBAL DEVICES / CONNECTIONS AVERAGE PER CAPITA

2017

2022

Growth

Average Number of Devices and Connections per **Capita**

2.4

3.6

50%



29

85

193%

Average Traffic per User per Month
GB

Number of connected devices per capita is growing
The average traffic per user is growing at a much faster rate

Source: Cisco VNI Forecast Update, http://www.ieee802.org/3/ad_hoc/bwa2/public/calls/19_0624/nowell_bwa_01_190624.pdf

GLOBAL DEVICE CONNECTION GROWTH (AVERAGE)

North America			
(Mb/s)	2017	2022	CAGR
Fixed Broadband	43.2	94.2	16.9%
Wi-Fi	37.1	83.8	17.7%
Cellular	16.3	42.0	20.8%

Western Europe			
(Mb/s)	2017	2022	CAGR
Fixed Broadband	37.9	76.0	14.9%
Wi-Fi	25.0	49.5	14.6%
Cellular	16.0	50.5	25.8%

Central & Eastern Europe			
(Mb/s)	2017	2022	CAGR
Fixed Broadband	32.8	46.7	7.3%
Wi-Fi	19.5	32.8	11.0%
Cellular	10.1	26.2	21.0%

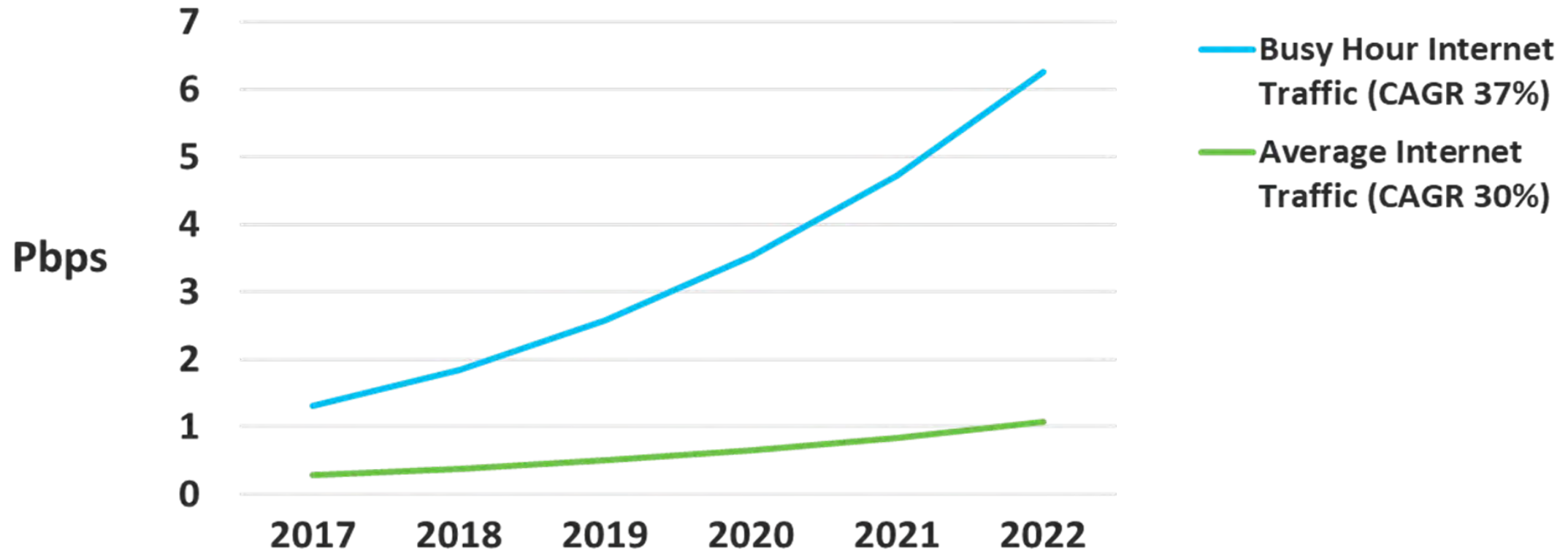
Latin America			
(Mb/s)	2017	2022	CAGR
Fixed Broadband	11.7	28.1	19.2%
Wi-Fi	9.0	16.8	13.3%
Cellular	4.9	17.7	29.3%

Middle East & Africa			
(Mb/s)	2017	2022	CAGR
Fixed Broadband	7.8	20.2	21.0%
Wi-Fi	6.2	11.2	12.6%
Cellular	4.4	15.3	28.3%

Asia Pacific			
(Mb/s)	2017	2022	CAGR
Fixed Broadband	46.2	98.8	16.4%
Wi-Fi	26.7	63.3	18.8%
Cellular	10.6	28.8	22.1%

Source: Cisco VNI Forecast Update, http://www.ieee802.org/3/ad_hoc/bwa2/public/calls/19_0624/nowell_bwa_01_190624.pdf

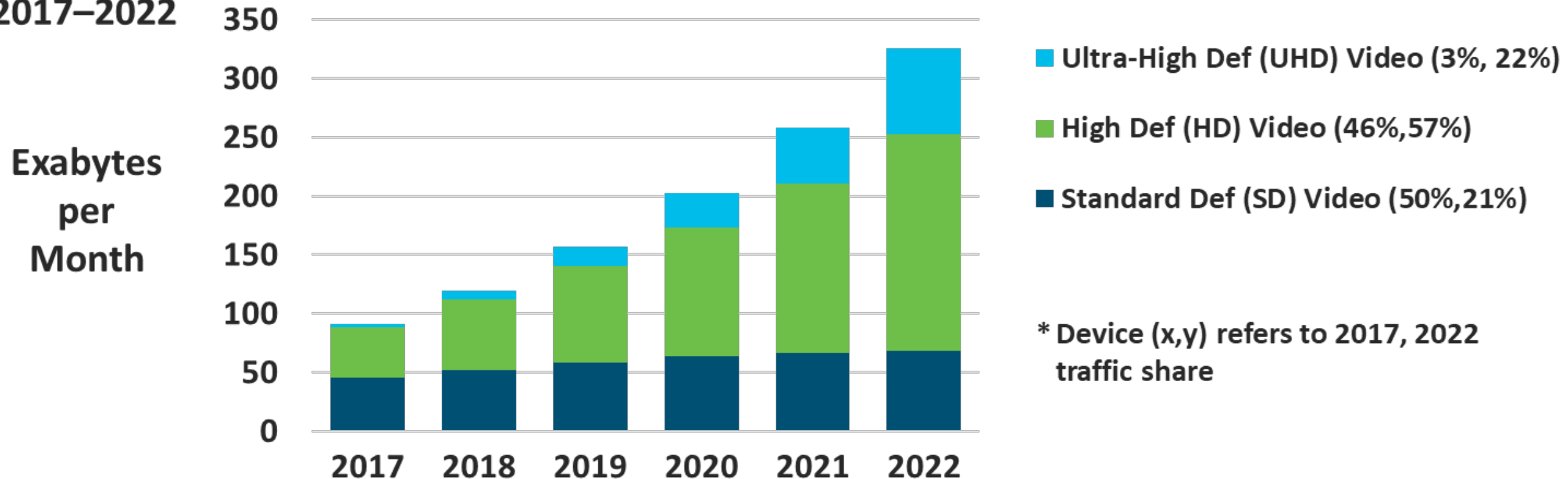
GLOBAL INTERNET TRAFFIC BUSY-HOUR VS AVERAGE HOUR



Source: Cisco VNI Forecast Update, http://www.ieee802.org/3/ad_hoc/bwa2/public/calls/19_0624/nowell_bwa_01_190624.pdf

IMPACT OF "DEFINITION" ON IP VIDEO GROWTH

29% CAGR
2017–2022

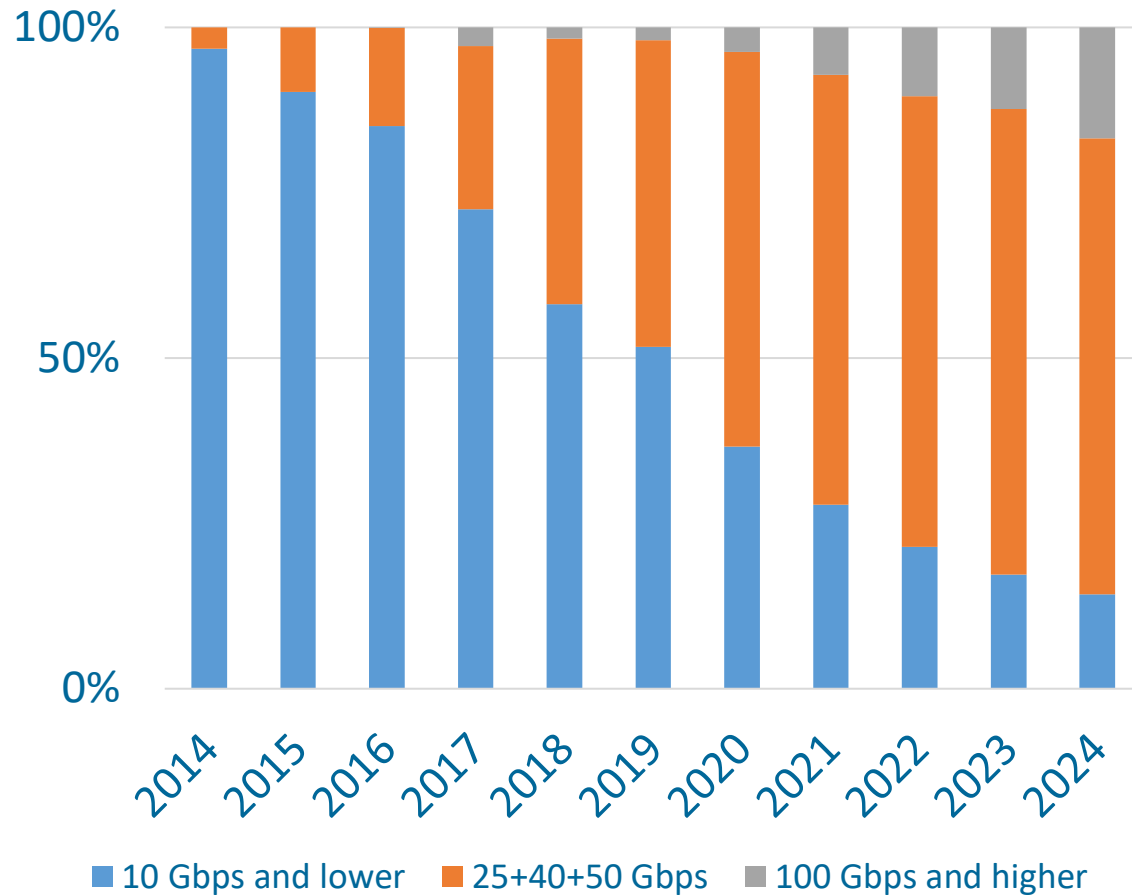


Growth in the adoption of HD and UHD dominate IP video traffic

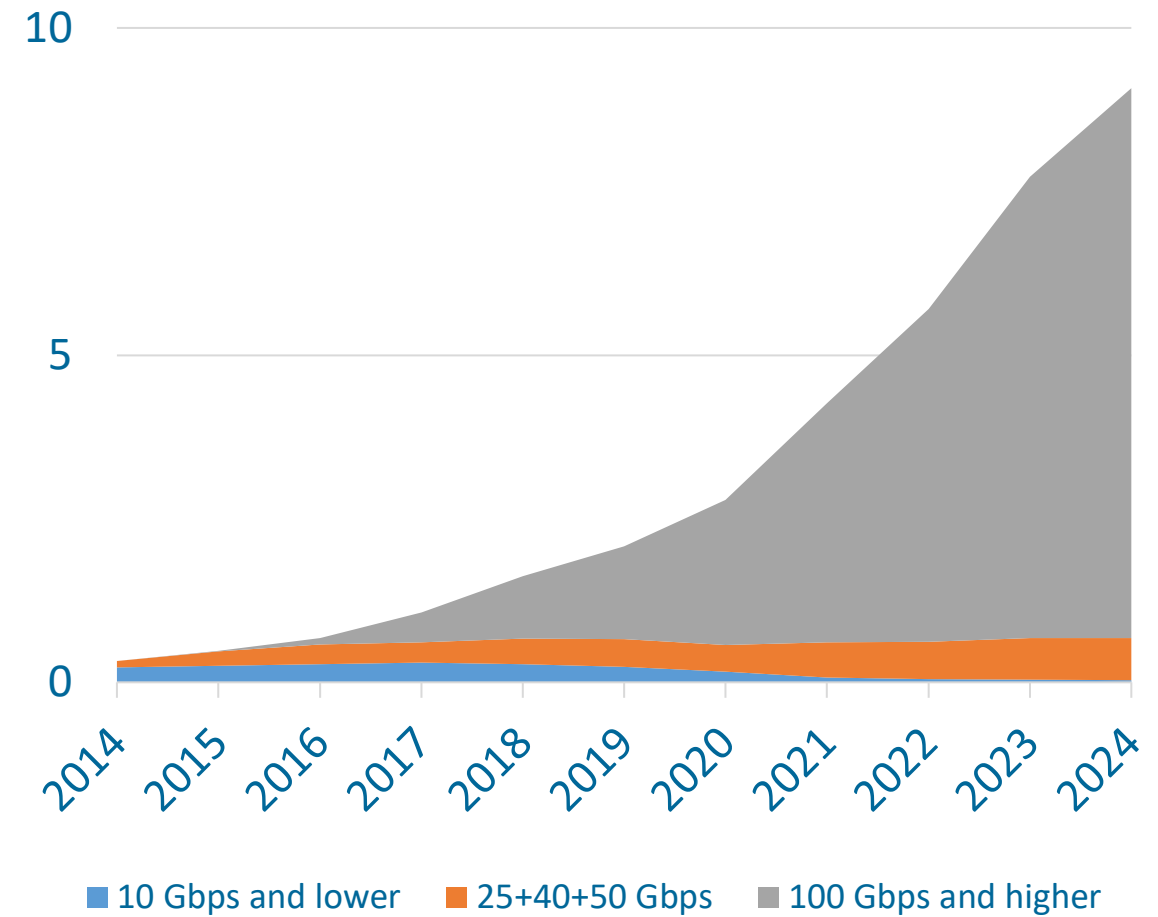
Source: Cisco VNI Forecast Update, http://www.ieee802.org/3/ad_hoc/bwa2/public/calls/19_0624/nowell_bwa_01_190624.pdf

DATA CENTER CAPACITY CONTINUES TO GROW

Enterprise / Cloud Server Unit Shipments*



Switch Capacity Shipments in Eb/s**

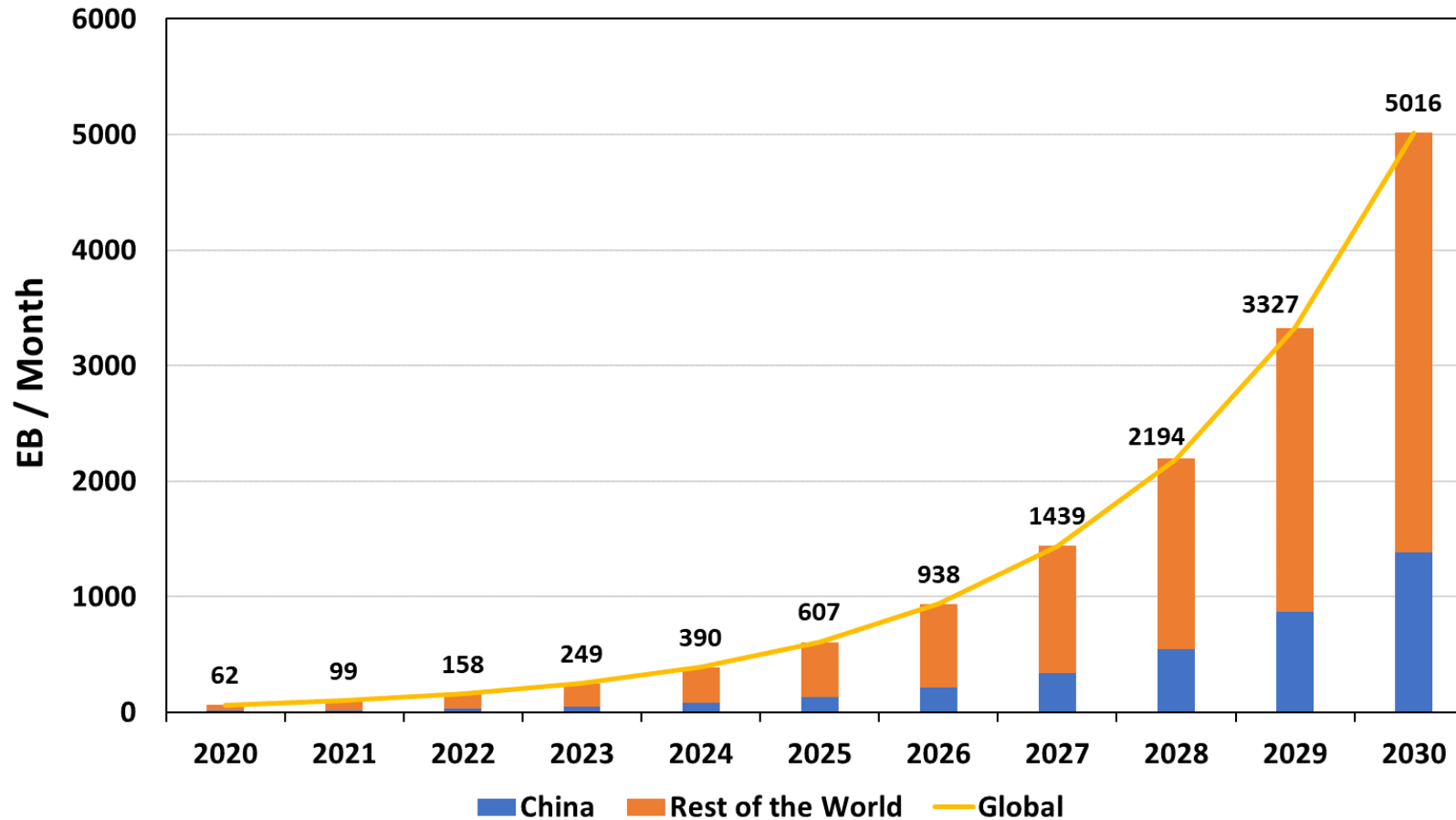


* Percent of annual server shipments categorized by speed of the attached controllers and adapters

** Annual port capacity shipped on Data Center Ethernet Switches measured in exabits per second



ESTIMATION OF MOBILE TRAFFIC



Global mobile traffic is exponential and may even be underestimated

Source: Report ITU-R M.2370-0: IMT traffic estimates for the years 2020 to 2030, <https://www.itu.int/pub/R-REP-M.2370-2015>