IEEE 802.3 NEA Ad hoc
28 Sept 2020

IEEE 802.3 Call for Interest
CFI Consensus Presentation
Draft Development

“Beyond 400 Gb/s Ethernet“

John D’Ambrosia
Futurewei Technologies
U.S. Subsidiary of Huawei

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
- 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

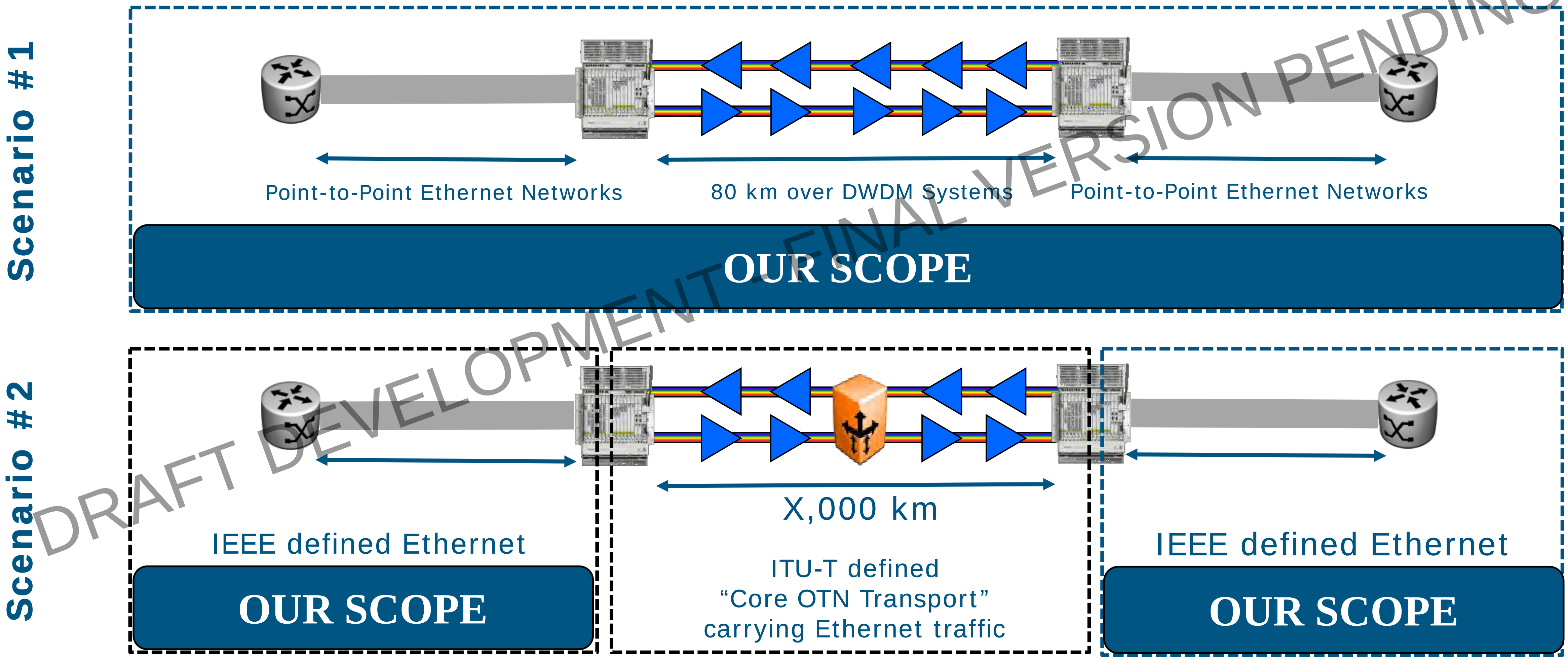
- **Speakers**
  - **John D'Ambrosia, Futurewei (U.S. Subsidiary of Huawei)**
  - **Ray Nering, Cisco**
  - **Adam Healey, Broadcom**

- **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



Potential for Technology Reuse

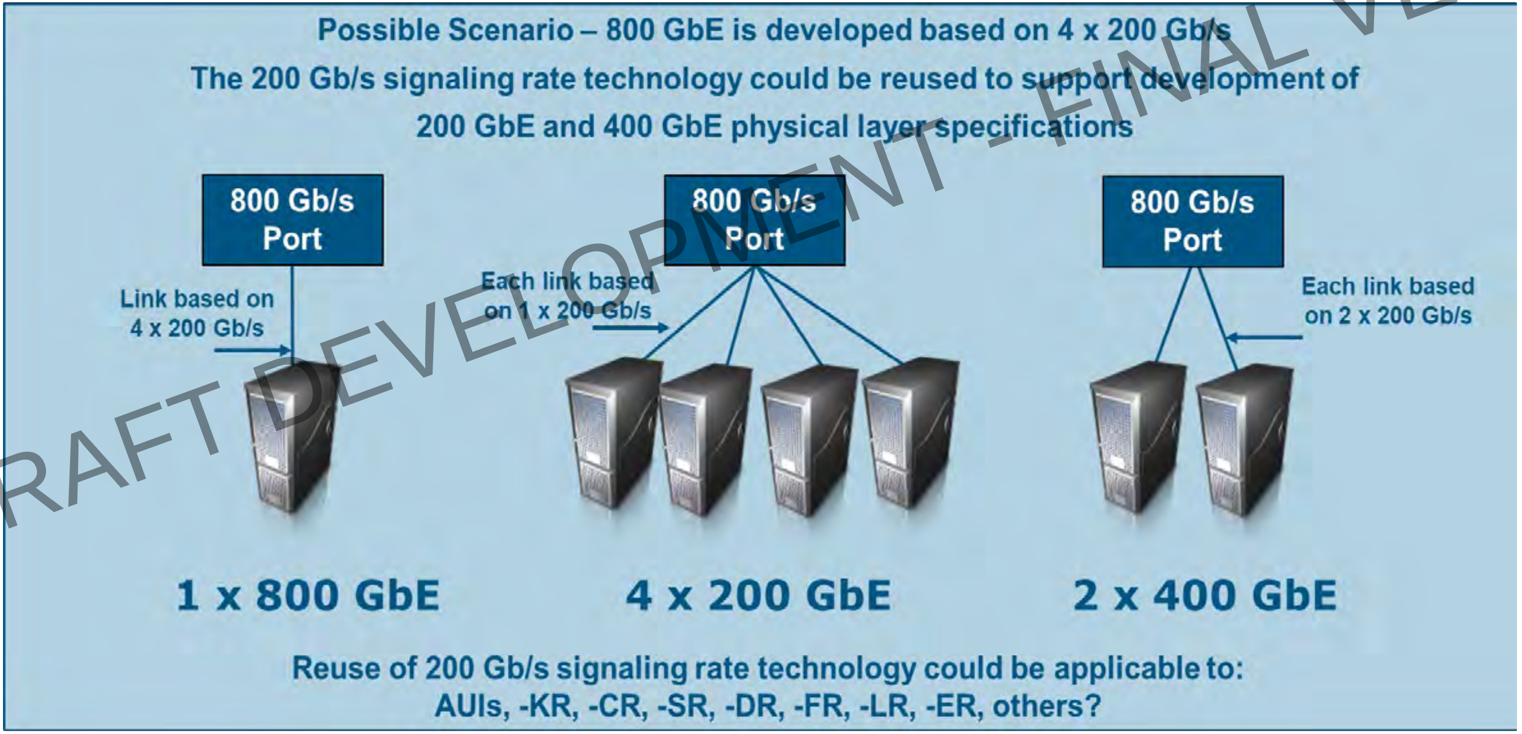
TODAY

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

A POSSIBLE FUTURE



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

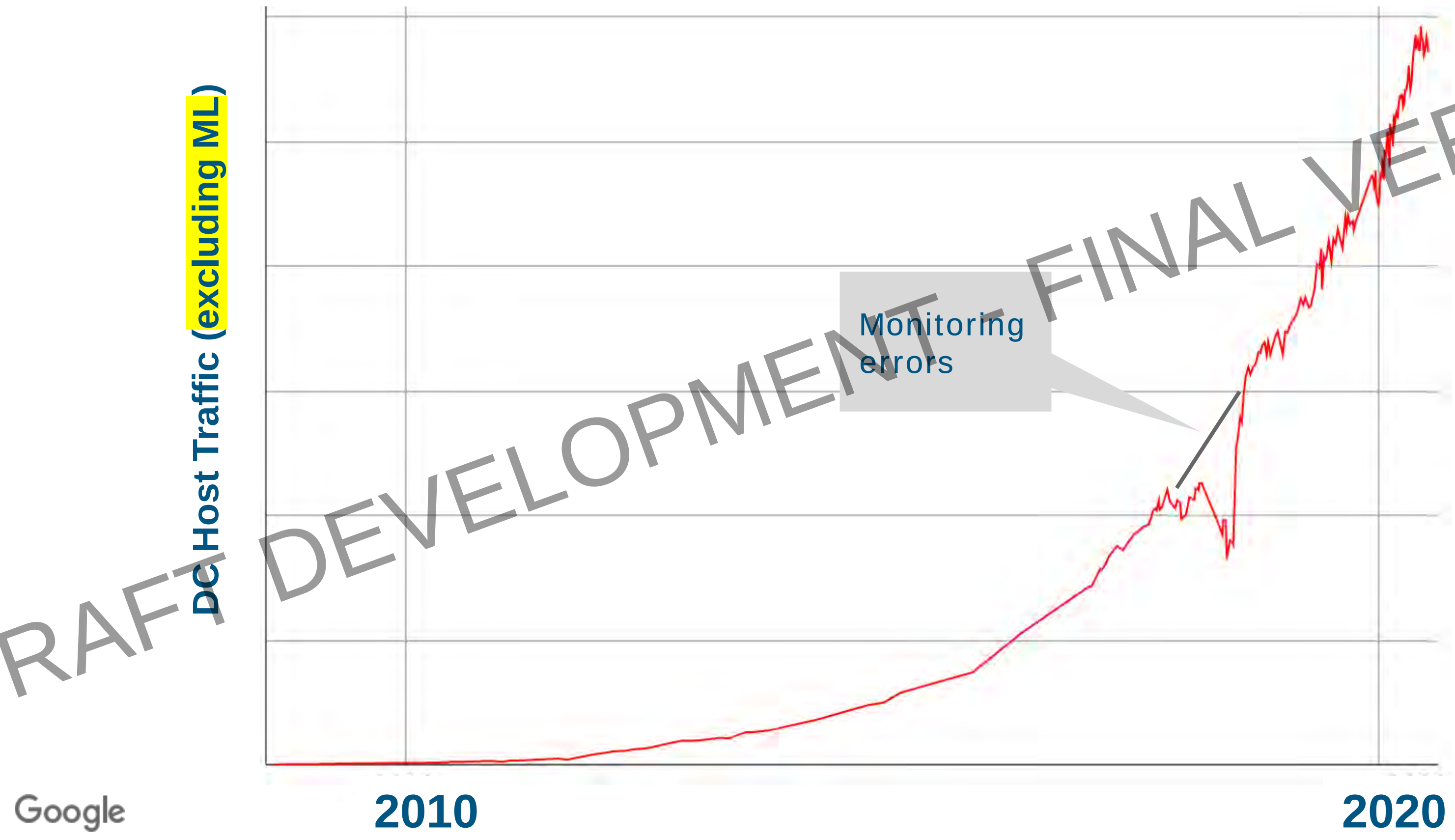
Cedric Lam, Google

MARKET PRESSURES FOR BEYOND 400 GbE

Presented by
Ray Nering

DATA CENTERS CONTINUE AS A PRIMARY DRIVER

DC Traffic Continues to Grow Rapidly (Regular Servers)



Courtesy - Cedric Lam, Google

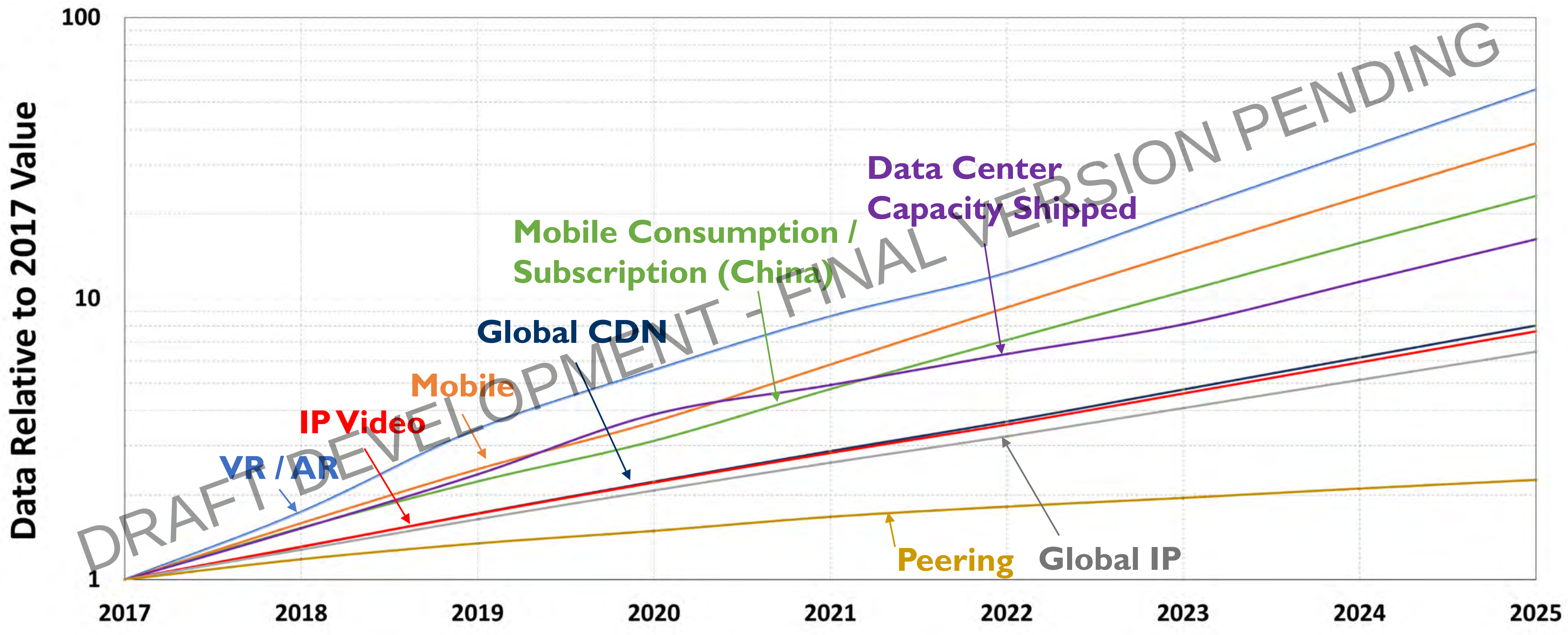
THE SONG REMAINS THE SAME

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

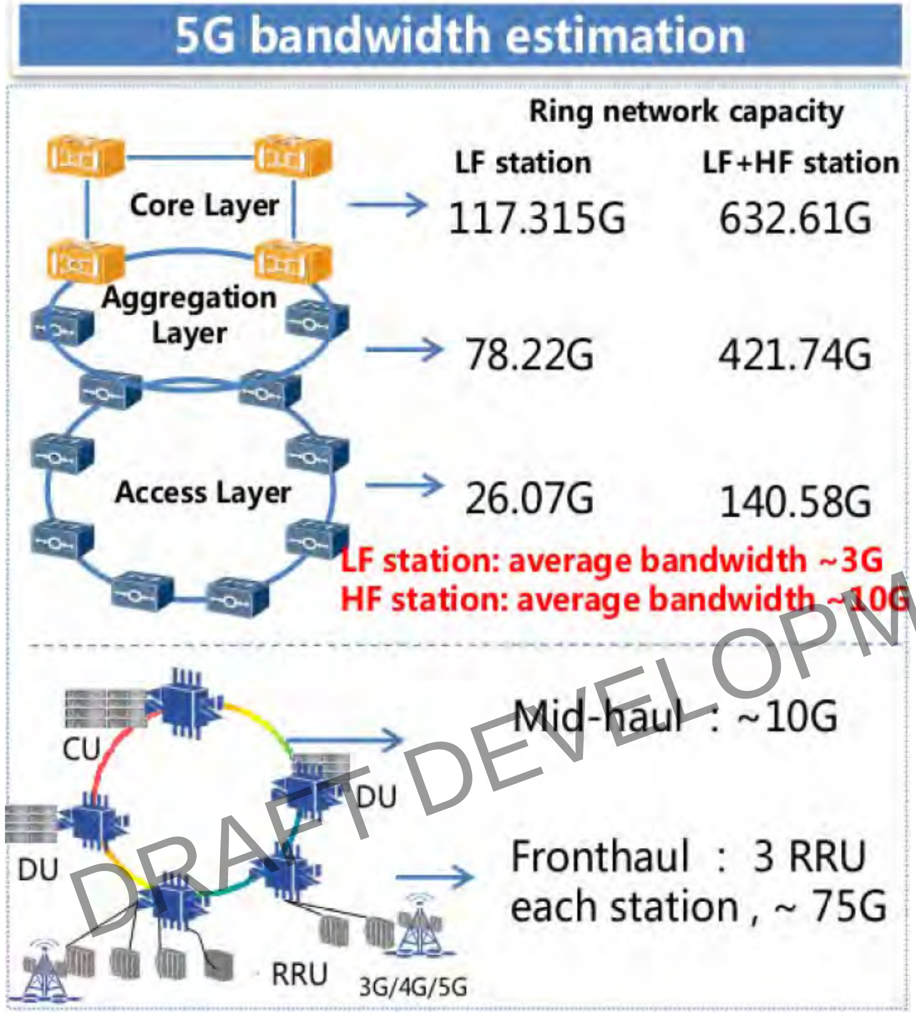
Increased # of users	x	Increased access methods and rates	x	Increased services	=	Bandwidth Explosion

- 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



EXAMPLE EMERGING APPLICATION – 5G BACKHAUL

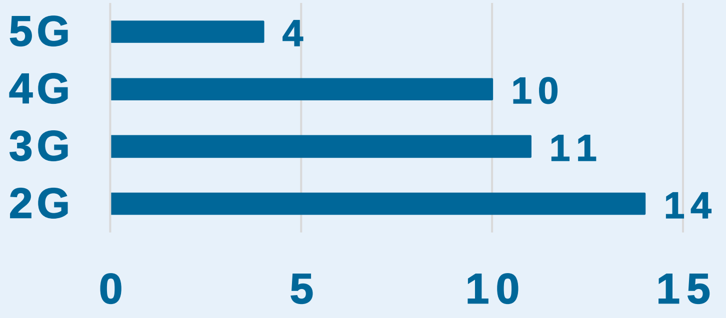


Source: http://www.ieee802.org/3/B10K/public/18_01/wang_b10k_01b_0118.pdf

	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/

Omdia projects 91 million global 5G connections by end of 2020

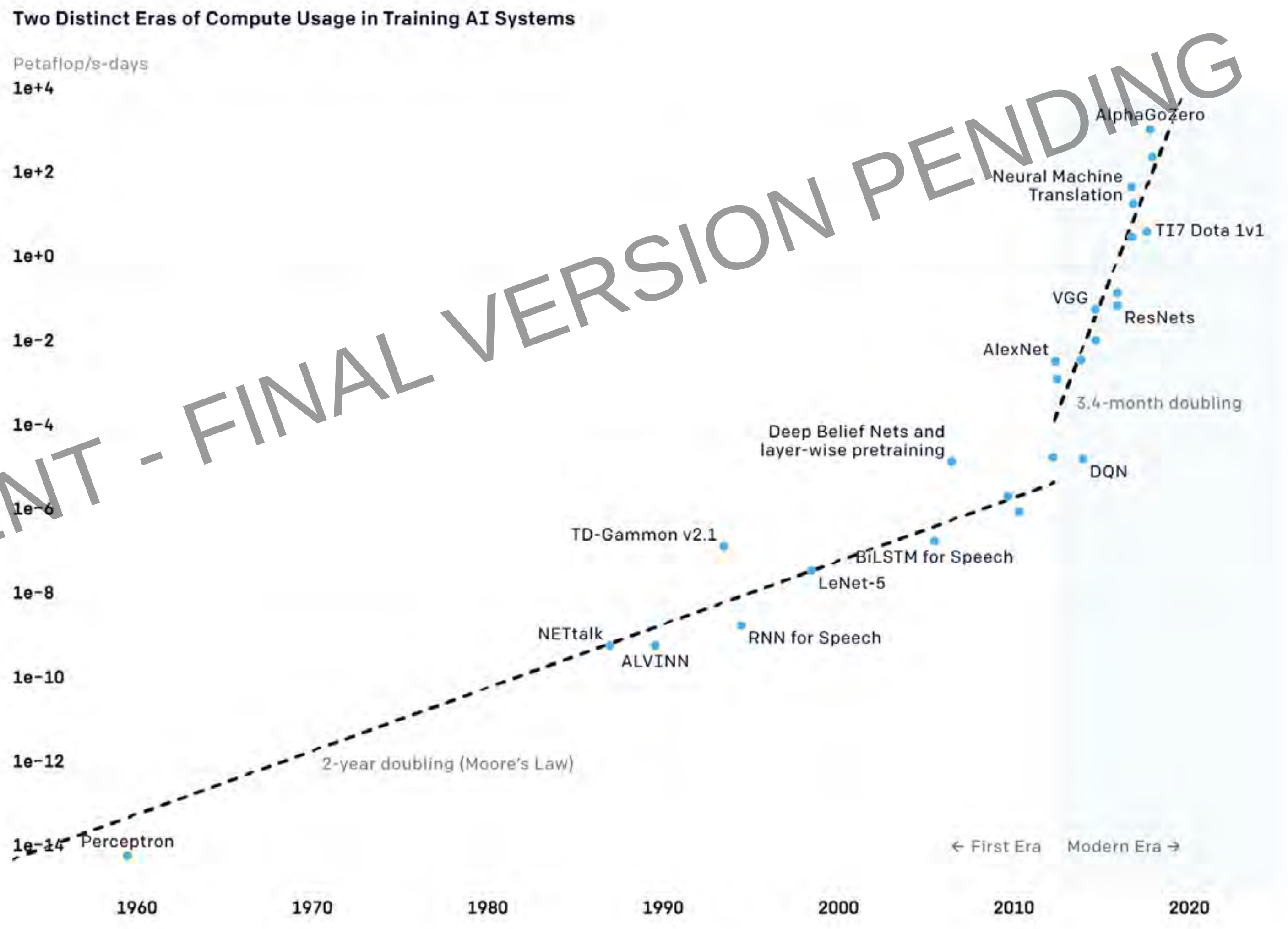


# of Quarters to ≈17.8 million Connections

Source: https://www.5gamericas.org/5gs-year-one-fast-start-and-healthy-growth/

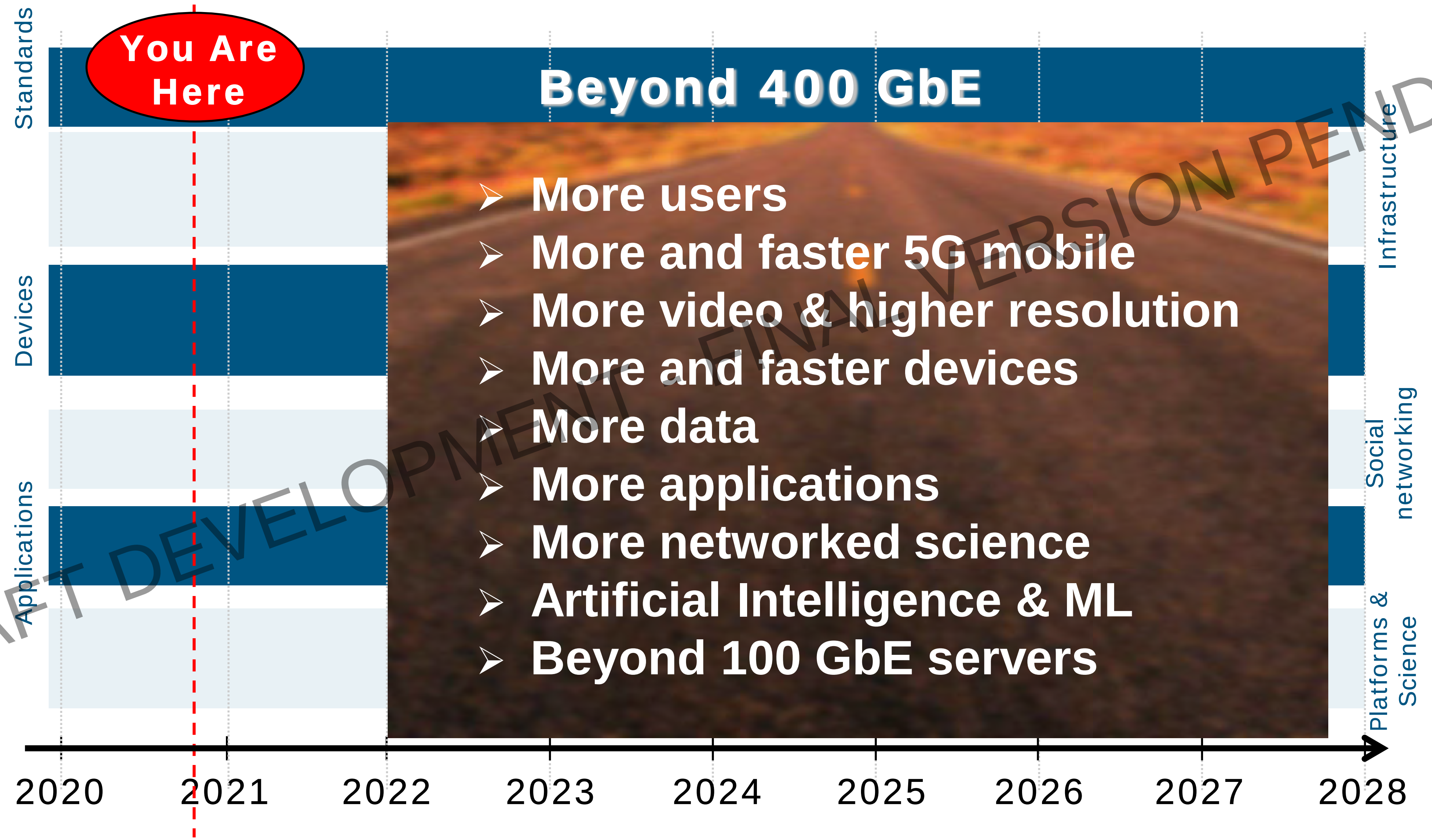
ARTIFICAL INTELLIGENCE & COMPUTE

- 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



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

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 ROADMAP TO BEYOND 400 GbE

Presented by
Adam Healey

Understanding the Typical Physical Challenges

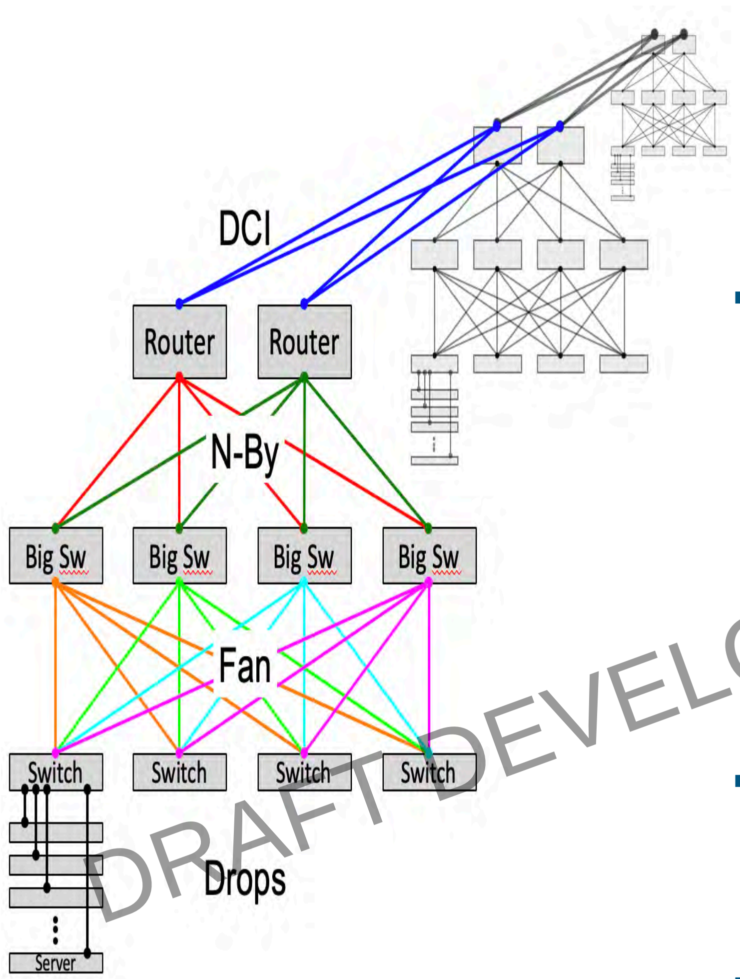


Figure courtesy Jim Theodoras, HG Genuine

Beyond 400 GbE (Serial)	80 km	SMF	DWDM
Beyond 400 GbE (Serial? / WDM / Parallel fibers)	500m to 40 km	SMF	Duplex Fiber
	50 m to 500 m	SMF MMF	Fiber (duplex or parallel)
> 100 GbE	< 30m	MMF twin axial	MMF twin axial

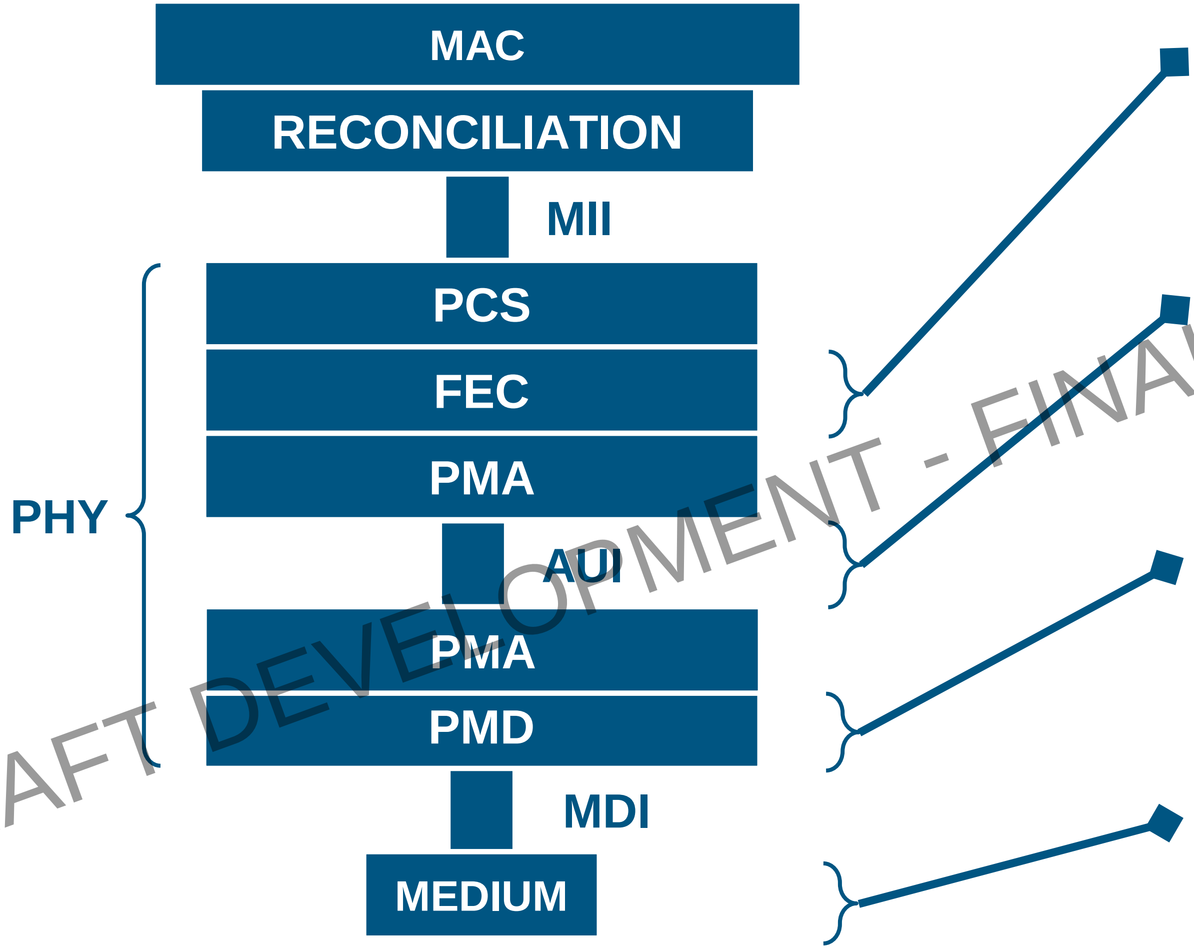
Beyond 400 GbE C2C / C2M AUI Development

Coherent

?

Direct Detect

THE CHALLENGES TO BEYOND 400 GBE



Forward Error Correction

- AUI Specific?
- PHY Specific?
- Multiple variants? Architecture impact?

Electrical Functions

- Increase interface channel count?
- Increase interface rate?
- Increase interface modulation order?

Optical Functions

- Increase interface channel count?
- Increase interface rate?
- Increase interface modulation order?

Media

- Increase interface channel count?
- Increase fiber count?
- Increase lambda count?
- Breakout?

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

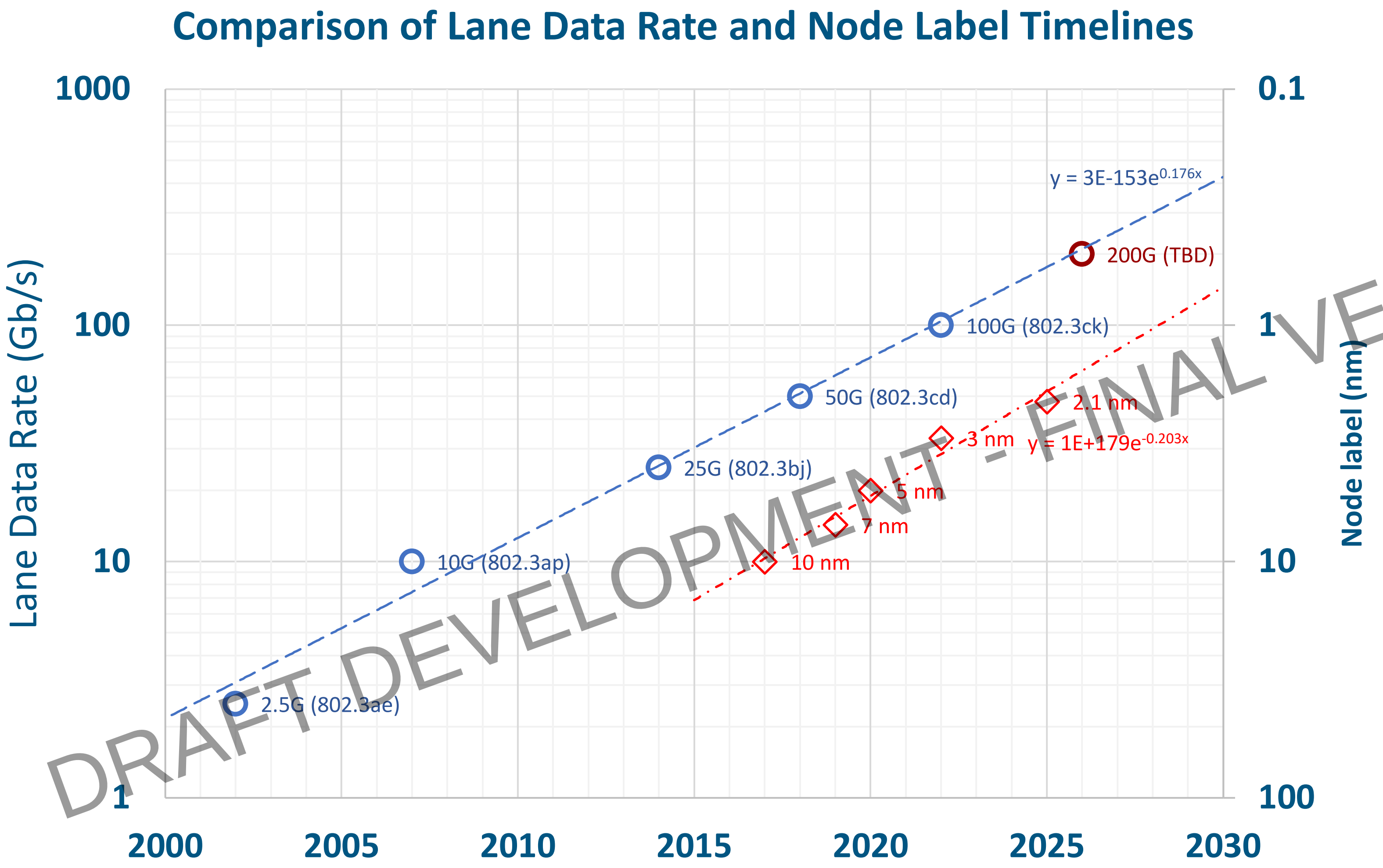
Source – Mark Gustlin, Cisco; Mike Li, Intel; Shawn Nicholl, Xilinx

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

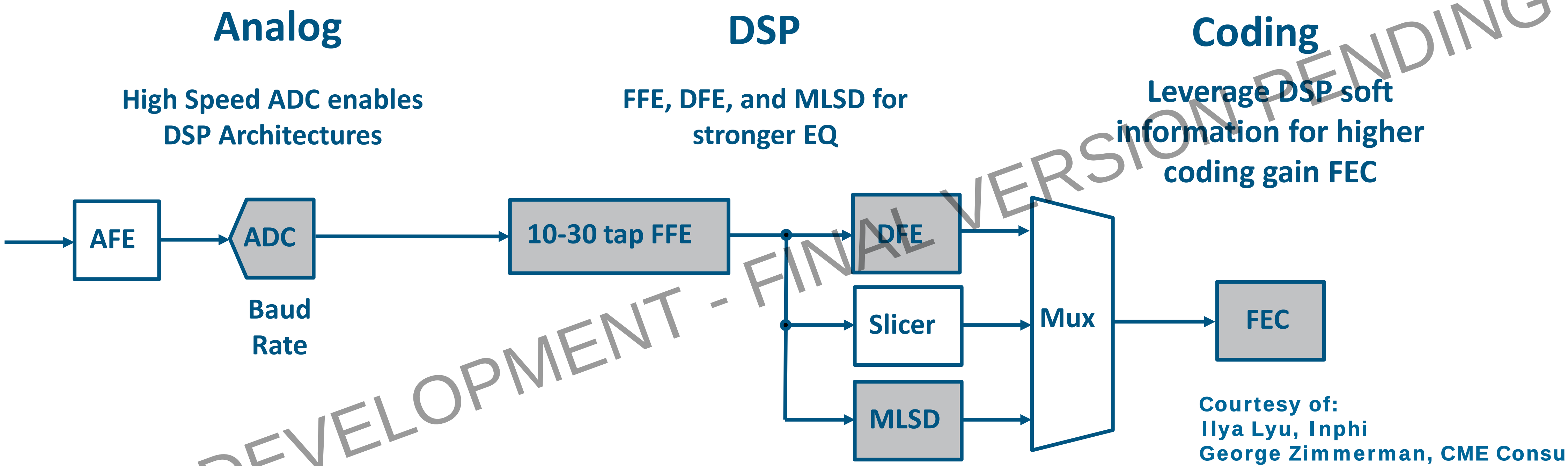
CMOS Roadmap



- 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

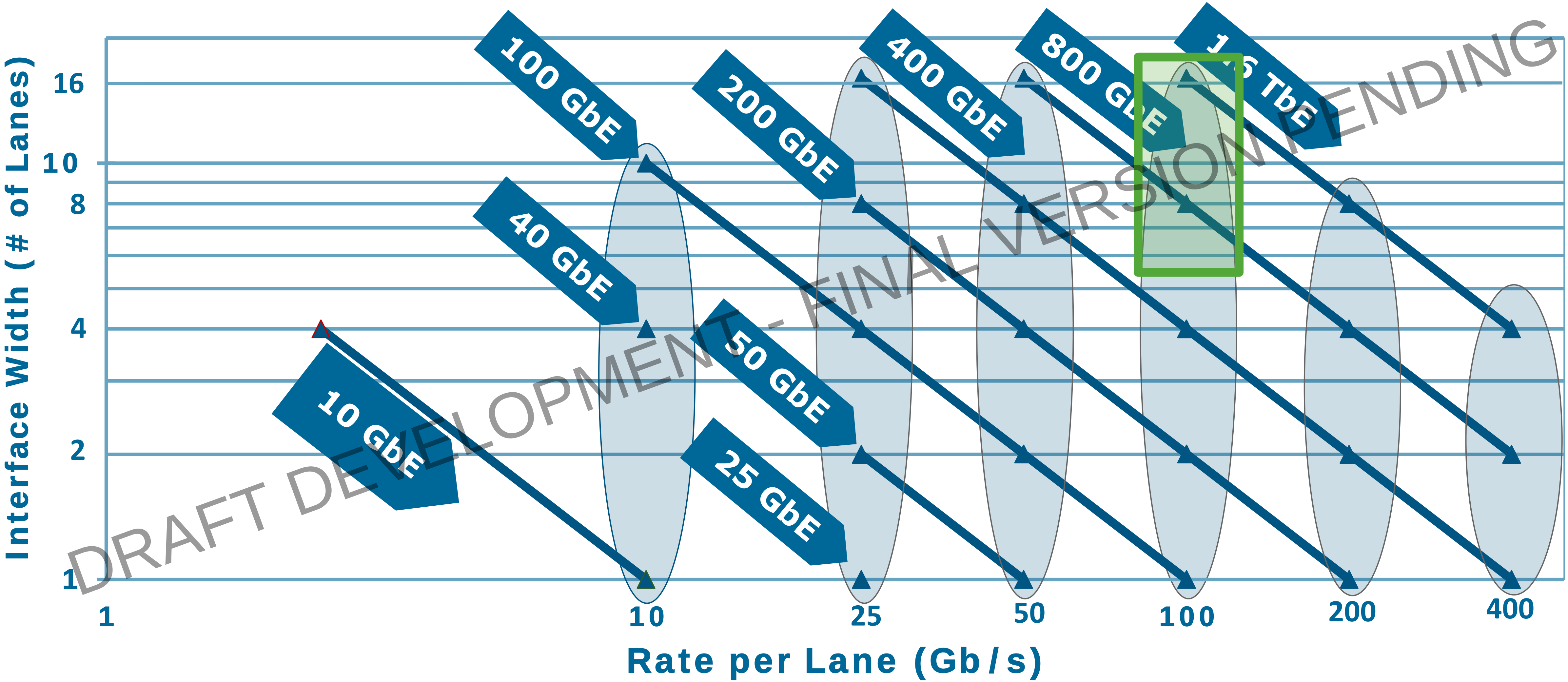


Courtesy of:
Ilya Lyu, Inphi
George Zimmerman, CME Consulting
John D'Ambrosia, Futurewei

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

Beyond 400 GbE - Leveraging 100 Gb/s Signaling

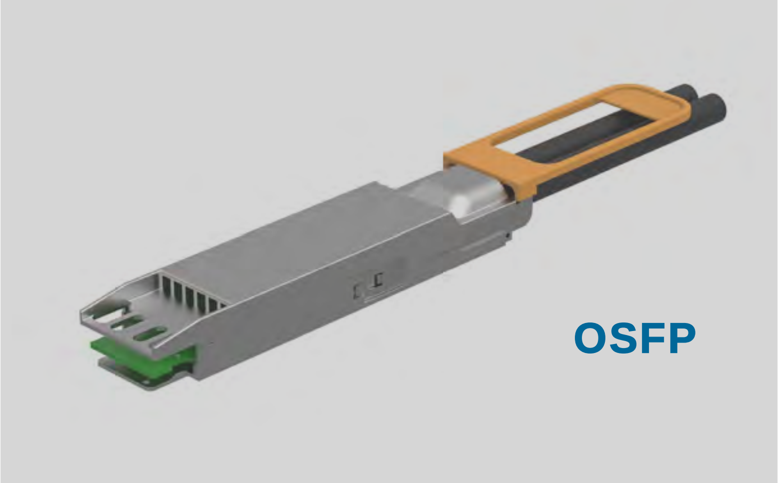


Industry Efforts - 100 Gb/s Signaling

- IEEE 802.3
  - Standard – IEEE P802.3bs – 400GBASE-DR4 (4x100G)
  - 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 G electrical and optical interface specifications)
  - OIF Common Electrical Interface 112G Efforts
  - 100G Lambda MSA (100Gb/s optical interfaces specifications)

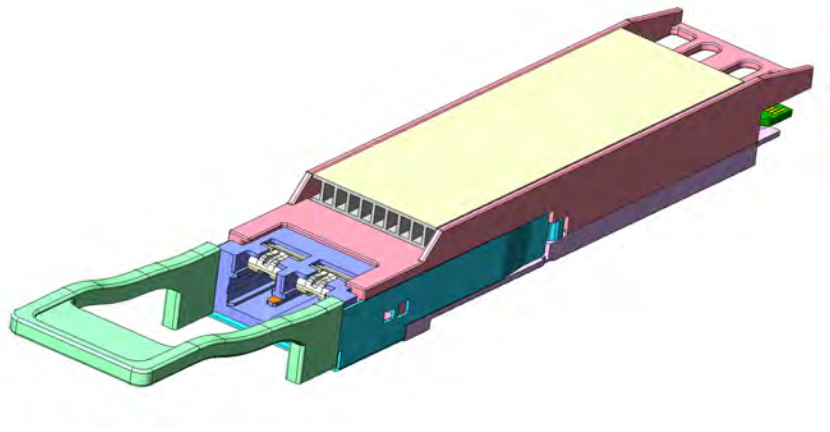
800 Gb/s Industry Activities

- **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



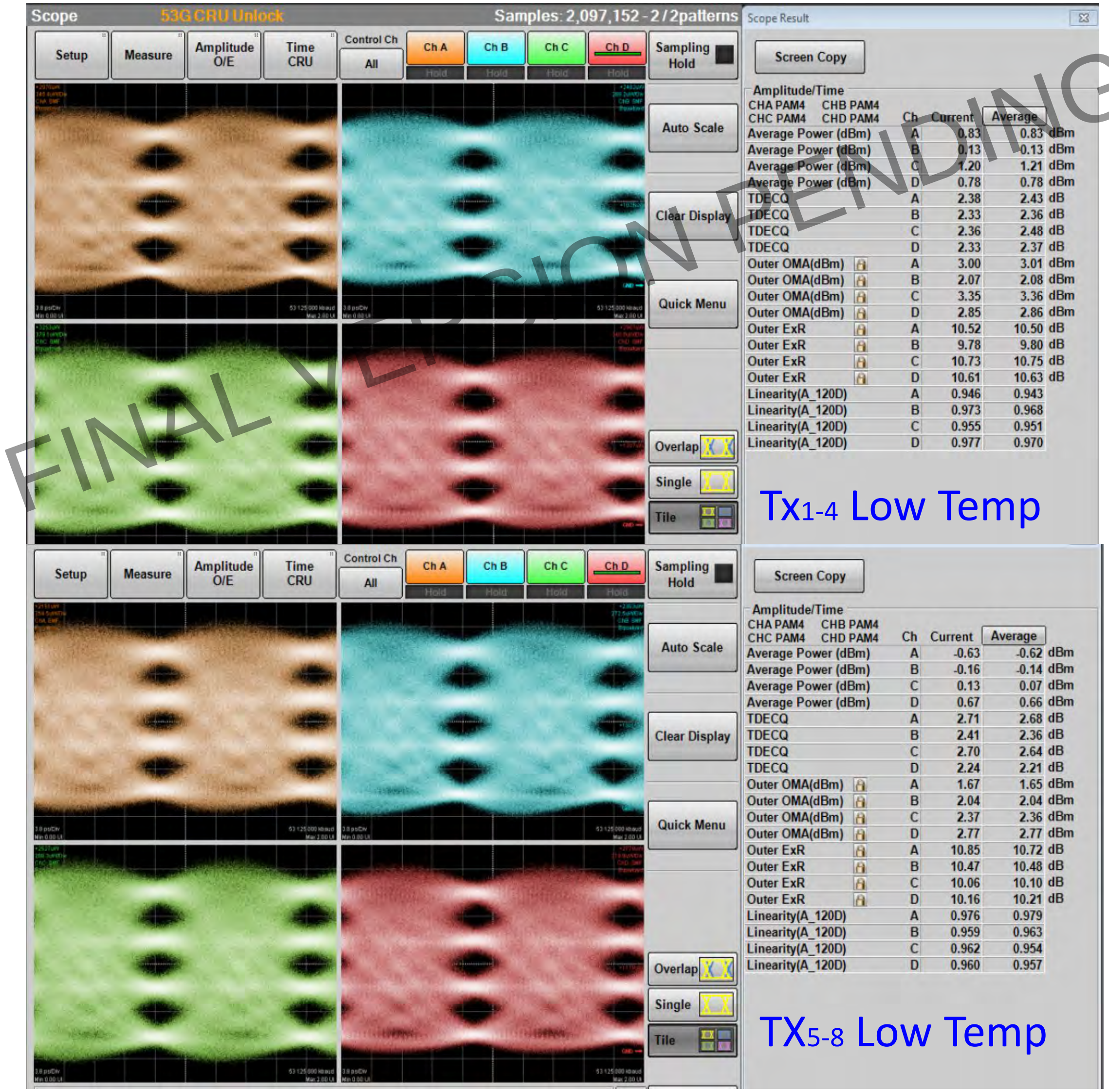
Source– Nathan Tracy, TE Connectivity

Example: 800 Gb/s OSFP Capacity Module

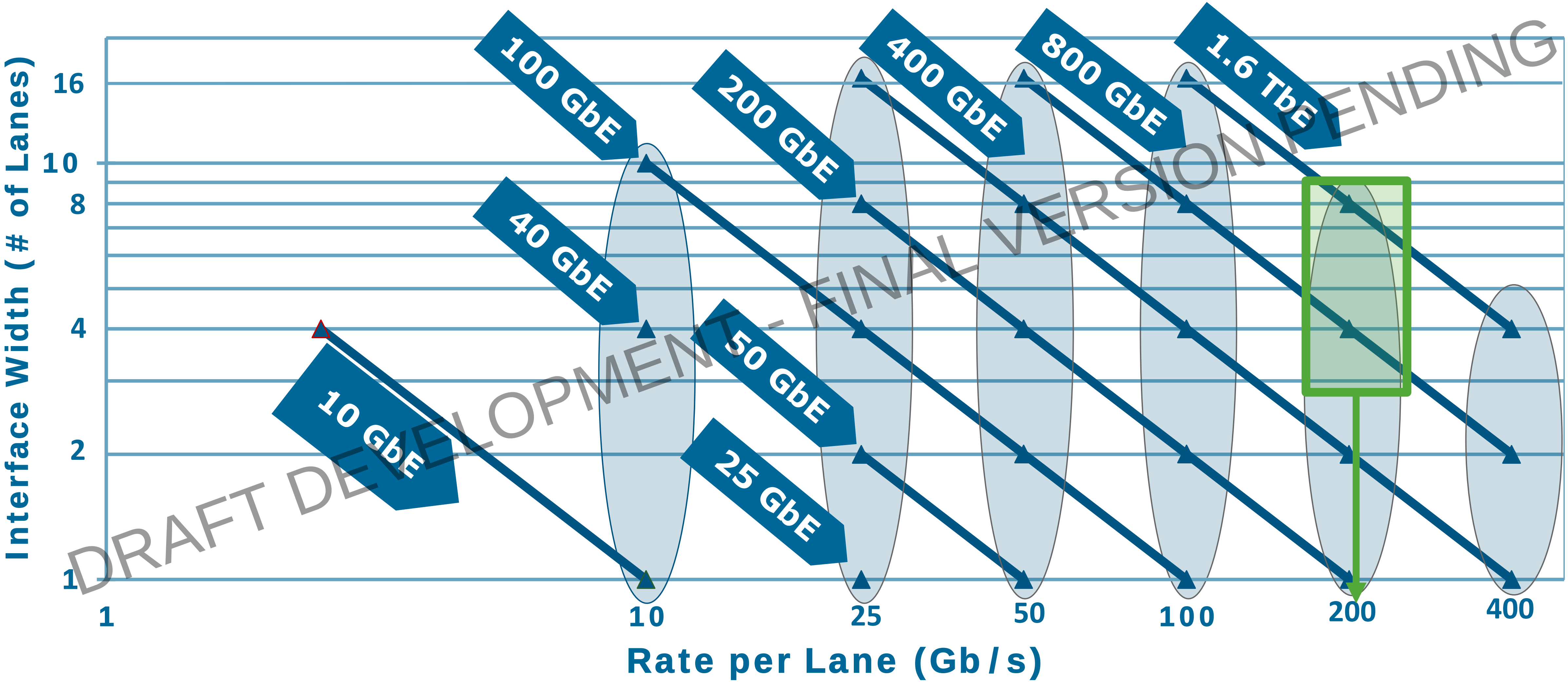


- OSFP Form Factor
- Targeting 2km:
  - 8 x 100 GbE with MPO-16
  - 2 x 400 GbE with CS connector
- OIF CEI-112G-VSR interface
- 0~70degC 18W, 10~60C 17W
- 7nm DSP inside

Source – Osa Mok, Innolight



Beyond 400 GbE - Leveraging 200 Gb/s Signaling



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*; 2*Lumentum, 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**

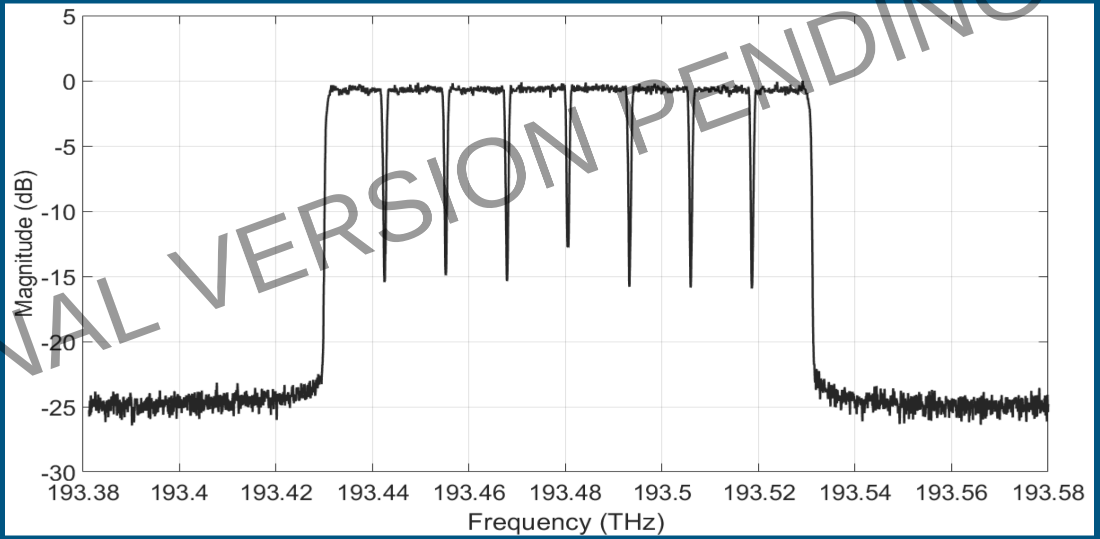
800 Gb/s Single Wavelength Transmission

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!

800 Gb/s single wavelength transmission over 730km in real world long-haul network



8 subcarrier constellation

https://www.lightreading.com/optical-ip/infinera-windstream-tout-optical-networking-milestone/d/d-id/761738

Source – Ted Sprague, Infinera

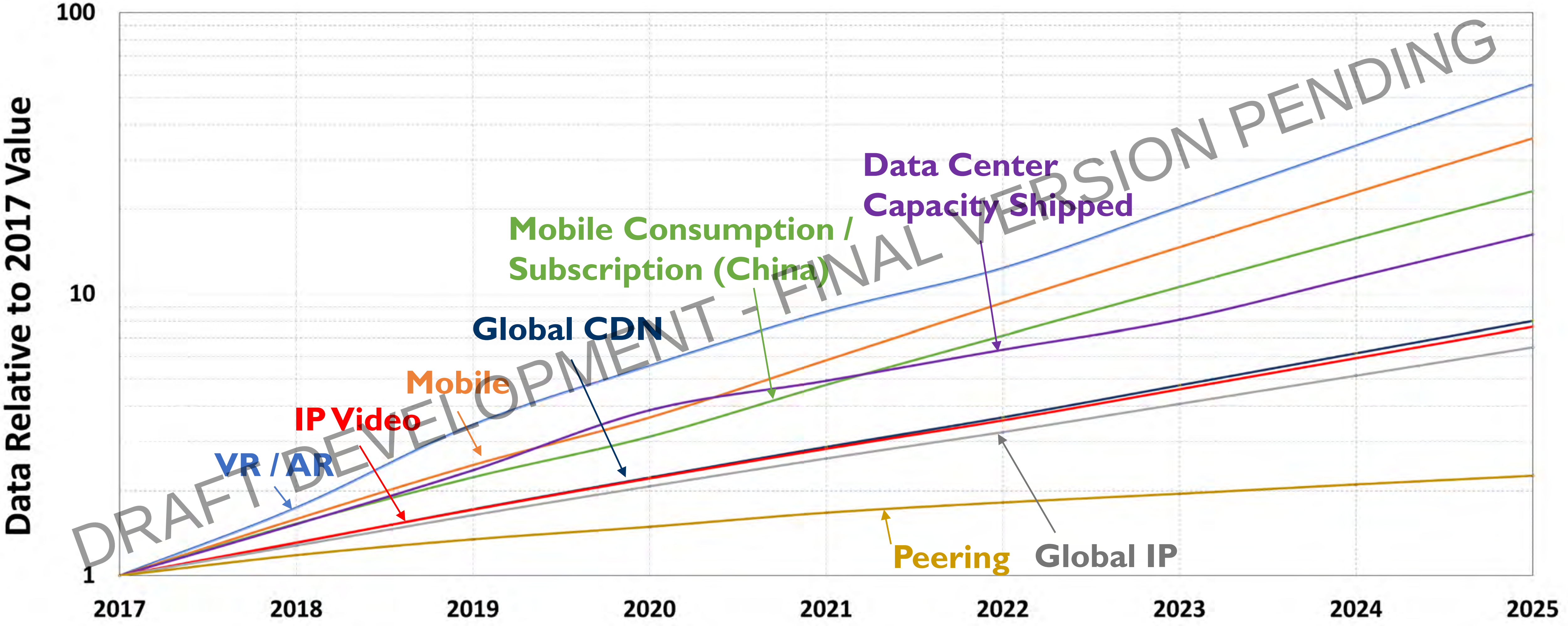
SUMMARY

- 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?

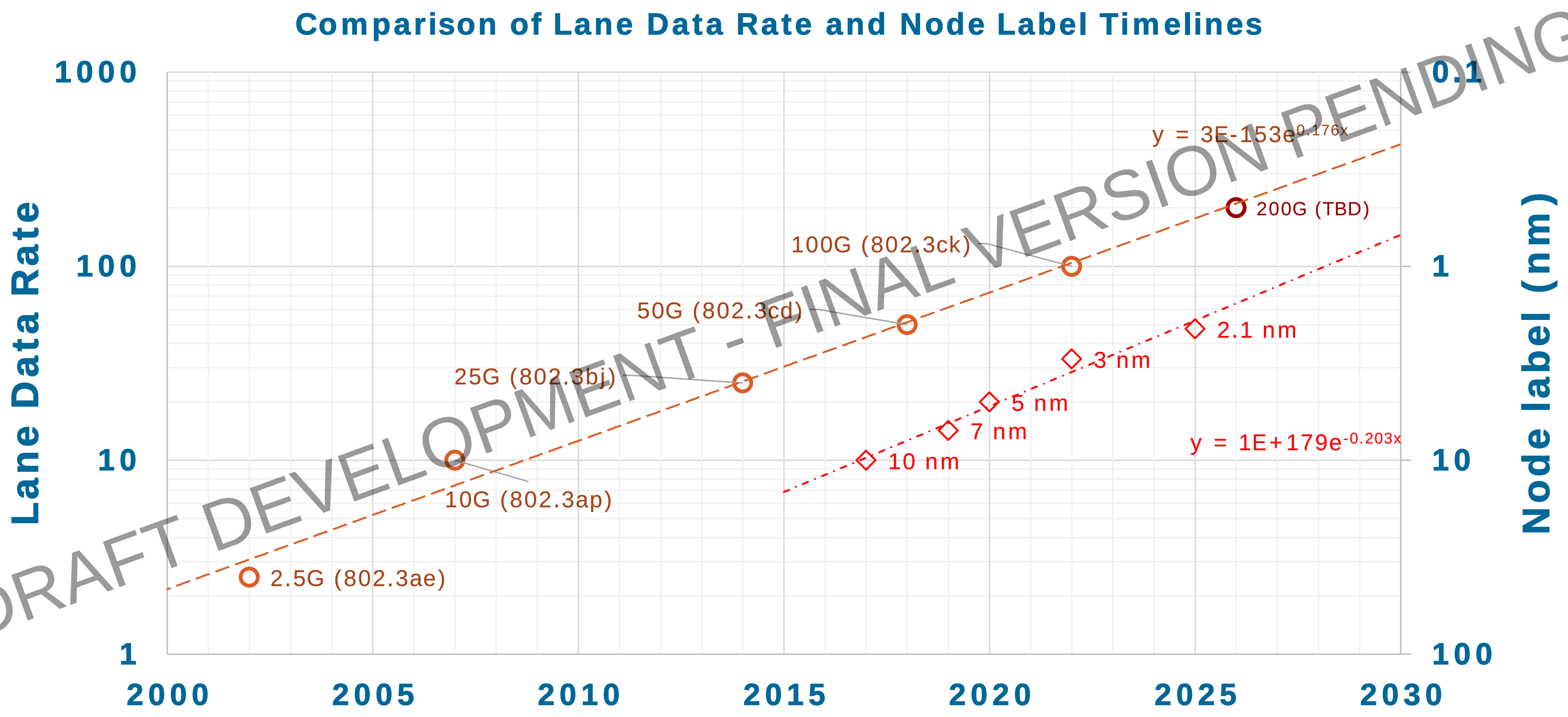
Presented by
John D'Ambrosia

The 2020 Ethernet Bandwidth Assessment



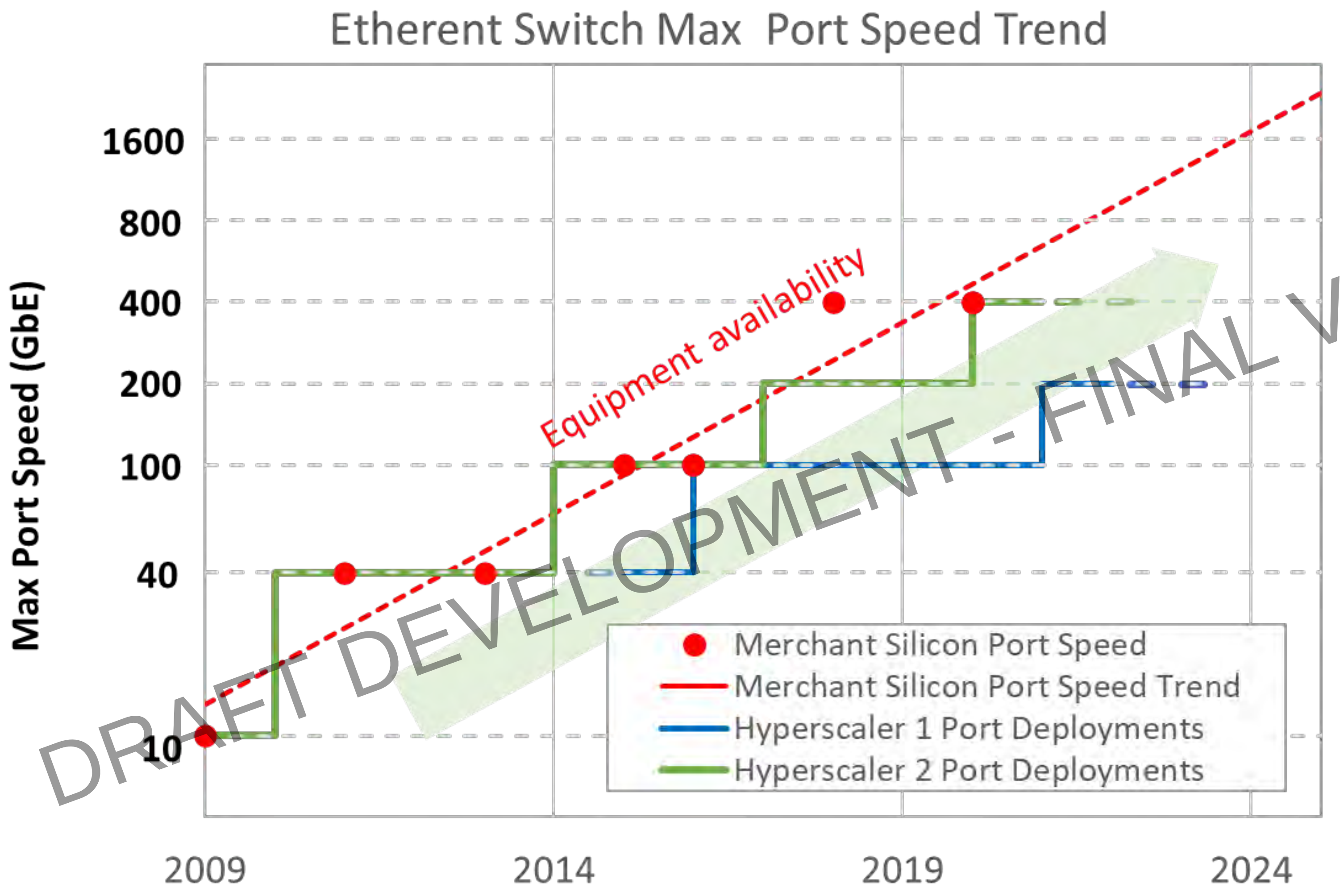
Source: https://bit.ly/802d3bwa2

TRENDLINE – SERDES DEVELOPMENT



Source: Matt Brown, Huawei

Hyperscale Ethernet Deployment – Port Speed



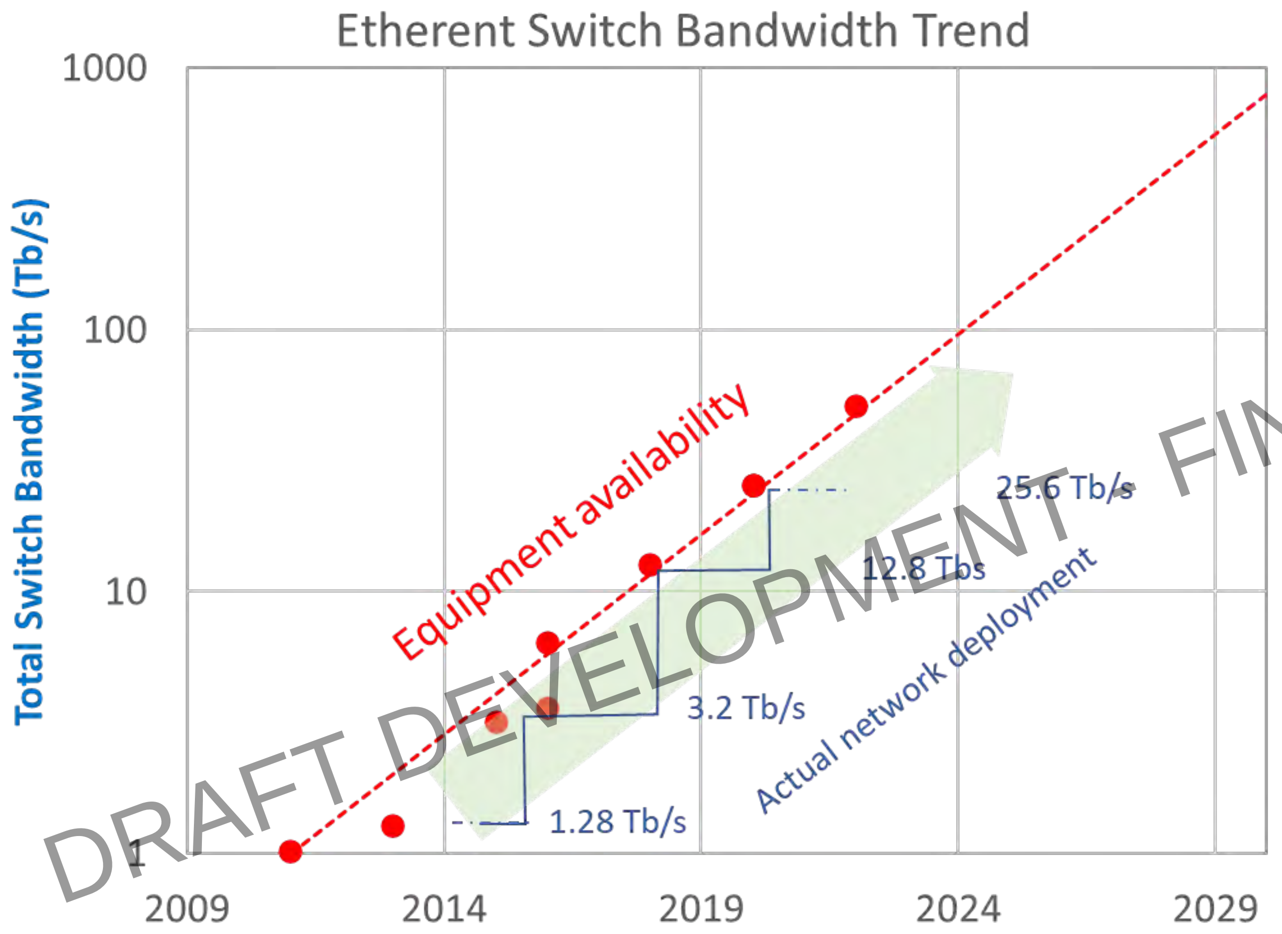
Key observation:

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

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

Understanding the Typical Physical Challenges

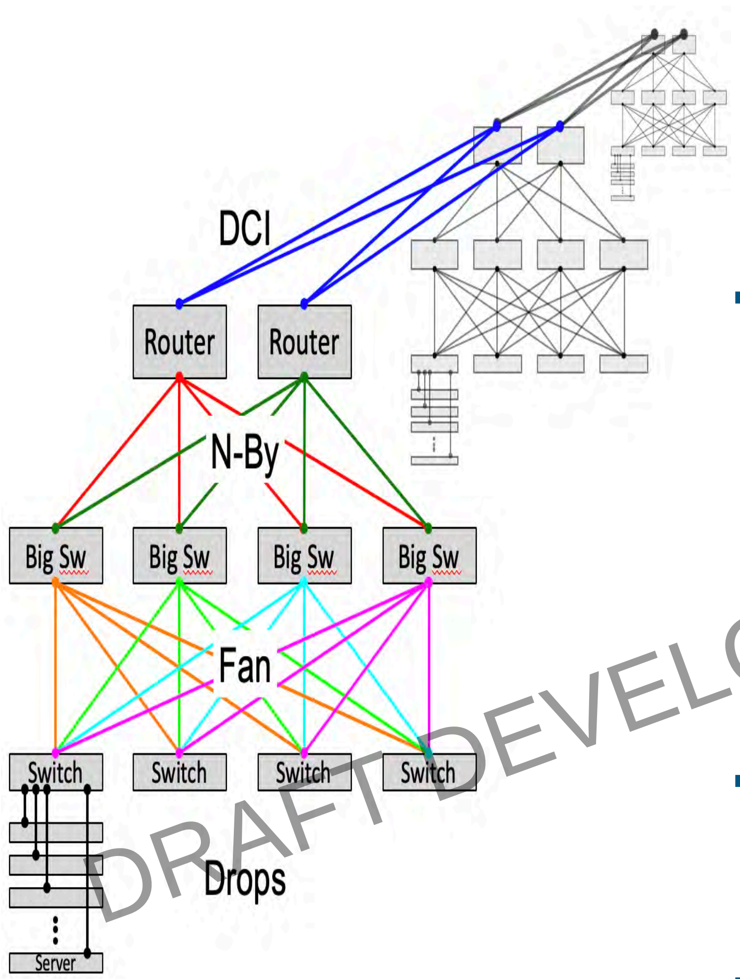


Figure courtesy Jim Theodoras, HG Genuine

Beyond 400 GbE (Serial)	80 km	SMF	DWDM
Beyond 400 GbE (Serial? / WDM / Parallel fibers)	500m to 40 km		Duplex Fiber
	50 m to 500 m	SMF MMF	Fiber (duplex or parallel)
> 100 GbE	< 30m	MMF twin axial	MMF twin axial

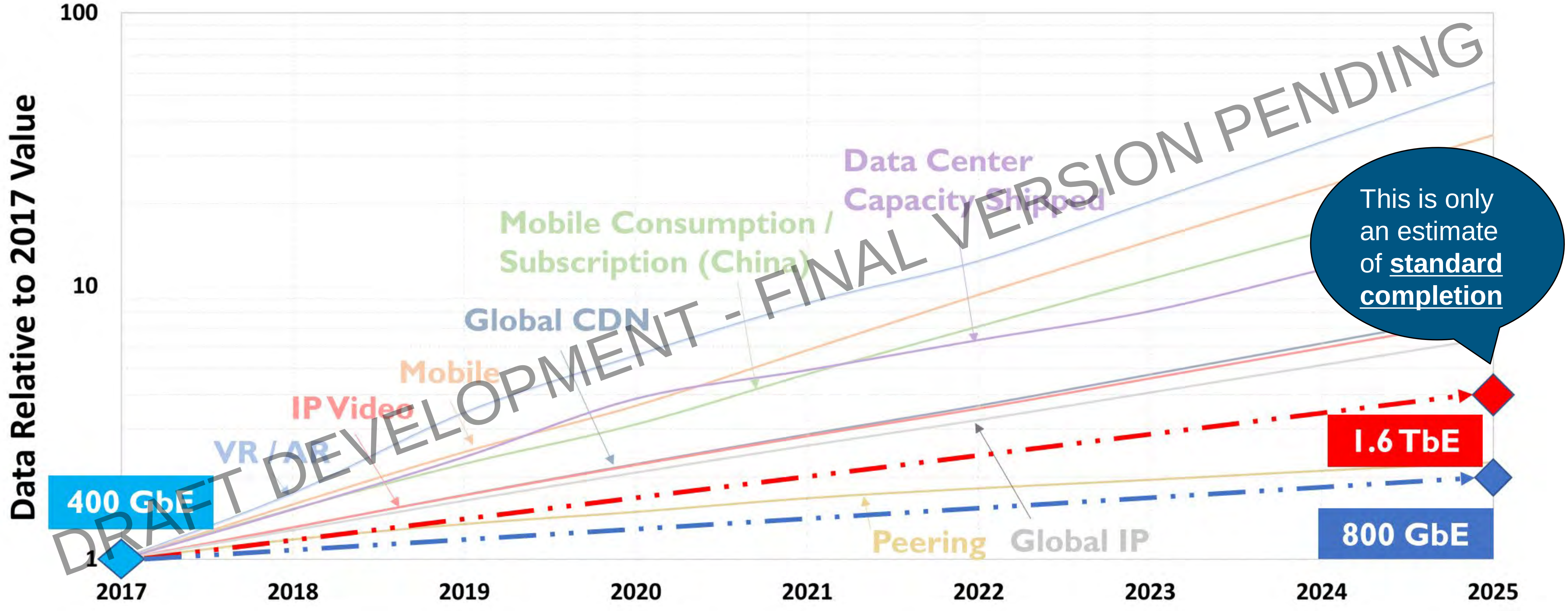
Beyond 400 GbE C2C / C2M AUI Development

Coherent

?

Direct Detect

CONSIDERING THE NEXT ETHERNET RATE STANDARD



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

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) (as of 9/26/20)

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

Supporters (Page 2 of 3) (as of 9/26/20)

Lokesh	Kabra	Synopsys
Mark	Kimber	Semtech
Kishore	Kota	Inphi
Cedric	Lam	Google
Dominic	Lapierre	EXFO
Greg	Le Cheminant	Keysight Technologies
David	Lewis	Lumentum
Jon	Lewis	Dell Technologies
Junjie	Li	China Telecom
Mike	Li	Intel
Robert	Lingle	OFS
Hai-Feng	Liu	HG Genuine
Kent	Lusted	Intel
Ilya	Lyubomirsky	Inphi
Valerie	Maguire	Siemon
Jeff	Maki	Juniper
David	Malicoat	Malicoat Networking Solutions
Eric	Maniloff	Ciena
Flavio	Marques	Furukawa Electric
Brett	McClellan	Marvell
Larry	McMillan	Western Digital
Rich	Mellitz	Samtec
Guangcan	Mi	Huawei
Osa	Mok	Innolight
Inder	Monga	Esnet
Dale	Murray	LightCounting
Ray	Nering	Cisco
Shawn	Nicholl	Xilinx
Gary	Nicholl	Cisco
Paul	Nikolich	Independent
David	Ofelt	Juniper
Kumi	Omori	NEC
Tom	Palkert	Samtec
Earl	Parsons	CommScope
Vasu	Parthasarathy	Broadcom
Jerry	Pepper	Keysight Technologies
Phong	Pham	EPCOMM Inc.
David	Piehler	Dell Technologies
Rick	Pimpinella	Panduit

Supporters (Page 3 of 3) (as of 9/26/20)

Rick	Rabinovich	Keysight Technologies
Sridhar	Ramesh	Maxlinear
Olindo	Savi	Hubbell
Ed	Sayre	North East Systems Associates, Inc.
Steve	Sekel	Keysight Technologies
Steve	Shellhammer	QualComm
Priyank	Shukla	Synopsys
Scott	Sommers	Molex
Yoshiaki	Sone	NTT
Massimo	Sorbara	GlobalFoundries
Ted	Sprague	Infinera
Henk	Steenman	AMS-IX
Rob	Stone	Facebook
Steve	Swanson	Corning Incorporated
Bharat	Tailor	Semtech
Tomoo	Takahara	Fujitsu
Jim	Theodoras	HG Genuine USA
Nathan	Tracy	TE Connectivity
Viet	Tran	Keysight Technologies
Jeff	Twombly	Credo Semiconductor

Ed	Ulrichs	Intel
Paul	Vanderlaan	UL LLC
Prasad	Venugopal	Arista Networks
Xinyuan	Wang	Huawei
Winston	Way	Neophotonics
Markus	Weber	Acacia Communications
Yangling	Wen	Futurewei
Tom	Williams	Acacia Communications
James	Withey	Fluke
Chongjin	Xie	Alibaba
Shuto	Yamamoto	NTT
Zhiwei	Yang	ZTE
James	Young	Commscope
Xu	Yu	Huawei
Hua	Zhang	Hisense Broadband
Wenyu	Zhao	CAICT
Xiang	Zhou	Google
Yan	Zhuang	Huawei
George	Zimmerman	CME Consulting
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 participation in the "Beyond 400 Gb/s Ethernet" Study Group in IEEE 802.3
  - Tally: (Results to be processed after call)

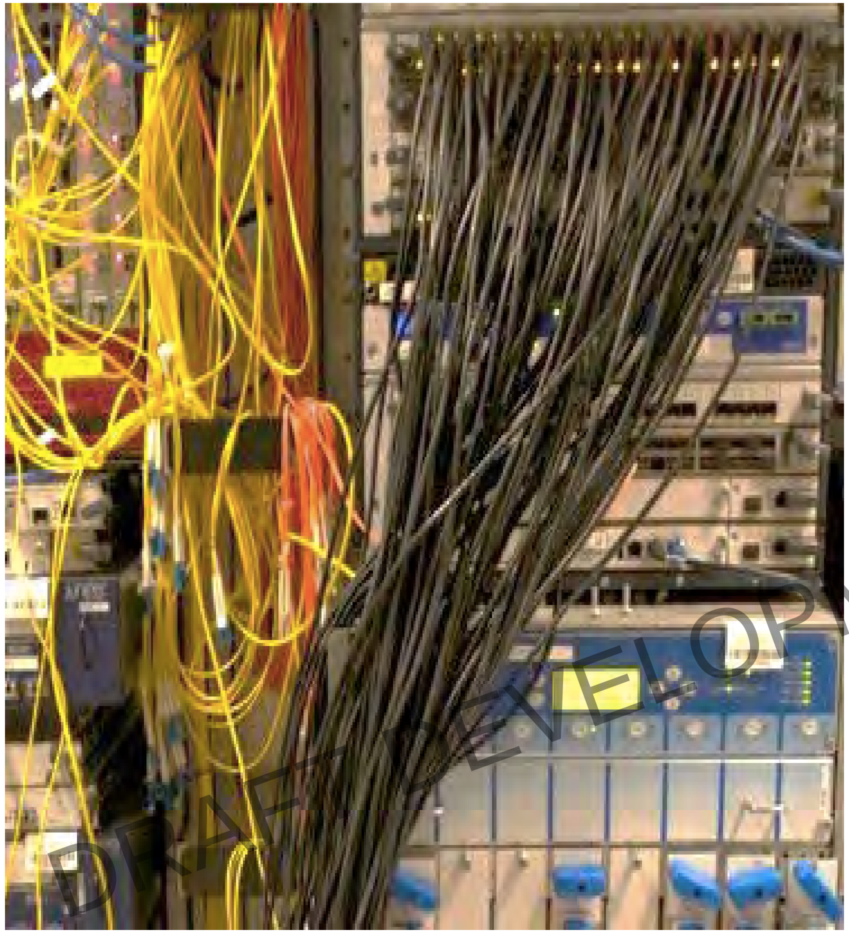
Future work

- 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

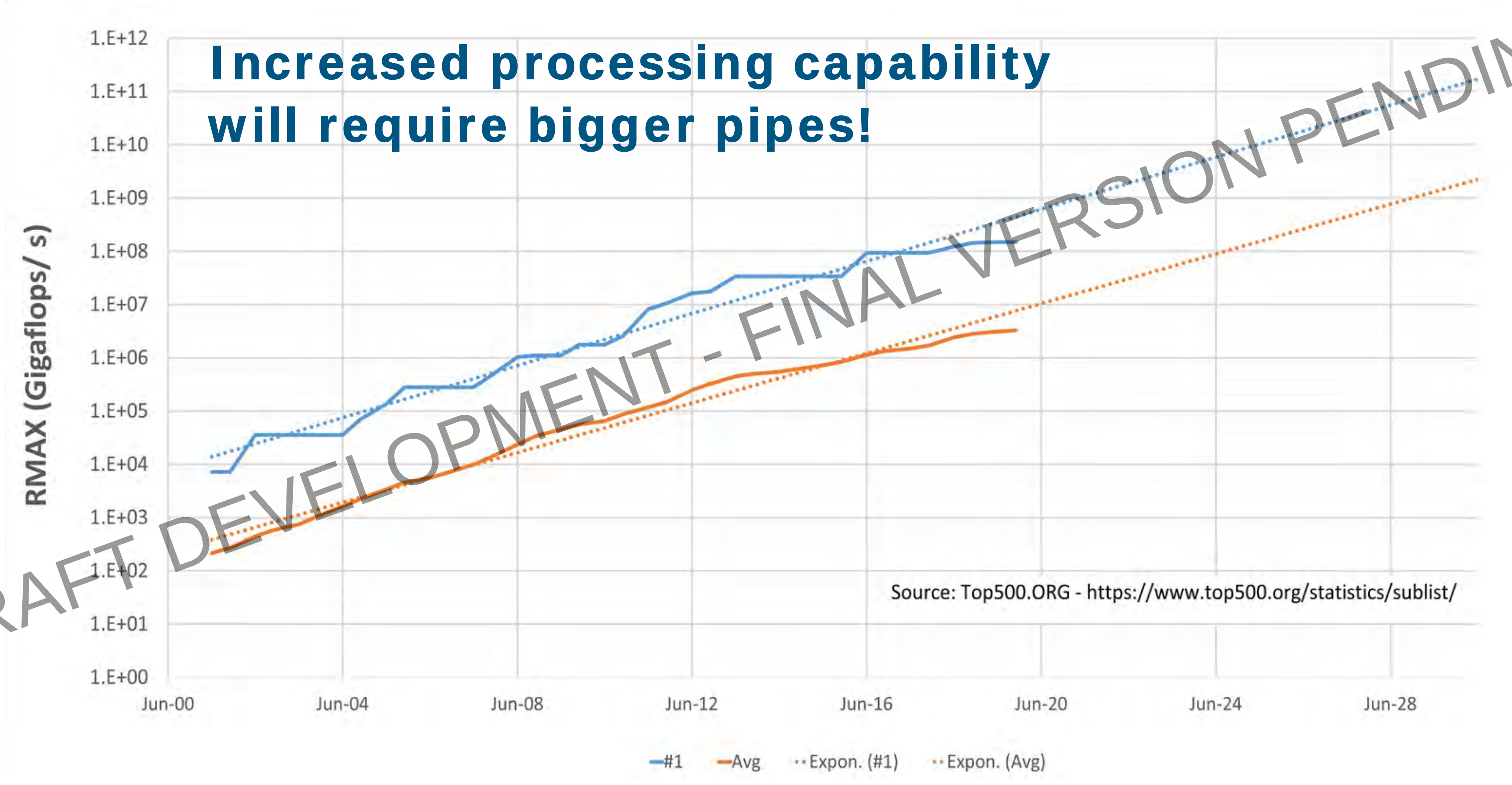
LINK AGGREGATION WILL NOT SUFFICE



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**
  - **Exponential bandwidth growth implies:**
    - **Exponential growth in number of links**
    - **Growth in operational & management issues**
  - **Doesn't scale forever.**
- **Faster links address these issues *and they will be LAGGed!***

HIGH PERFORMANCE COMPUTING

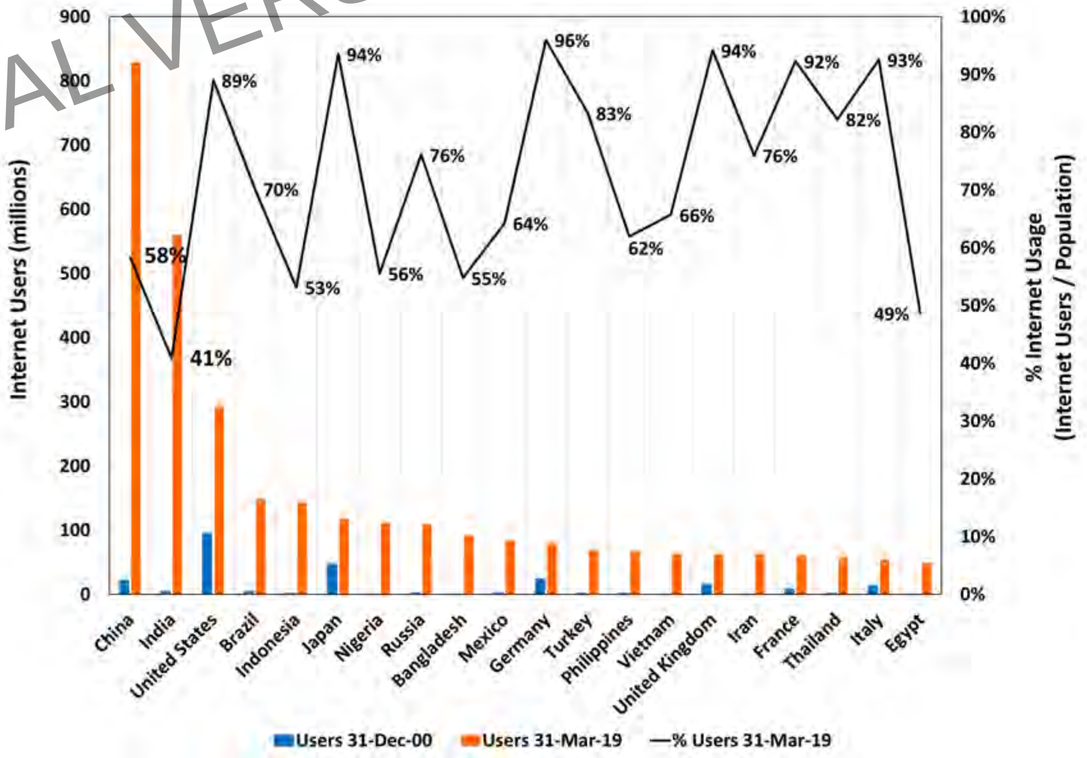


WORLD INTERNET USAGE

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
3. 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%
Average Traffic per User per Month **GB**	29	85	193%

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

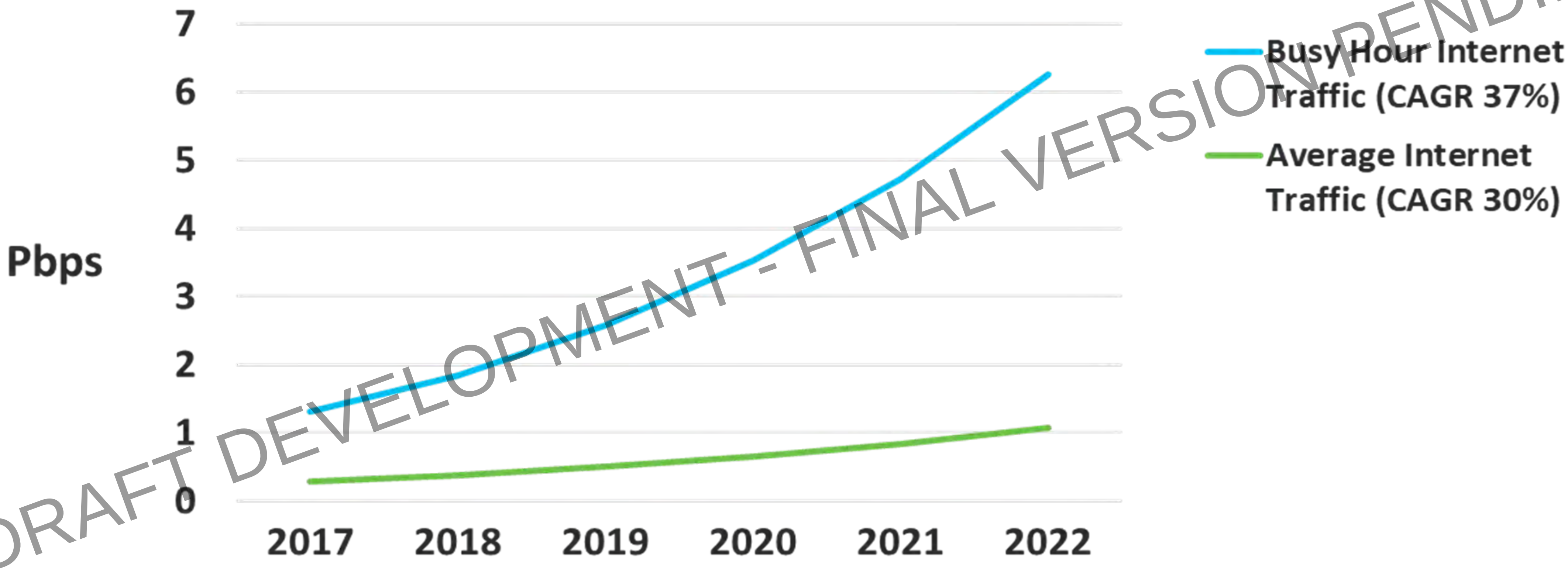
(Mb/s)	2017	2022	CAGR
Fixed Broadband	7.8	20.2	21.0%
Wi-Fi	6.2	11.2	12.6%
Cellular	4.4	15.3	28.3%

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%

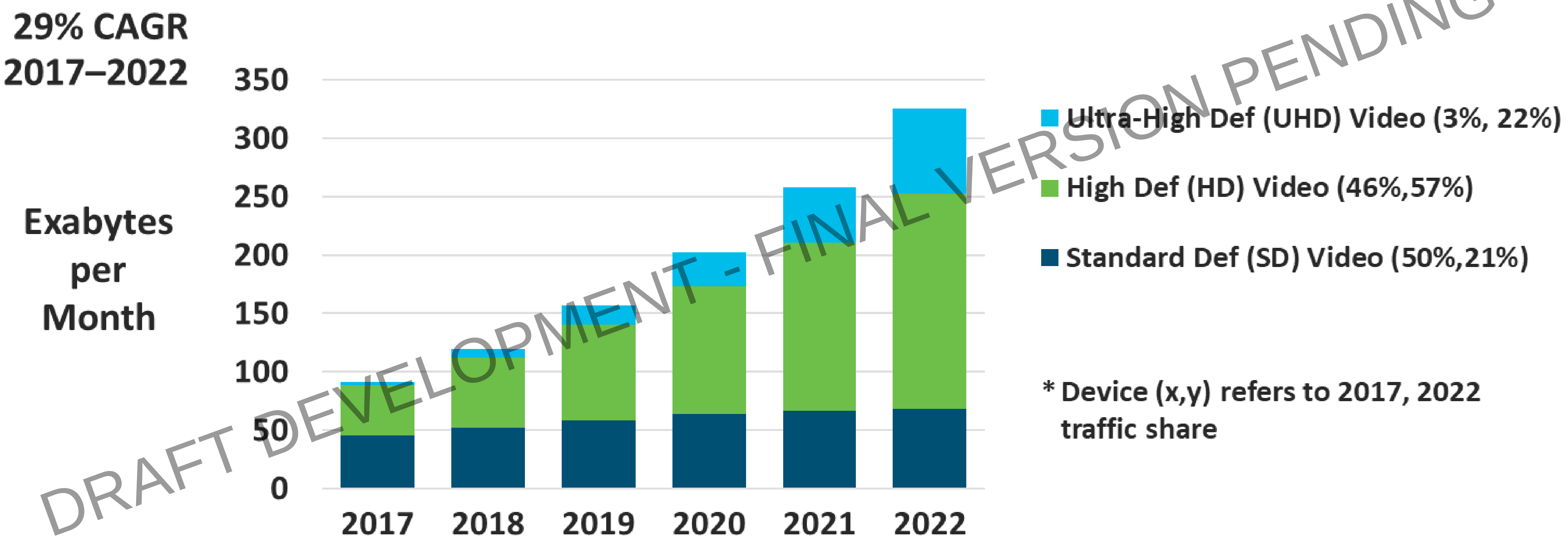
Source: Cisco VNI Forecast Update, http://www.ieee802.org/3/ad_hoc/bwa2/public/calls/19_0624/nowell_bwa_01_190624.pdf

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

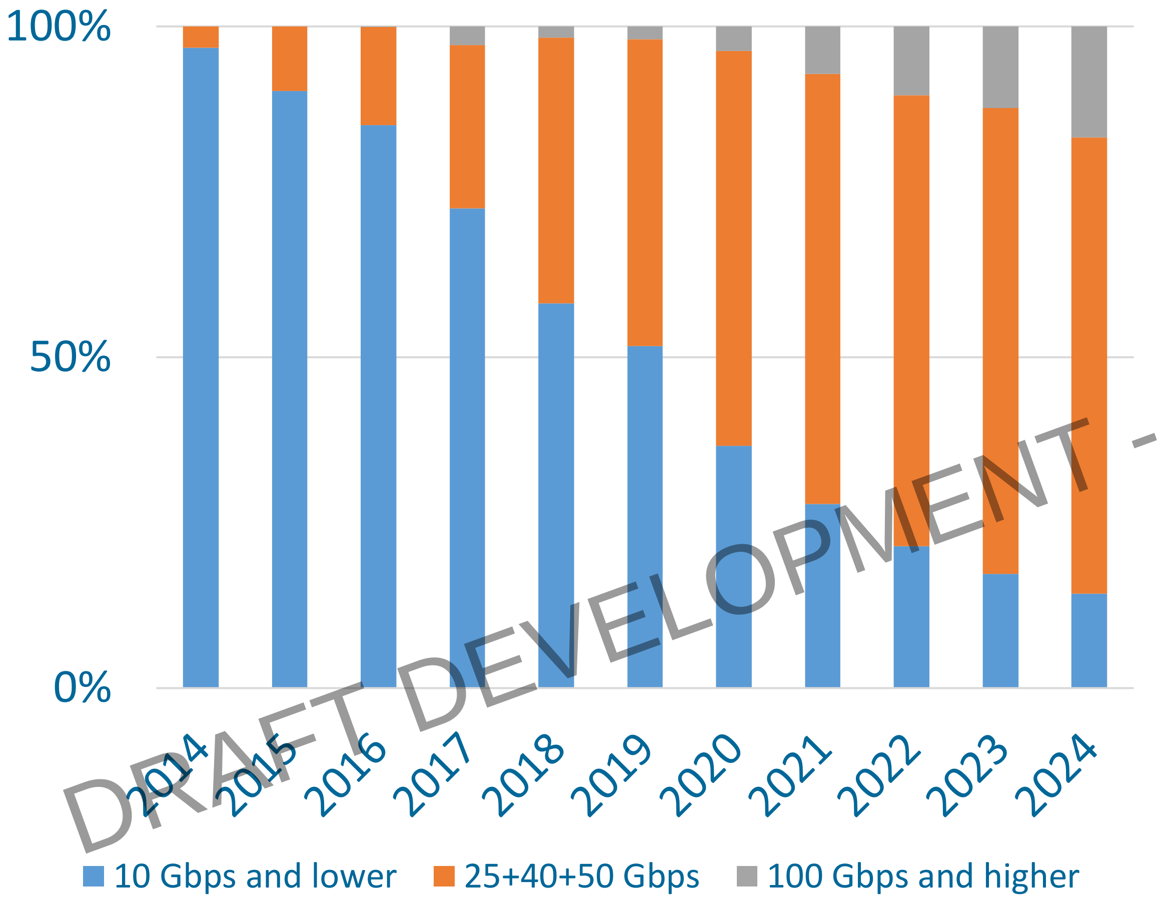


Growth in the adoption of HD and UHD dominate IP video traffic

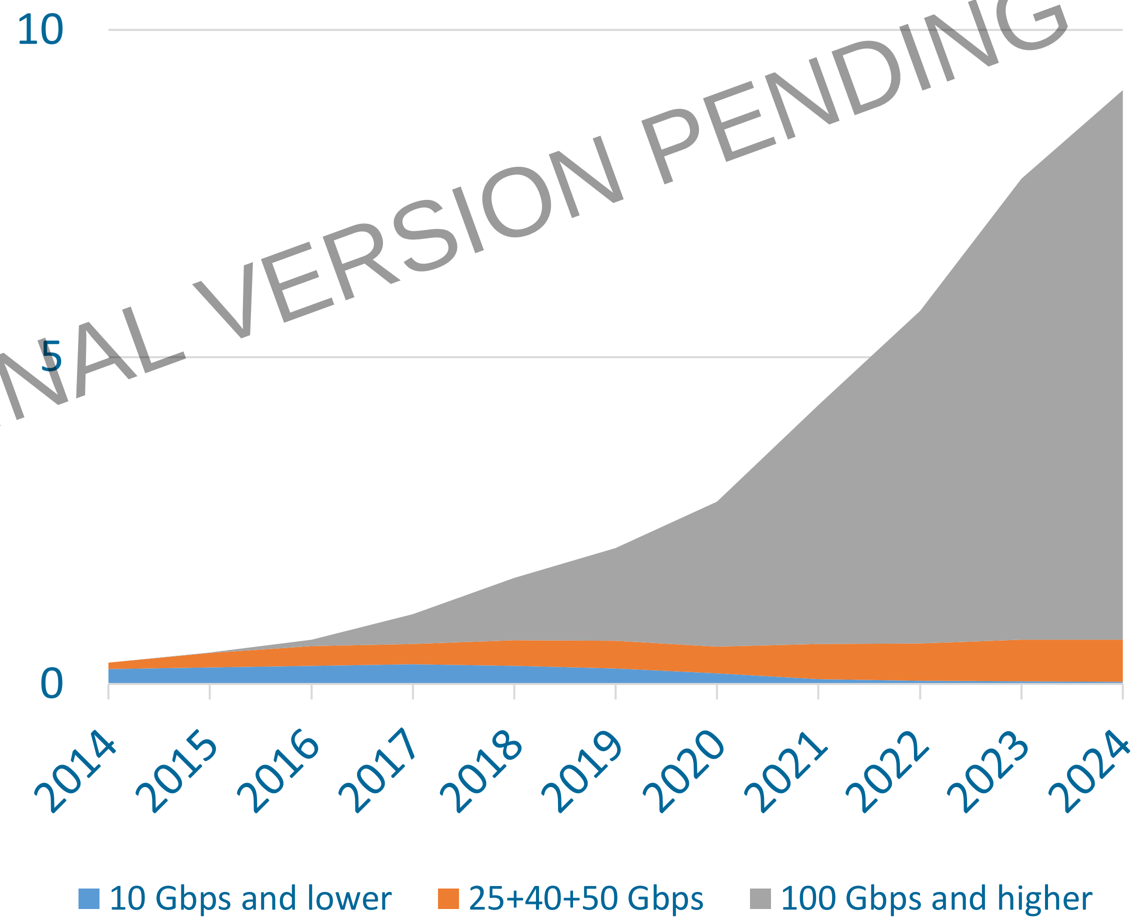
Source: Cisco VNI Forecast Update, http://www.ieee802.org/3/ad_hoc/bwa2/public/calls/19_0624/nowell_bwa_01_190624.pdf

DATA CENTER CAPACITY CONTINUES TO GROW

Enterprise / Cloud Server Unit Shipments*



Switch Capacity Shipments in Eb/s**

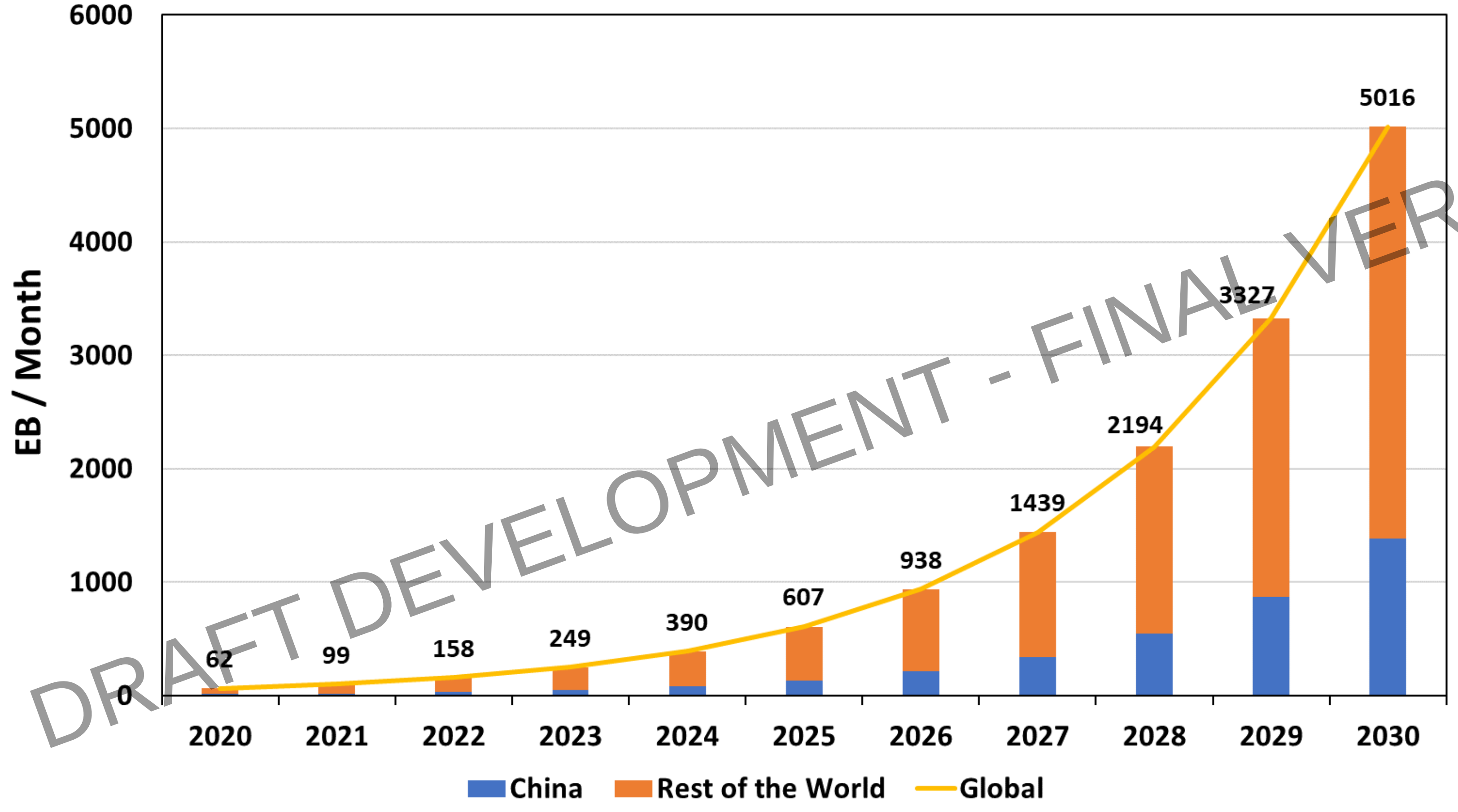


* Percent of annual server shipments categorized by speed of the attached controllers and adapters

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

DELL'ORO GROUP

ESTIMATION OF MOBILE TRAFFIC



Global mobile traffic is expediential 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