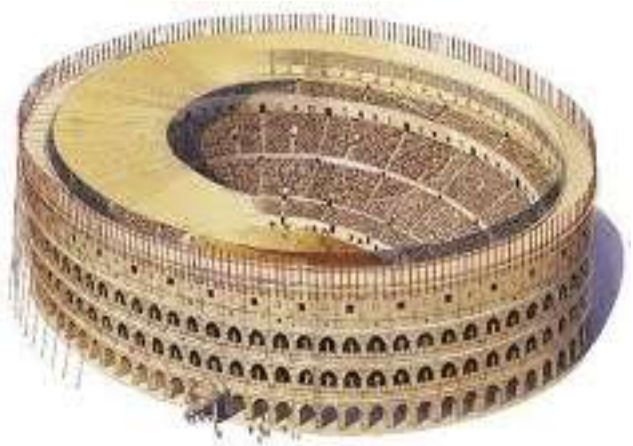
Did the Optics Industry Blunder by Switching Intra-Datacenter Links from NRZ to PAM4? Will More DSP like PAM6 and Coherent Follow, or Will WDM and Parallel Save the Day?

Chris Cole

OFC Rump Session

June 9, 2021



Start
6:00 – 6:05

WDM vs. DSP Team Format Maximizes Your Entertainment

- WDM & DSP Team Captains (Chris & Ilya, respectively) organize the Rump Session
- They start the Session with introductory presentations
- Followed by presentations by four WDM vs. DSP Team Provocateur Matched Pairs
- Presentations (50% time) are followed by vigorous audience participation (50% time)
    - tough questions
    - insightful comments
    - different perspectives
- Do not be shy, long-winded, and make any corporate pitches (you will be cut-off)
- Do challenge the Provocateurs and each other, and be entertained
- On behalf of the Provocateurs, the Captains greet you:
    - Moritūrī tē Salūtant (those who are about to die salute you)

Provocateur Matched Pair Example

Colosseum

Murmillo

Tracio

Triumphant Provocateur

Vanquished Provocateur

Agenda

WDM Team					DSP Team				
Role	PPT Start	Q&A Start	Name	Affiliation	**Role**	PPT Start	Q&A Start	Name	Affiliation
Editor	6:05	6:15	Chris Cole	II-VI (Adviser)	**Suma Rudis**	6:20	6:30	Ilya Lyubomirsky	Marvell
Secutor	6:35	6:40	Boris Murmann	Stanford University	**Reciario**	6:45	6:50	Dan Sadot	Ben Gurion University
Murmillo	6:55	7:00	Shigeru Kanazawa	NTT	**Tracio**	7:05	7:10	Xiang Zhou	Google
Provocator	7:15	7:20	Peter Winzer	Nubis Comm.	**Scissor**	7:25	7:30	Henry Sun	Infinera
Hoplomaco	7:35	7:40	Chris Pfistner	Avicena Tech	**Equite**	7:45	7:50	Yi Cai	Soochow University

Optical Datacom NRZ vs. PAM4 Debate

- NRZ was used on all 25G and lower speed λs
  - 1G λs : 1GbE
  - 10G λs: 10GbE, 40GbE
  - 25G λs: 25GbE, 100GbE
- IEEE chose PAM4 modulation for 50G copper lanes in 2012
- NRZ vs. PAM4 50G λs debate started in IEEE in 2012
  - 200GbE & 400GbE project
  - PAM4 25Gbaud adopted in 2015
  - Enabled reuse of 50G PAM4 SerDes technology in development for ASICs
  - Enabled reuse of 25G λs tech. (25Gbaud) for perceived quicker time to market

Shannon-Hartley Theorem (from Cole IEEE 802.3bs, 12 Mar 2015, p.3)

$C = B \log_2 (1 + S/N)$

C ≜ Channel capacity

B ≜ Bandwidth

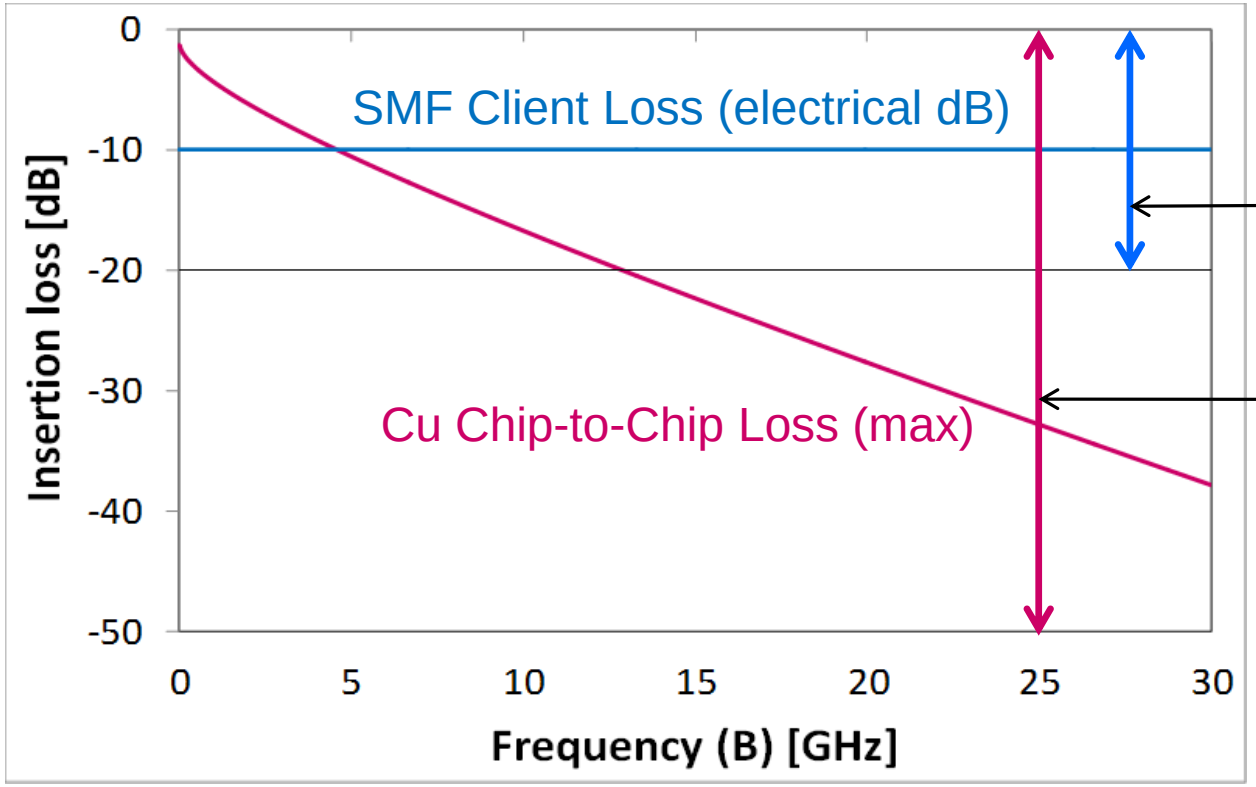
S ≜ Signal Power

N ≜ Noise Power

Guidance to increase C:

- If B limited, increase S/N to support higher order modulation (HOM)
- If S/N limited, increase B to support higher Baud rate

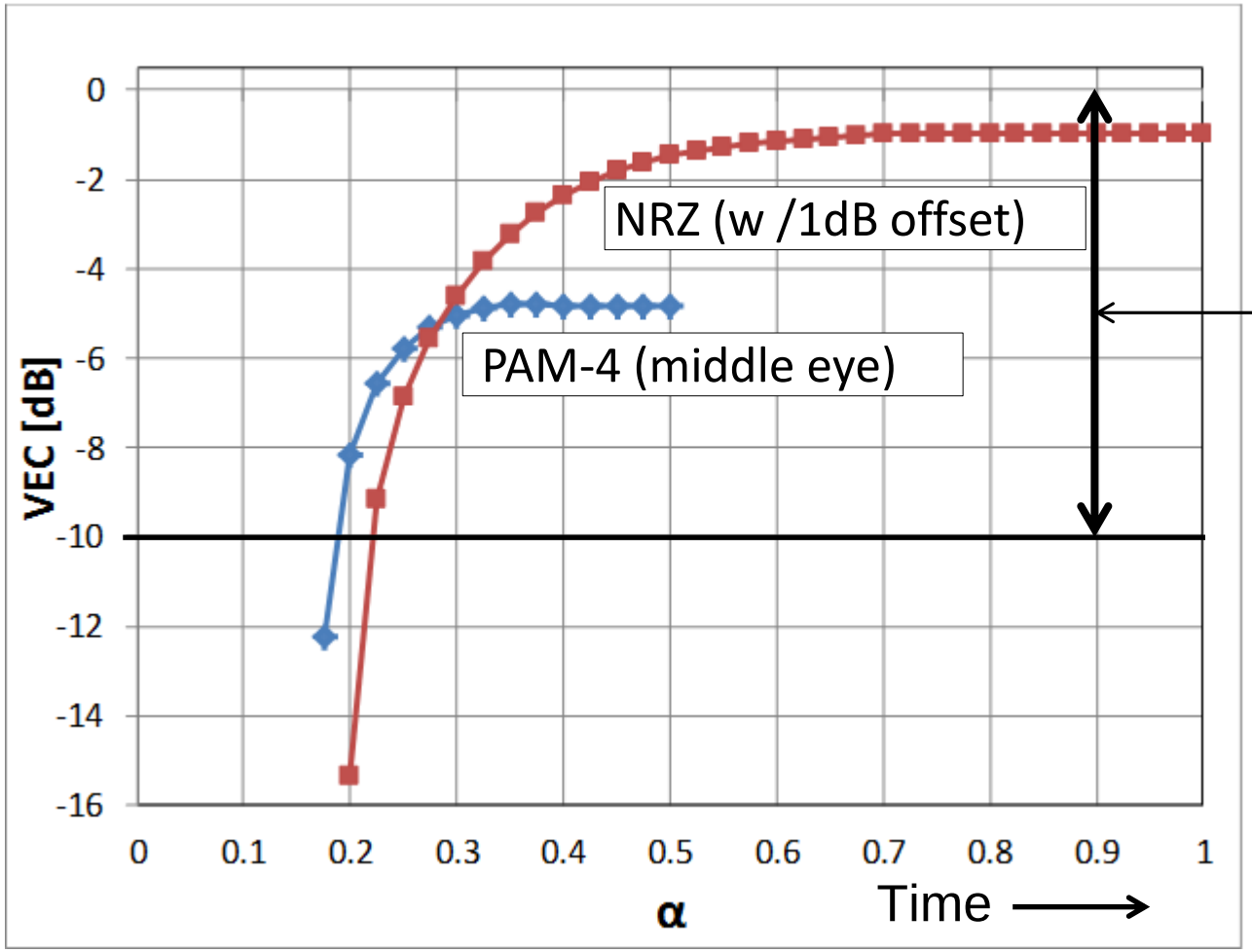
Channel Loss & TRX S/N (from Cole IEEE 802.3bs, 12 Mar 2015, p.4,5)



S/N no FEC BTB	Limitation		Modu-lation Guide
	Channel B	TRX S/N	
SMF TRX	No	Yes	NRZ
Cu SerDes	Yes	No	HOM

Component Bandwidth & VEC (from Cole IEEE 802.3bs, 12 Mar 2015, p.7-11)

VEC improves with component bandwidth (B) which increases over time.



noise penalty offsets VEC by ~1dB (B_{NRZ}/B_{PAM-4} dependent)

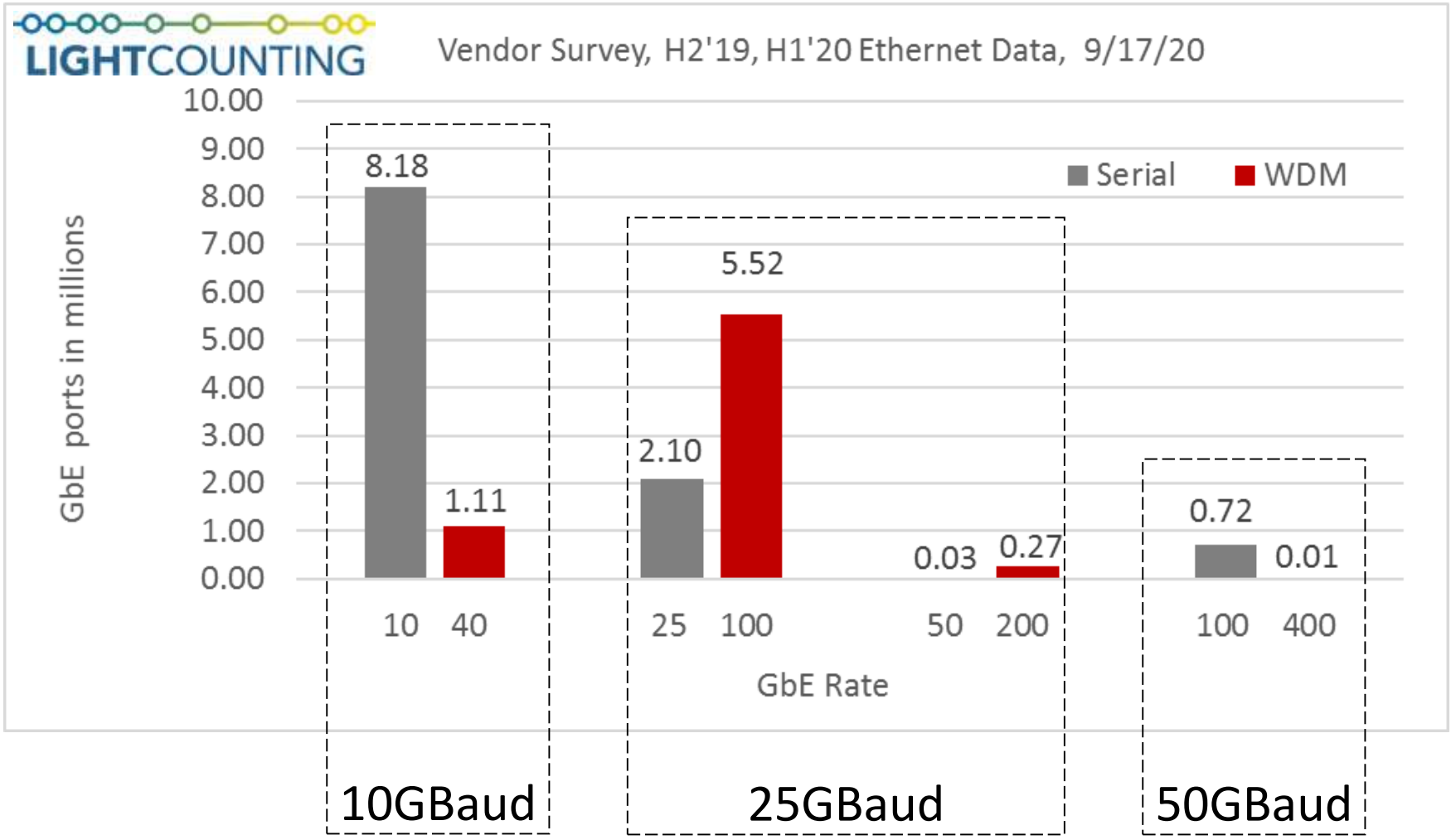
α = B / bit-rate

Discussion (from Cole IEEE 802.3bs, 12 Mar 2015, p.20)

- For SMF client interfaces, NRZ is the preferred choice if feasible, because it has the highest optics margin
- If not feasible, Parallel, WDM, or HOM, separately or in combination are required
- As component bandwidth increases with time, NRZ optics margin improves the most which drives down cost

  (ex. 10G Serial NRZ optics)
- HOM (ex. PAM-4) permanently locks in S/N penalty limiting optics margin improvement, even as component bandwidth increases

Ethernet Annual Port Shipments (from Cole IEEE 802.3 SG, 20 March 2020, p.3)



Did the Optics Industry Blunder by Switching from NRZ to PAM4?

- It sure did!
- 25GBaud PAM4 reduced the cost & time to market of initial low-volume shipments
- Predictably optical component bandwidth increased over time
- 50GBaud technology matured and is now shipping
- 25Gbaud PAM4 optics are ramping to millions of ports
- 50Gbaud NRZ optics, if adopted, would instead be ramping to millions of ports
- PAM4 3dB SNR penalty is permanently locked-in
- Significant power and cost penalty is there for the lifetime of 25Gbaud PAM4 optics

- **The views expressed in this presentation are the author's and do not represent a formal position by II-VI Incorporated.**

Q&A
6:15 – 6:20

MARVELL

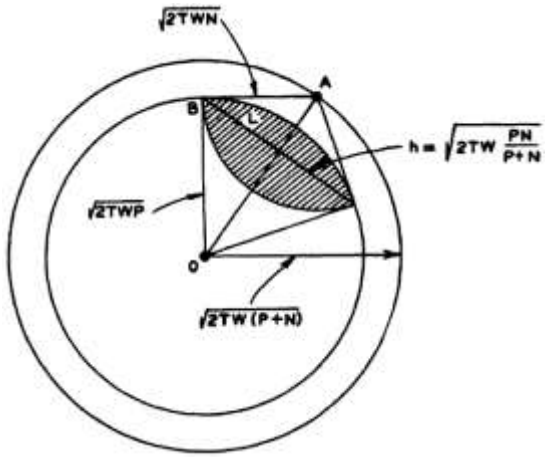
The Tao of DSP

Ilya Lyubomirsky
Marvell Technology
OFC Rump Session
June 9, 2021

The Tao and Shannon Capacity

THEOREM 2: *Let P be the average transmitter power, and suppose the noise is white thermal noise of power N in the band W. By sufficiently complicated encoding systems it is possible to transmit binary digits at a rate*

$$C = W \log_2 \frac{P+N}{N} \qquad (19)$$

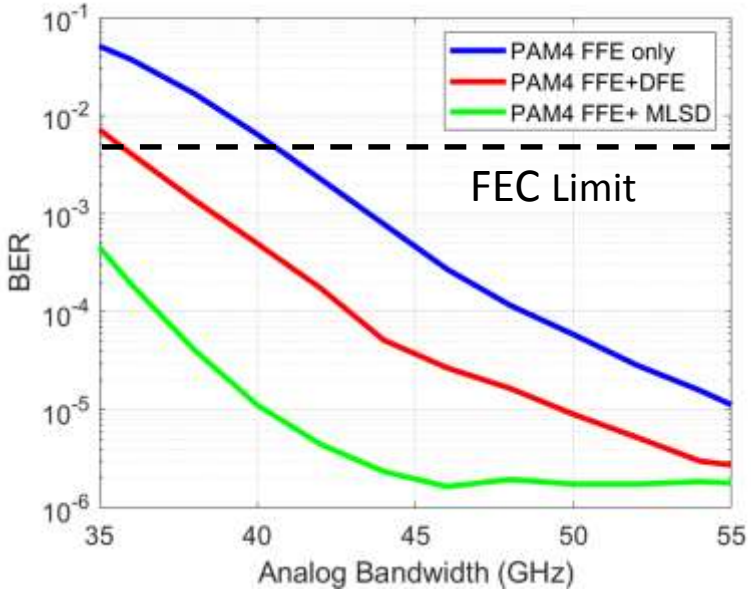


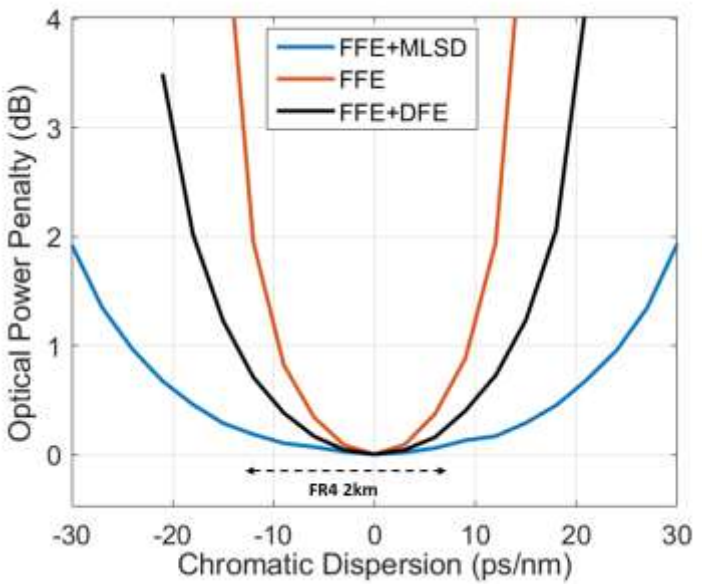
Shannon's geometrical proof of channel capacity does not name any specific modulation format or error control code! Ultimate channel capacity is achieved by exploiting all the available communication dimensions – infinite dimension in Shannon's proof – resembling a noise-like modulated signal.

"The Tao that can be told is not the eternal Tao. The name that can be named is not the eternal name. The nameless is the beginning of heaven and earth."

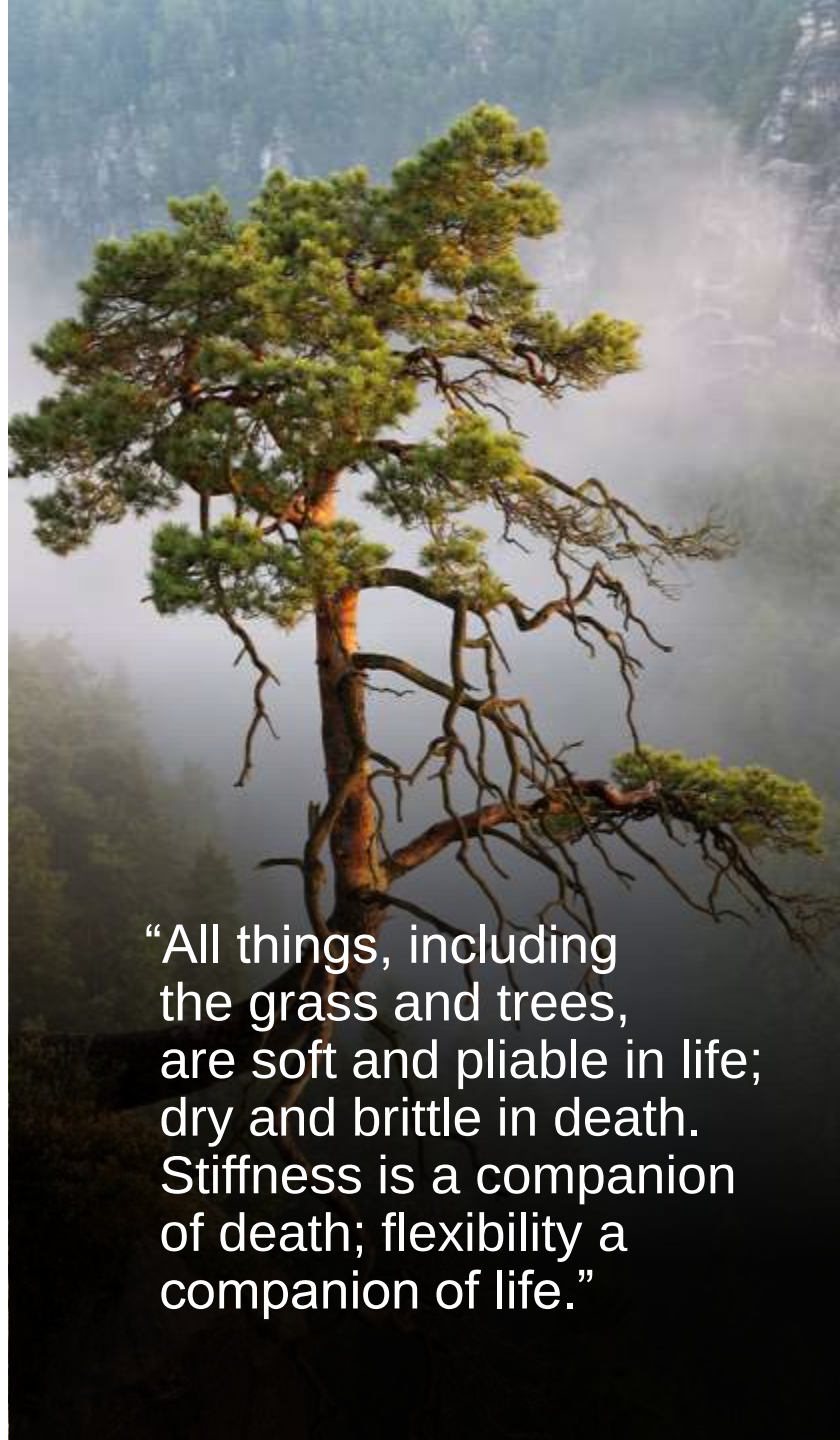
The Tao of DSP Based Equalization

200G per Lambda optical system simulations

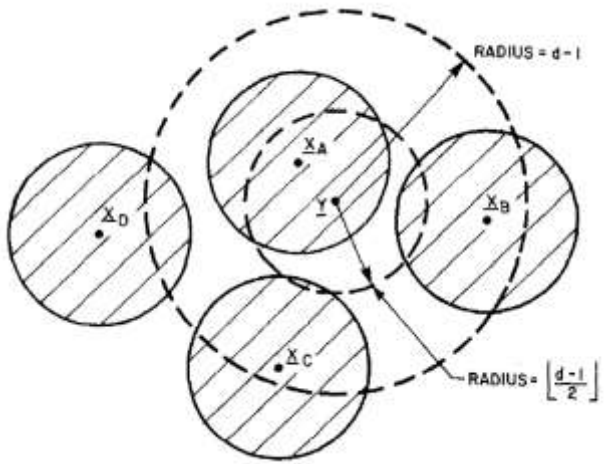


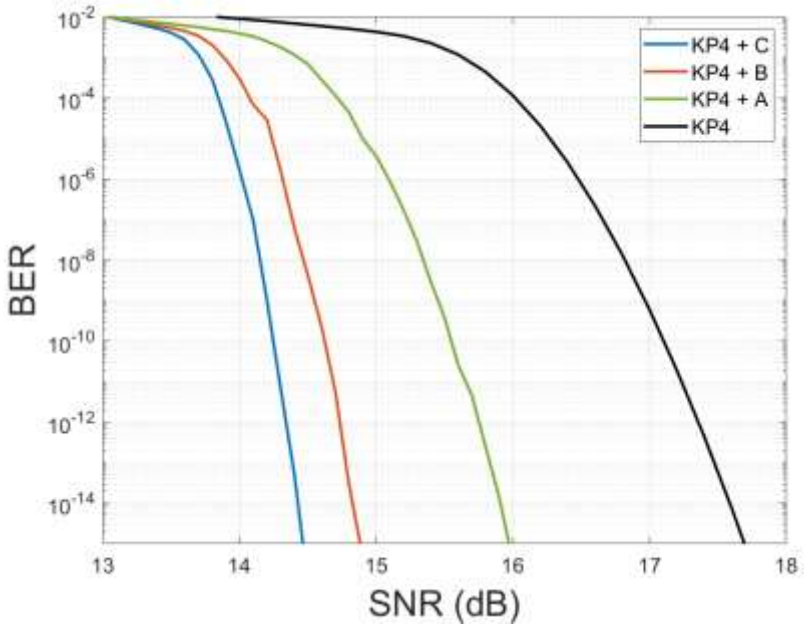


DSP enables very flexible and adaptable equalization able to compensate for many different impairments



The Tao of Soft Information

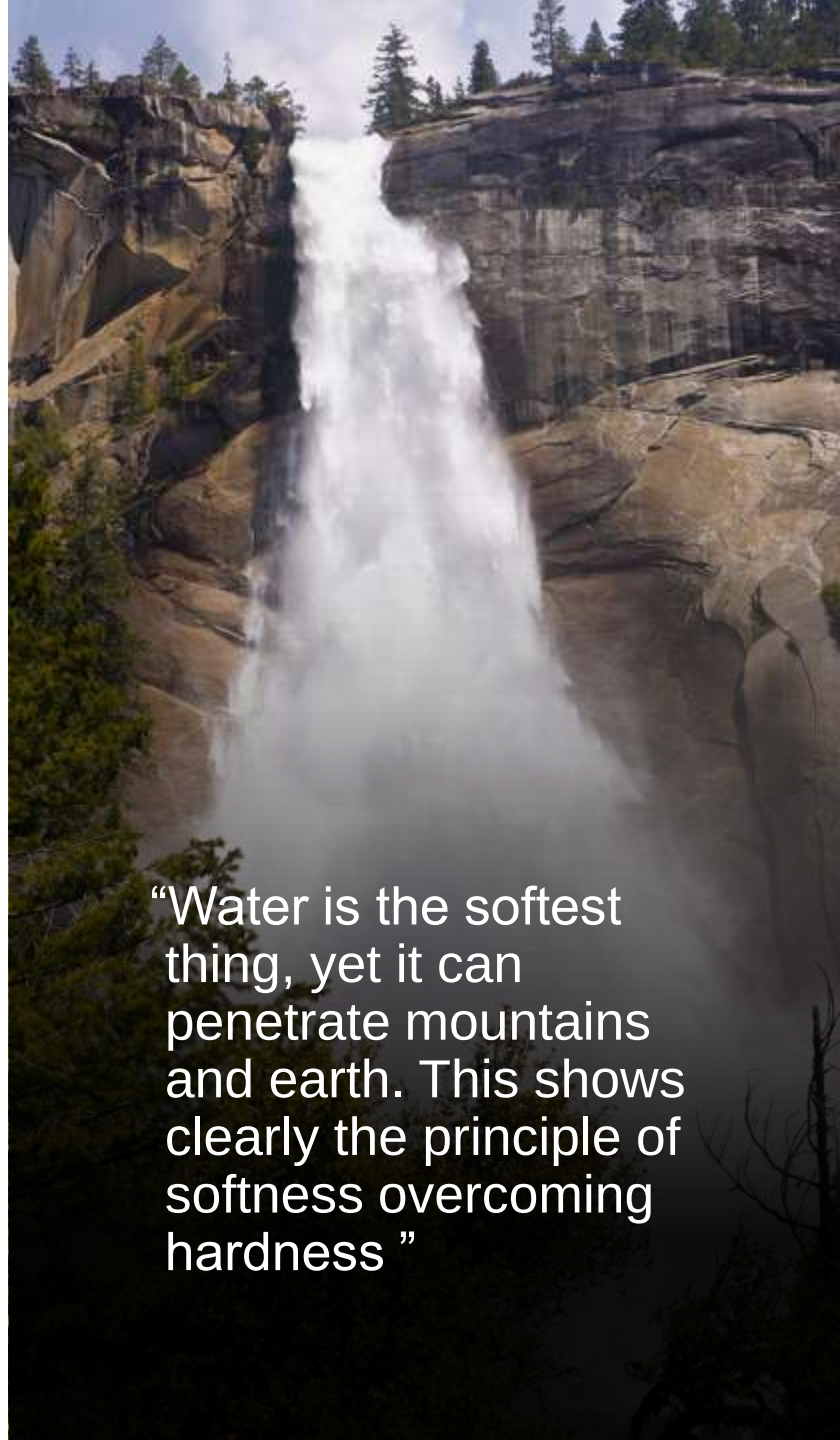




- Chase soft decoding algorithm
- Low-complexity, near maximum likelihood performance

ADC enables soft decision decoding for stronger FEC while keeping low latency and low power.

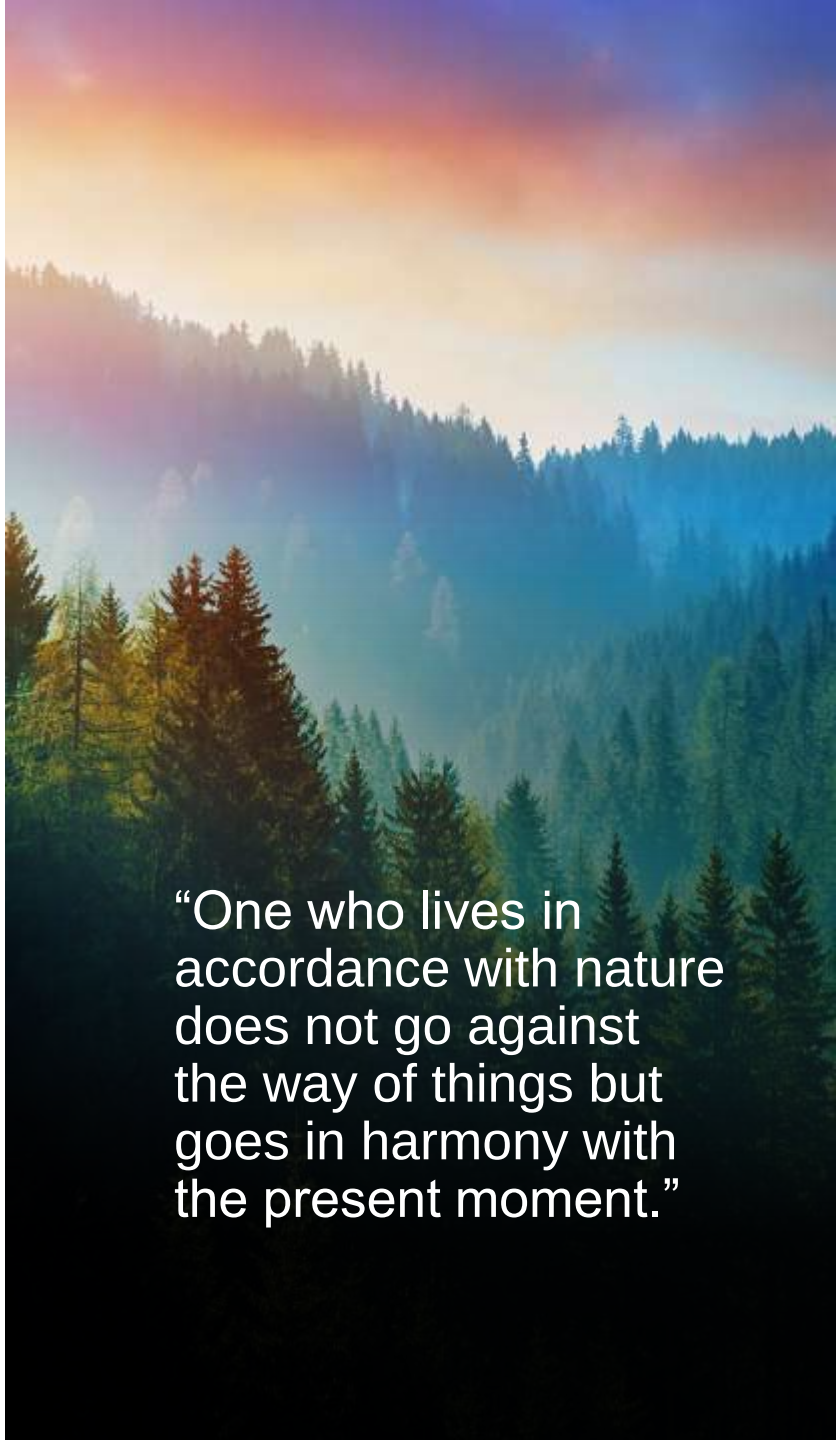
Stronger FEC enables higher optical loss budget and/or lower cost optics!



Why DSP always wins in the end?

Because DSP paradigm is in harmony with Nature (Tao)

- **DSP equalization is flexible, adaptable, and powerful** for compensating analog component and optics impairments resulting in lower cost and more robust solution
- **ADC/DSP enables soft decision decoding** for stronger FEC without increasing latency resulting in lower cost optics
- **DSP can enable any modulation format,** system designer can leverage the best modulation technique to fit the physics of the channel



Agenda

WDM Team					DSP Team				
Area	PPT Start	Q&A Start	Name	Affiliation	**Area**	PPT Start	Q&A Start	Name	Affiliation
Yang	6:05	6:15	Chris Cole	II-VI (Adviser)	**Yin**	6:20	6:30	Ilya Lyubomirsky	Marvell
Qian	6:35	6:40	Boris Murmann	Stanford University	**Kun**	6:45	6:50	Dan Sadot	Ben Gurion University
Zhen	6:55	7:00	Shigeru Kanazawa	NTT	**Xun**	7:05	7:10	Xiang Zhou	Google
Li	7:15	7:20	Peter Winzer	Nubis Comm.	**Kan**	7:25	7:30	Henry Sun	Infinera
Dui	7:35	7:40	Chris Pfistner	Avicena Tech	**Gen**	7:45	7:50	Yi Cai	Soochow University

MARVELL

DSP always wins in the end

Thank You

Q&A
6:30 – 6:35

DSP is Dragged Down by Analog Front End Energy

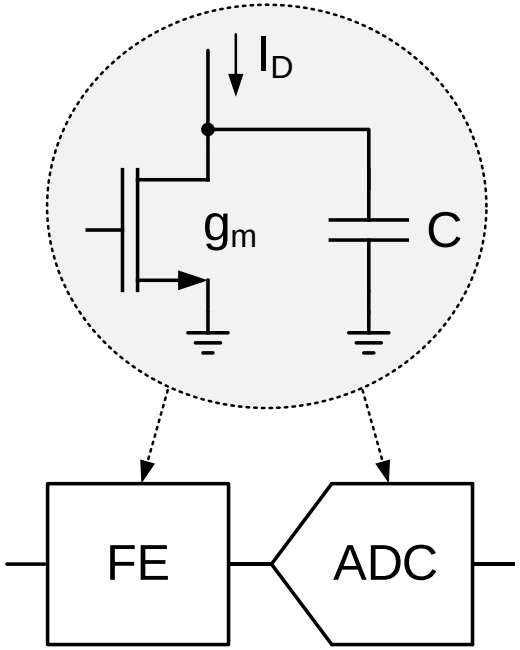
乾

Qian (Heaven)

Boris Murmann
OFC Rump Session
WDM Team
June 9, 2021
murmann@stanford.edu

Stanford | ENGINEERING
Electrical Engineering

murmann mixed|signal



Elementary gain stage
(amplifier, equalizer, slicer, etc.)

$$SNR \propto \left(\frac{kT}{C}\right)^{-1} \qquad BW \propto \frac{g_m}{C} \qquad P \propto I_D \propto \frac{g_m}{g_m/I_D} \propto \frac{g_m}{const.}$$

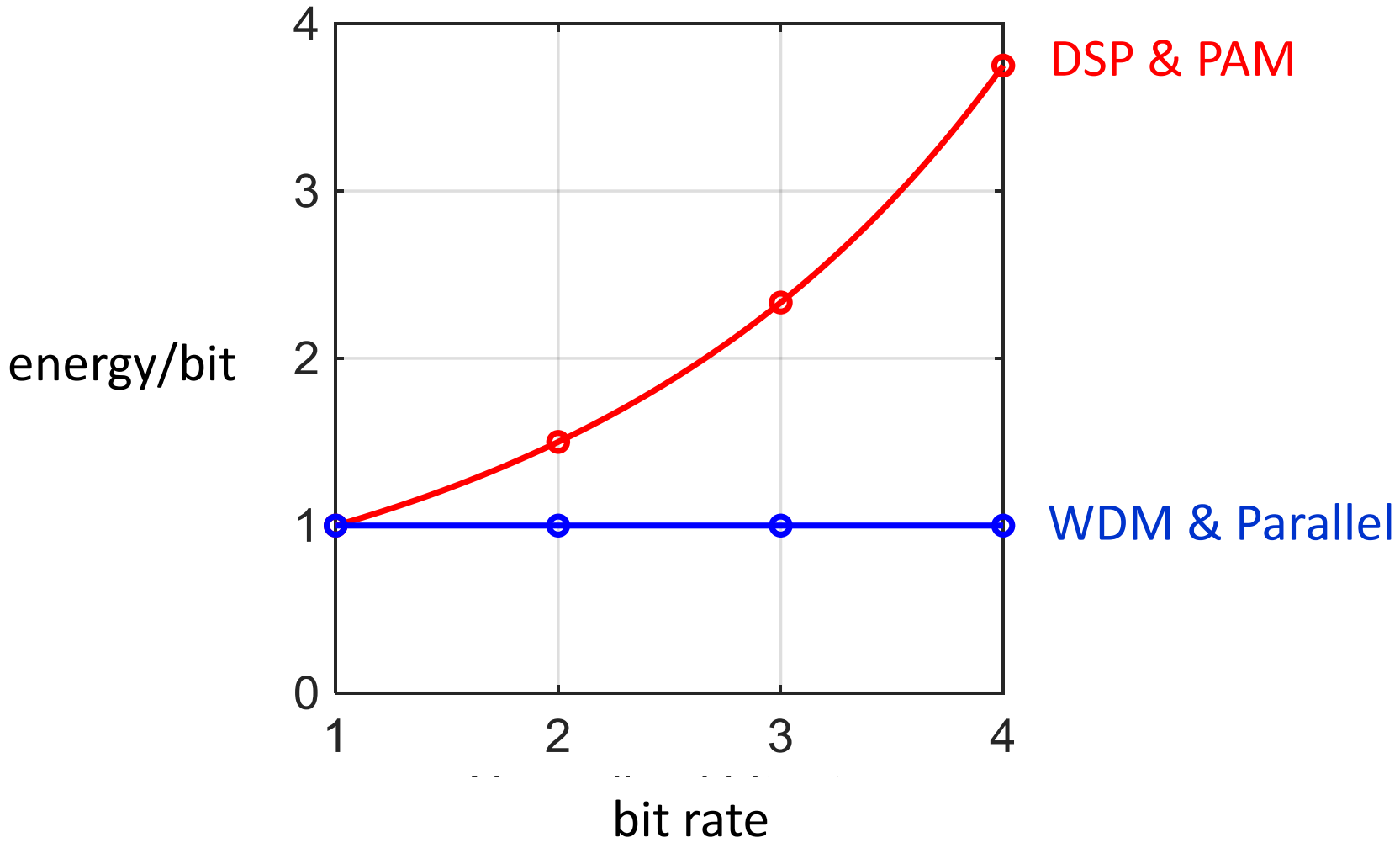
$$E = \frac{P}{BW} \propto kT \times SNR$$

Energy increases 4x per 6dB (1 bit)

PAM	2	4	8	16
Bit rate	1x	2x	**3x**	**4x**
SNR Penalty	0dB	4.8dB	8.5dB	11.8dB
Energy cost	1x	3x	**7x**	**15x**

➔ Packing more info into amplitude via PAM comes with superlinear energy cost

WDM Wins!



Q&A
6:40 – 6:45

坤
Kun (Earth)

Beyond PAM4
More bits/Baud is Better

Dan Sadot

Ben Gurion University, ECE, ISRAEL

OFC Rump Session

DSP Team

June 9, 2021

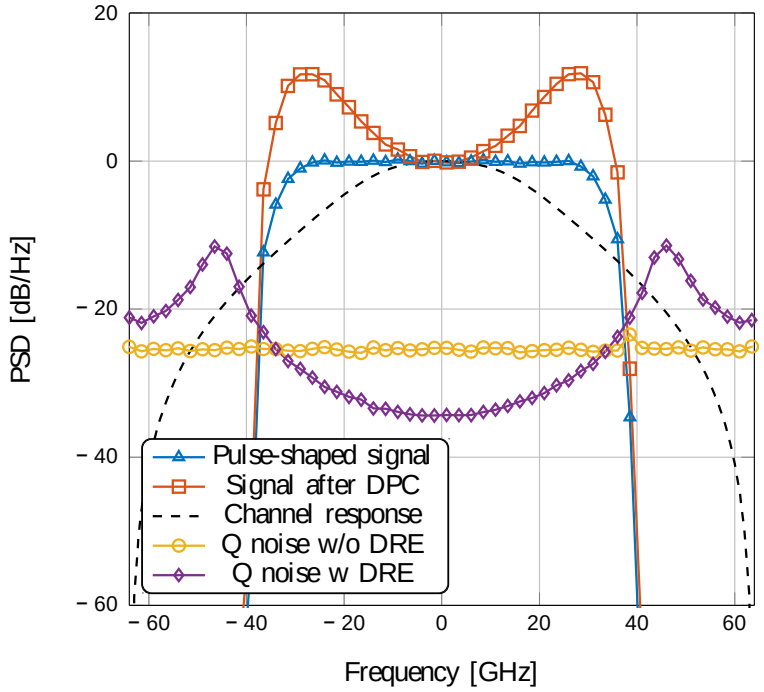
High Order Modulation Reduces Power & Cost

DSP Pre-Distortion

- Non-linear + reduced bandwidth compensation → Increases Modulation Swing + Baud
- DAC: enhances resolution → lowers ENOB
- ADC: reduces ENOB → lowers power

Benefits

- Direct detection:
  - High swing (PAM8)
  - High Baud (100GB)
- Coherent:
  - DFB lasers (low cost)
  - High swing (QAM64)
  - High /Baud (100GB)



Higher Bitrate with Same Photonics

DSP Up-scales Photonics

Q&A
6:50 – 6:55

震

Zhen (Thunder)

More NRZ lasers is better than less PAMn lasers

Shigeru Kanazawa, NTT Device Innovation Center

OFC Rump Session

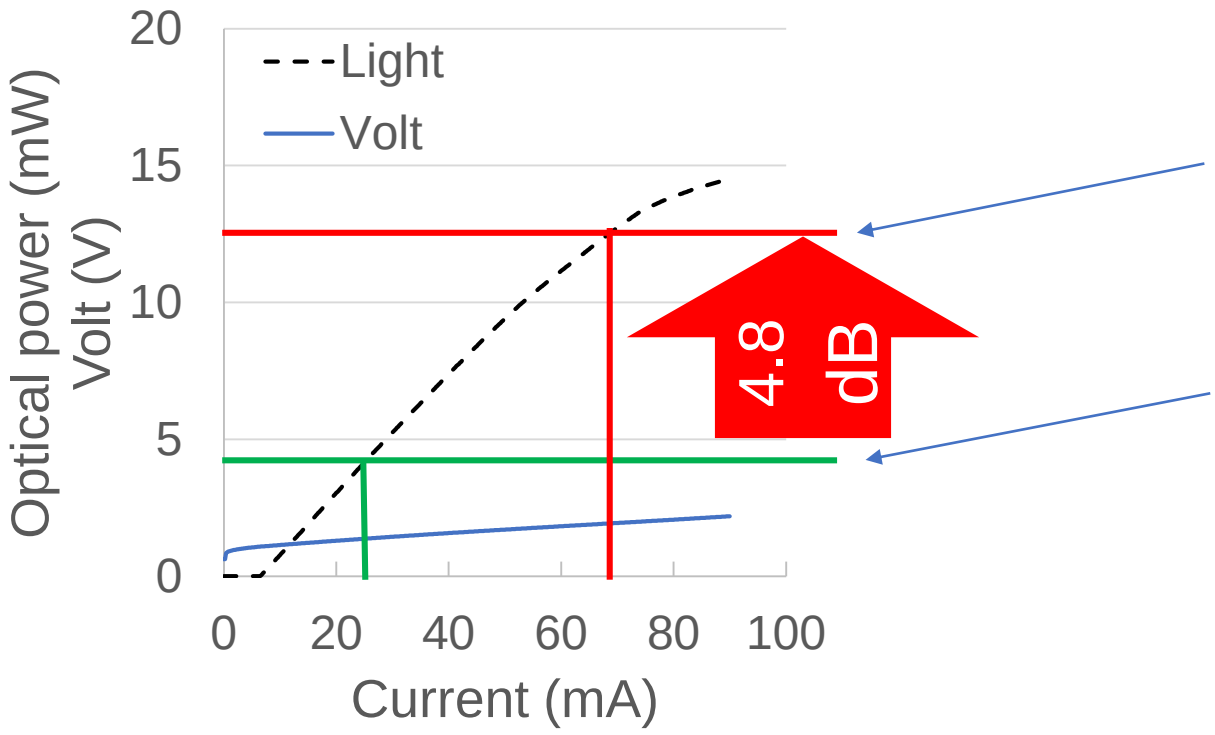
WDM team

June 9, 2021

2ch NRZ vs. 1ch PAM4 Laser Power (same bit rate)

PAM4 AOP = 4.8 dB + NRZ AOP

I/L and I/V characteristics of DML (L=150 μm, 25℃)



W. Kobayashi et. al., 2014 EL

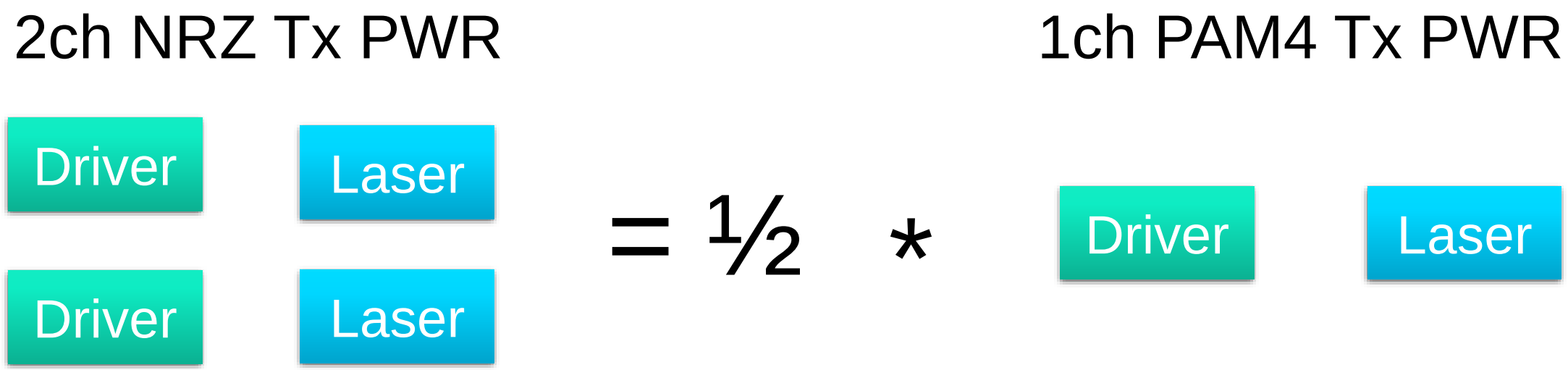
Laser power consumption

1ch PAM4 (+11 dBm):
70 mA × 1.95 V = 140 mW

2ch NRZ (+6.2 dBm):
25 mA × 1.37 V × 2ch = 70 mW

70 mW = ½ * 140 mW

More Simple Optics = Less Power



It’s time for optics to stop being the tail on the IC dog!

Q&A
7:00 – 7:05

Google

巽
Xun (Wind)

How to Scale Bandwidth & Reduce Cost

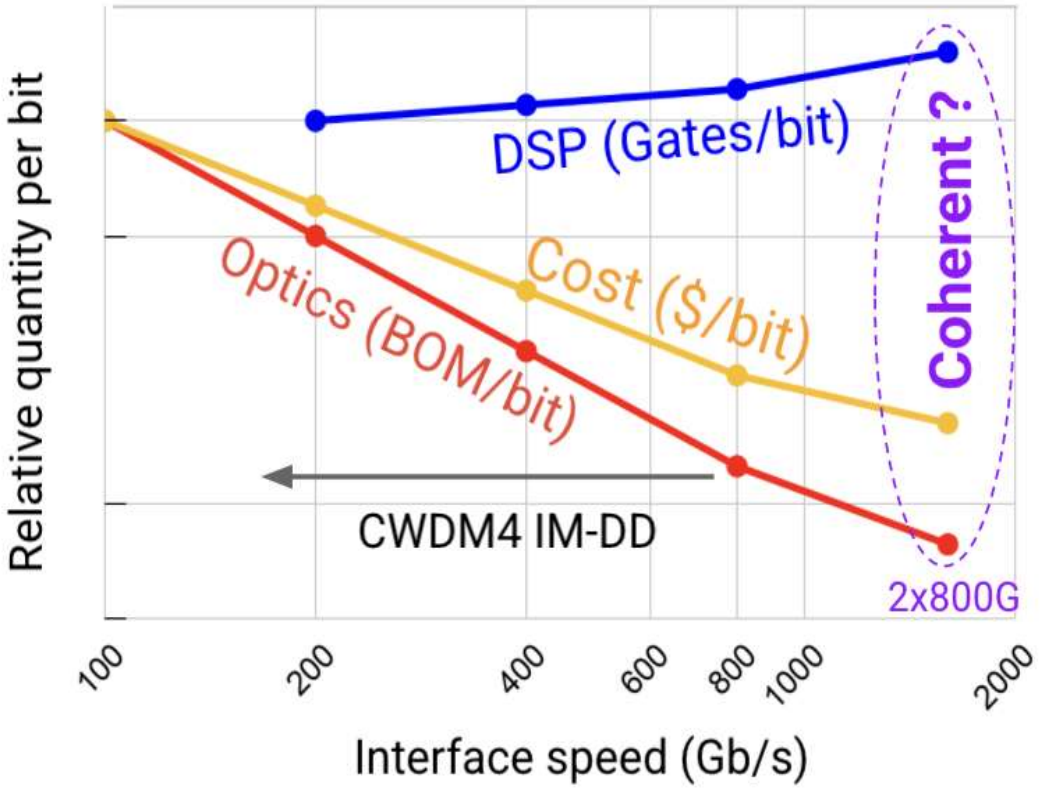
Xiang Zhou

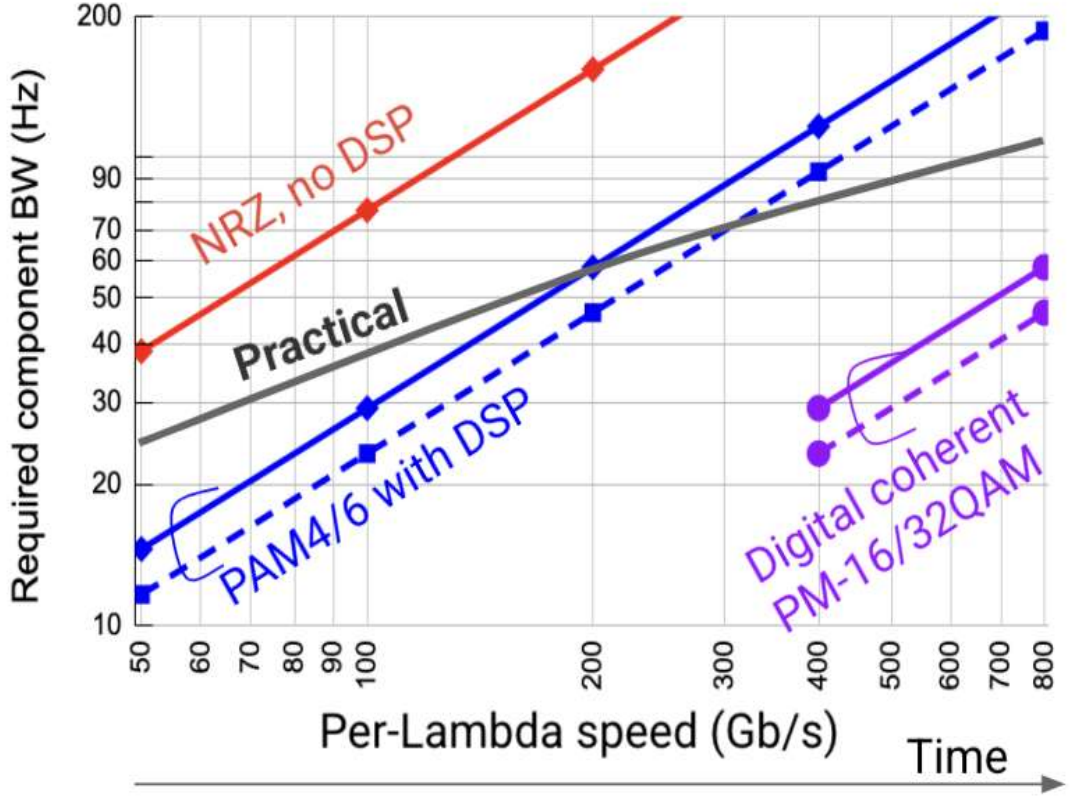
Platforms, Google Inc.

OFC Rump Session
DSP Team
June 9, 2021

Why DSP Enables Lowest-Cost Bandwidth Scaling

- Parallel optics cost scales linearly with BW
- DSP cost scales with CMOS: Sublinear!
- Constrained component BW: DSP increases lane speed and reduces optics per bit BOM





CMOS always wins!
Therefore the Future is more DSP & less Optics

Q&A
7:10 – 7:15

nubis COMMUNICATIONS

Parallel is Better than Complex Modulation

Peter Winzer

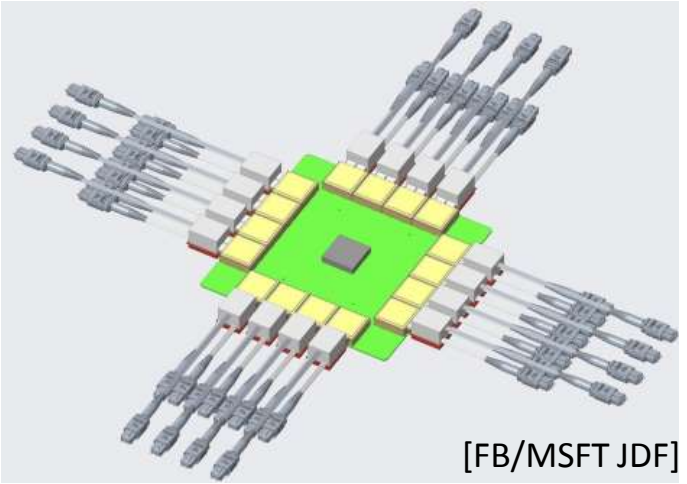
OFC Rump Session

WDM Team

June 9, 2021

The Intra-DC Challenge – What Matters?

- Transponder density
  - 2x every 2 years (50 Tbps, 100 Tbps, …)
  - DWDM long-haul system capacity crammed into ~10x10cm^2
    - ➔ Use massively integrated lower-speed active-optics arrays
    - ➔ **No need for bleeding-speed rates or higher-order modulation**
  - DSP logic needs chip real estate
    - ➔ **No space for sophisticated DSP blocks**
- Total link cost
  - Fiber costs are ¢/Gbps vs. $/Gbps for transponders
  - Massive fiber bundles cheaper than sophisticated transponders
    - ➔ **No need for high spectral efficiencies; needed in long-haul**
- Total energy consumption
  - Minimize optical *plus* electrical energy consumption
  - Do not just count "photons/bit"
    - ➔ **No power for sophisticated DSP**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Optical vs. **Electrical** Energy Contribution

Parallelism Beats Sophistication in the DC

More lanes gets you there faster than the most sophisticated car!

Q&A
7:20 – 7:25

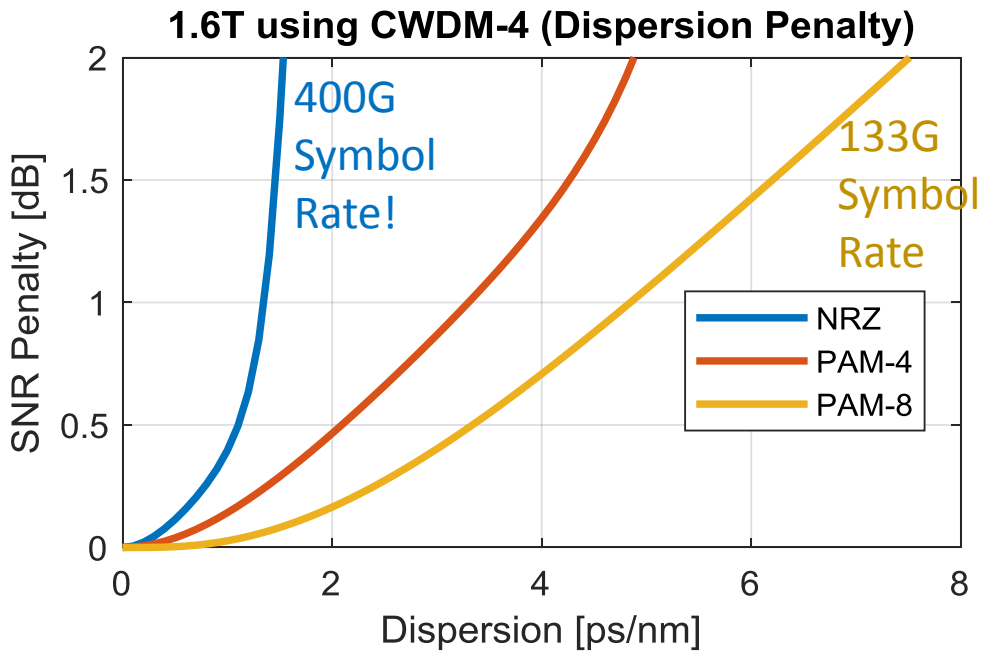
Infinera

Spectral Efficiency Requirement in the Data Center is Real

Han (Henry) Sun
OFC Rump Session
DSP Team
June 9, 2021

Spectral Efficiency (S.E.) in the Data Center

- Web 2.0 Data center operators require CWDM-4 (4λ 20nm grid)
  - Interoperates with lower data rates: low OpEx
  - Reuses CWDM laser & optics tech: low R&D, quick time-to-market
  - Enables diverse technical solutions from many suppliers: low cost
  - Uncooled operation minimizes power dissipation



Rich literature on even higher SE signaling still with Direct Detection (DD):

KK Receivers / DMT / Asymmetric DSB DD

High S.E. solutions are necessary at ≥1.6T

Spectral Efficiency (S.E.) Requirement in the Data Center is Real

Get high SE!

The opinions expressed in this presentation are the author's and do not represent Infinera Corporation.



Slow & Parallel Minimizes Cost & Power

Chris Pfistner

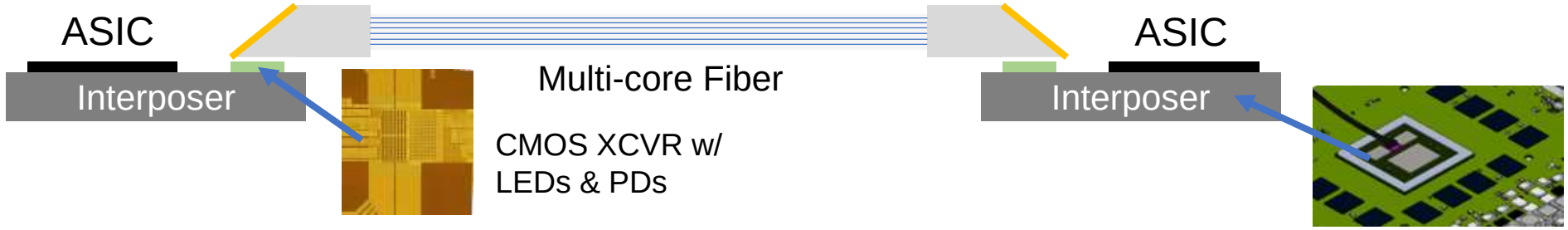
OFC Rump Session
WDM Team
June 9, 2021

avicena

Why Slow & Parallel?

- Great match to ASIC's slow and wide internal bus architectures:

- Enable low-cost, low-power NRZ:
  - No SerDes, no FEC → Low Latency & low Power

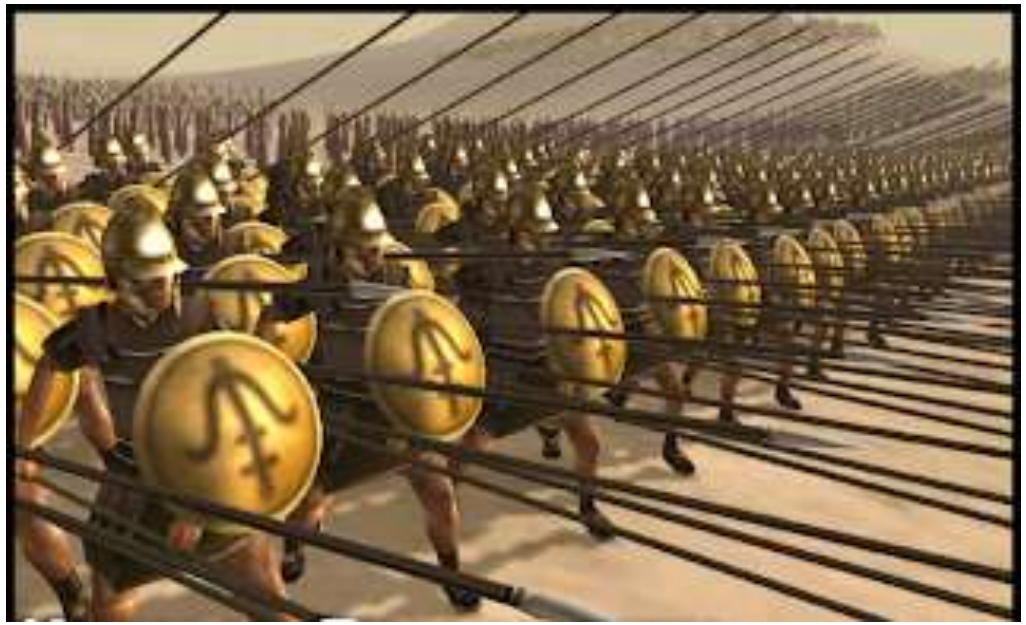


- Enable massively parallel:
  - Multi-core fiber with 100s to 1000s of lanes
  - Transmitter: Consumer micro-LEDs from high volume display industry at 1-10Gbps per lane
  - Receiver: Mature CMOS with integrated PDs
  - Silicon friendly MMF which is easy to align with relaxed coupling tolerances

→ **Achieve economies of scale by addressing a huge market with <10m reach**

Go Slow & Parallel from the Source to as far as possible …

… before making life more complicated!



Achieve 0.1pJ/bit

蘇州大學
SOOCHOW UNIVERSITY

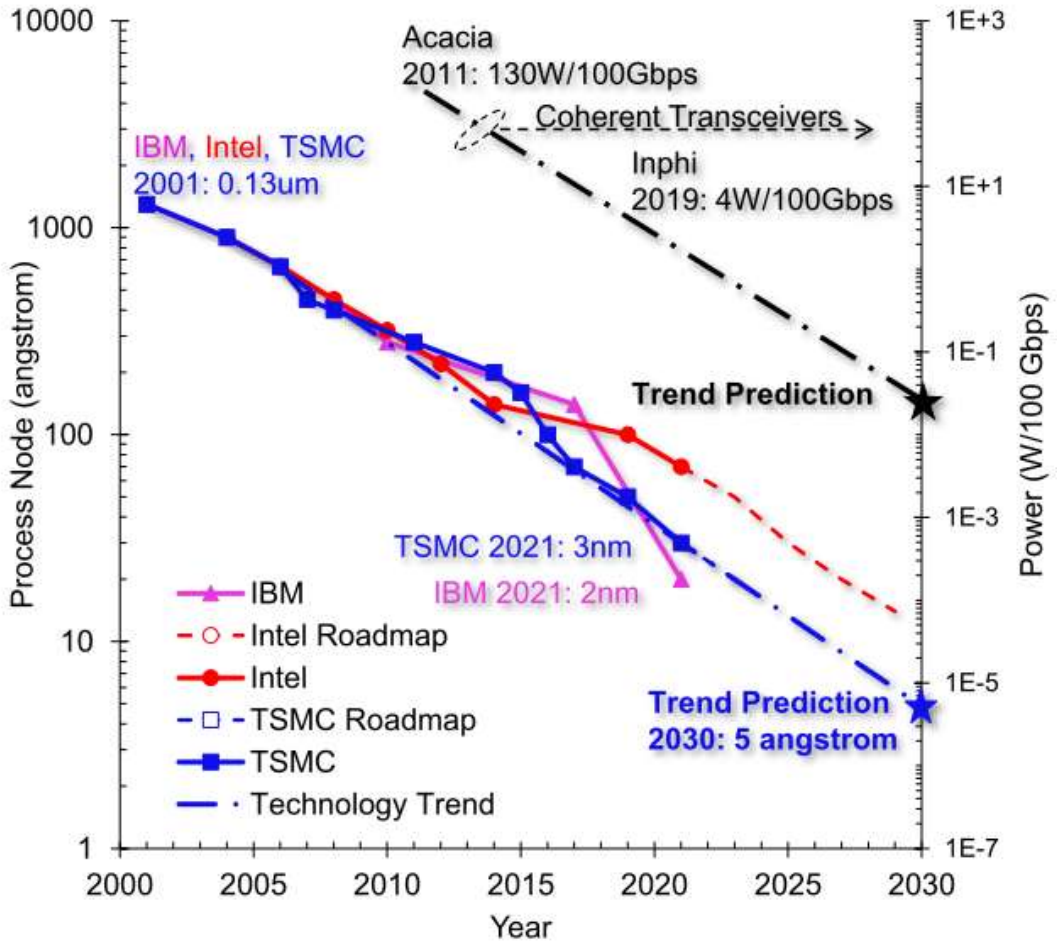
CMOS DSP Coherent is the Smart Parallel

Yi Cai
OFC Rump Session
DSP Team
June 9, 2021

艮
Gen (Mountain)

CMOS DSP Coherent vs. Photonic WDM Parallel Lanes

CMOS R&D: $ billions

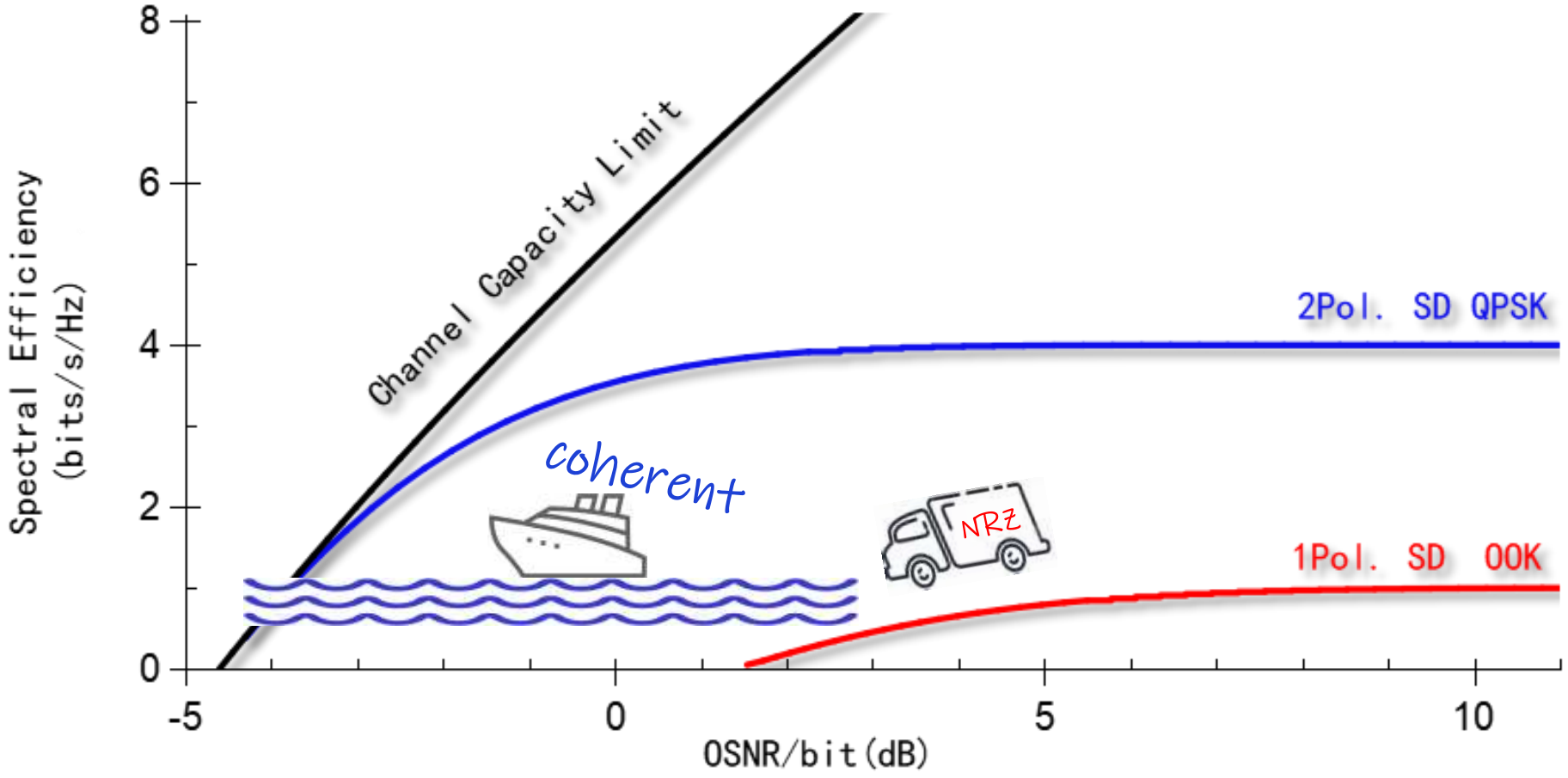


DSP quadrature & polarization vs. WDM lanes

100Gbaud Transceiver		1.6T	3.2T
NRZ (OOK)	λ	16 DWDM	32 DWDM
	N (levels)	2	2
	100G I/O	16	32
Coherent (QAM-N²)	λ	4 CWDM	4 CWDM
	N (levels)	2	4
	100G I/O	16	32

CMOS reduces cost and power of DSP Coherent lanes every year

DSP Coherent Spectral Efficiency Makes it the Smart Parallel



Obsolete NRZ truck sinks while Coherent yacht cruises along

Q&A
7:50 – 7:55

Audience Poll

No.	Question	Vote	
1	**Did the Optics Industry Blunder by Switching Intra-Datacenter Links from NRZ to PAM4?**		
	Yes	75	42%
	No	105	58%
2	**Will More DSP like PAM6 and Coherent Follow, or Will WDM and Parallel Save the Day?**		
	More DSP like PAM6 and Coherent	75	42%
	WDM and Parallel Save the Day	105	58%
3	**Which would you prefer to see more of?**		
	Gladiator Pairs fighting	92	51%
	Tao Masters teaching	88	49%

Poll
7:55 – 8:00

Will More DSP like PAM6 Follow, or Will WDM and Parallel Return?

The Rump Session Provocateurs trust

you were entertained and enlightened