IM-DD vs. Coherent in Datacenters: A Revisit in 2025

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Google Platforms Data Center Optics

Abstract This tutorial examines the progress and scaling limitations of IM-DD based optical technologies and explores how datacenter use cases optimized coherent technology, including a newly proposed polarization-folding, time-diversity approach and a novel single-sideband coherent detection technology—can address some of these challenges

OFC’25 M4C.1

Acknowledgement: E. Mao, C. Lam, H. Liu, E. Chen, S. Yin, M. Sotoodeh, L. Wang and R. Urata

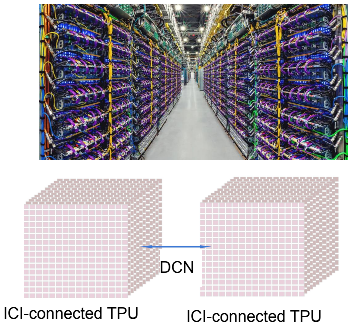
Outline

- Evolving datacenter (DC) interconnect requirements
- IM-DD: technical progress and scaling limitations
- Coherent optics for DC: fundamental and potential benefits
- Gaps and solutions for bringing coherent optics to DCs.

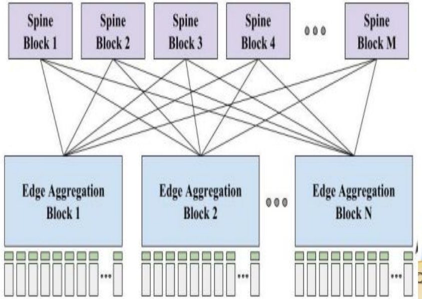
Interconnect for **Planet-scale** Computer

Intra-DC (Clusters, ML ICI)	Inter-DC (Campus)	DC to Backbone (Metro)	Global Inter-DC (Backbone, LH)
<1km	<10km	~80km	1000s km

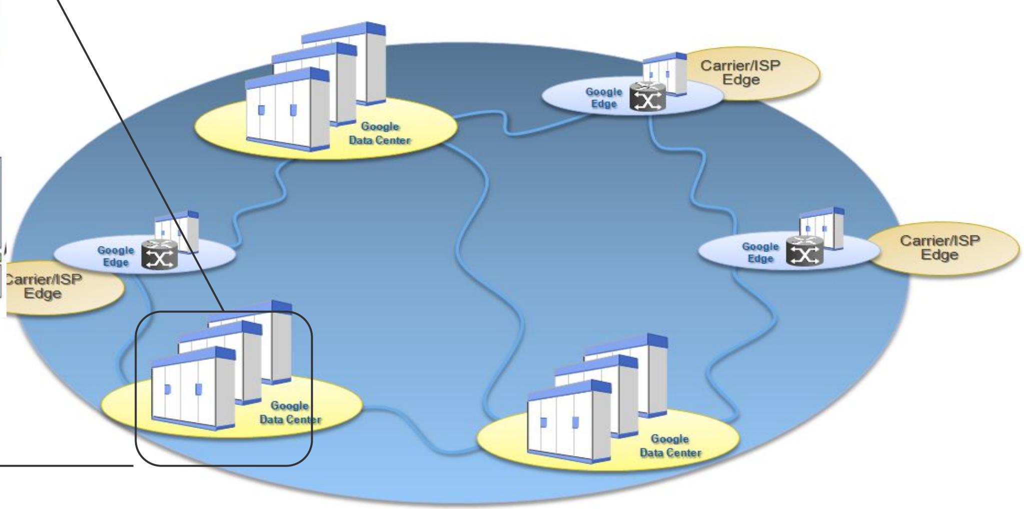
Distance →



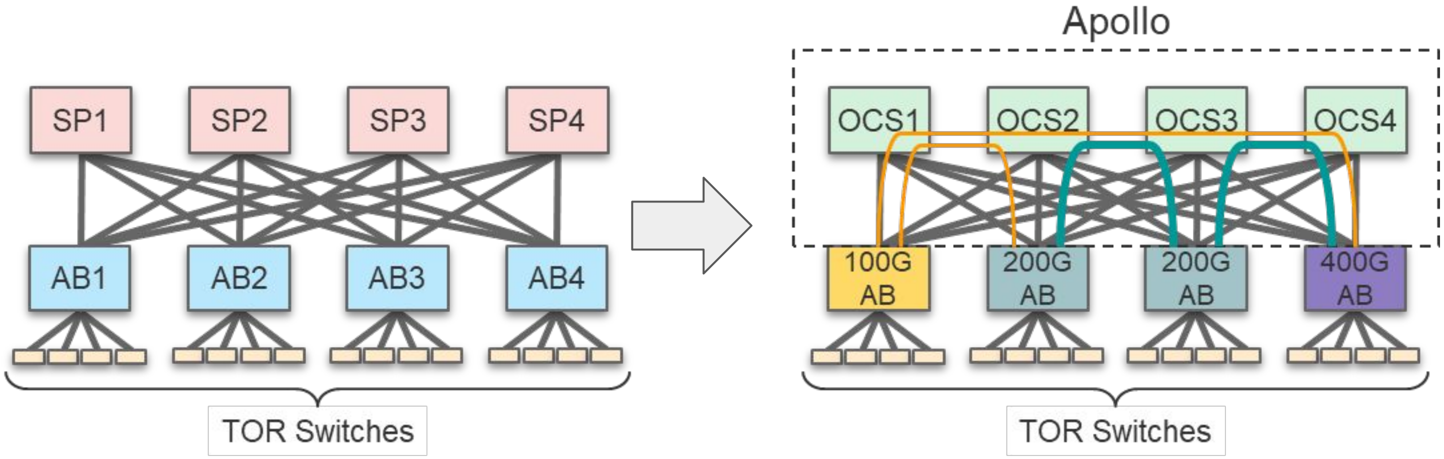
TPU ICI Network (Superpod)



DCN Fabric (Cluster)



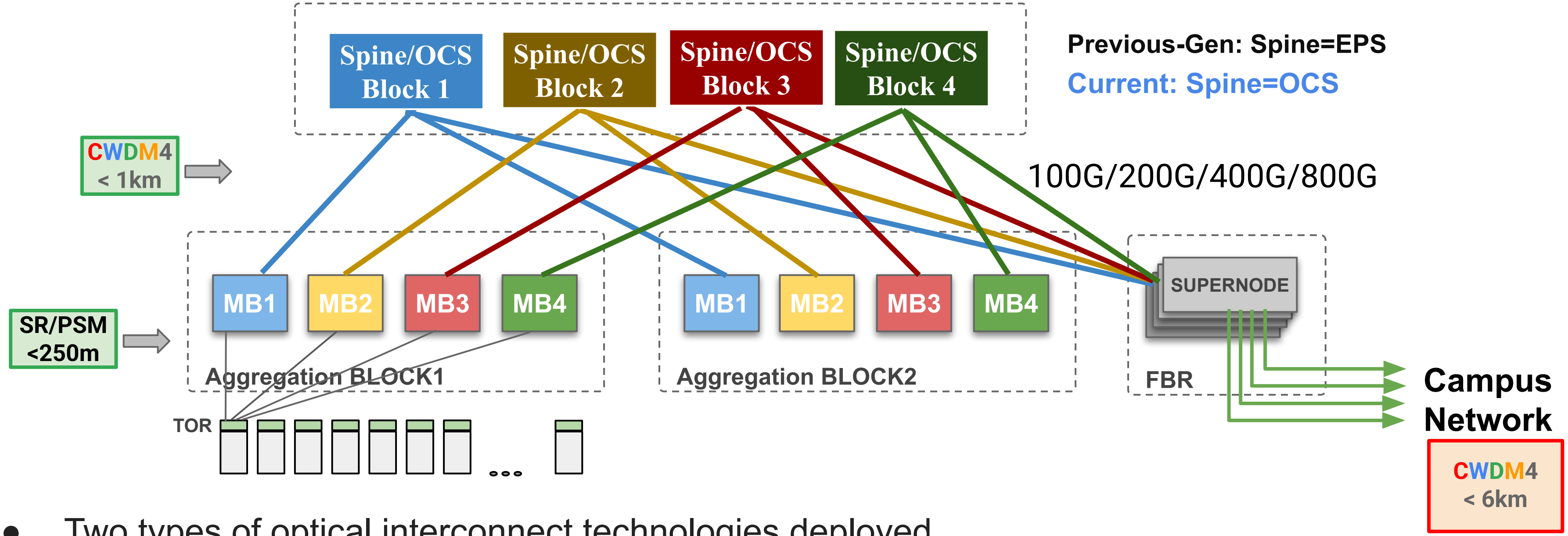
Google Intra-DC Fabric Evolution



L. Poutievski, et al., "Jupiter Evolving: Transforming Google's Datacenter Network via Optical Circuit Switches and Software-Defined Networking," SIGCOMM 2022

- **Left: Traditional Clos-based switch fabric**
  - SP - Spine switches
  - AB - Aggregation blocks
- **Right: Apollo/OCS layer replaces Spine switches**
  - Consists of OCS, single mode fiber, WDM transceivers
  - Elimination of spine layer for cost/power/latency reduction/Scaling
  - Reconfiguration of AB to AB connectivity enables Fabric Expansion, Topology Engineering

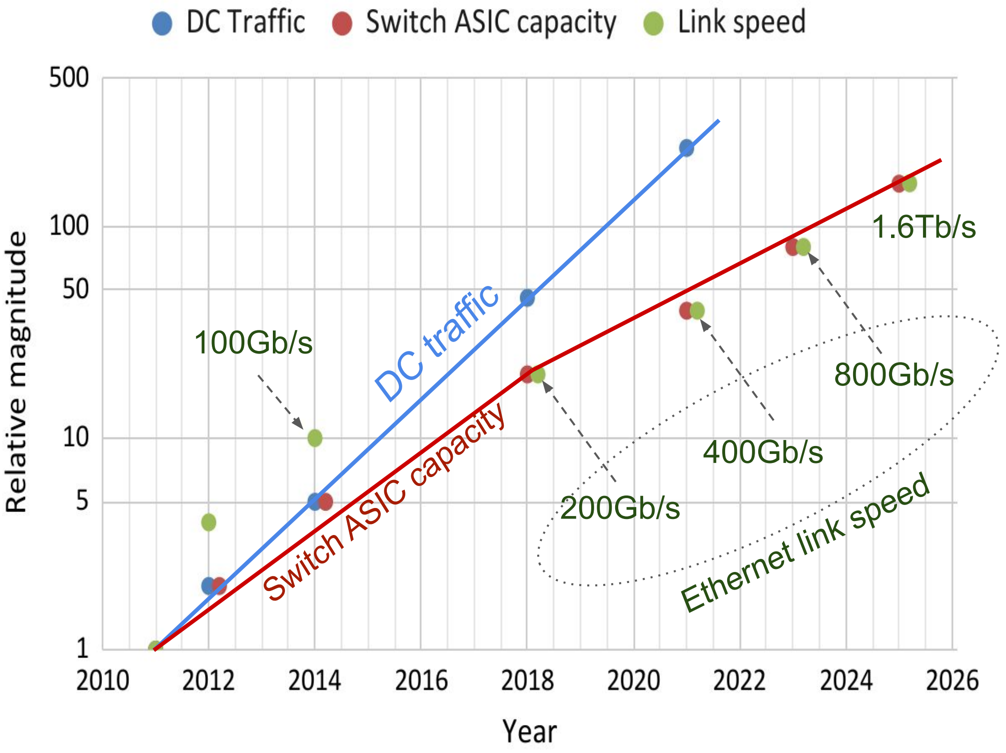
Optics in Intra-DC Fabric (Today)



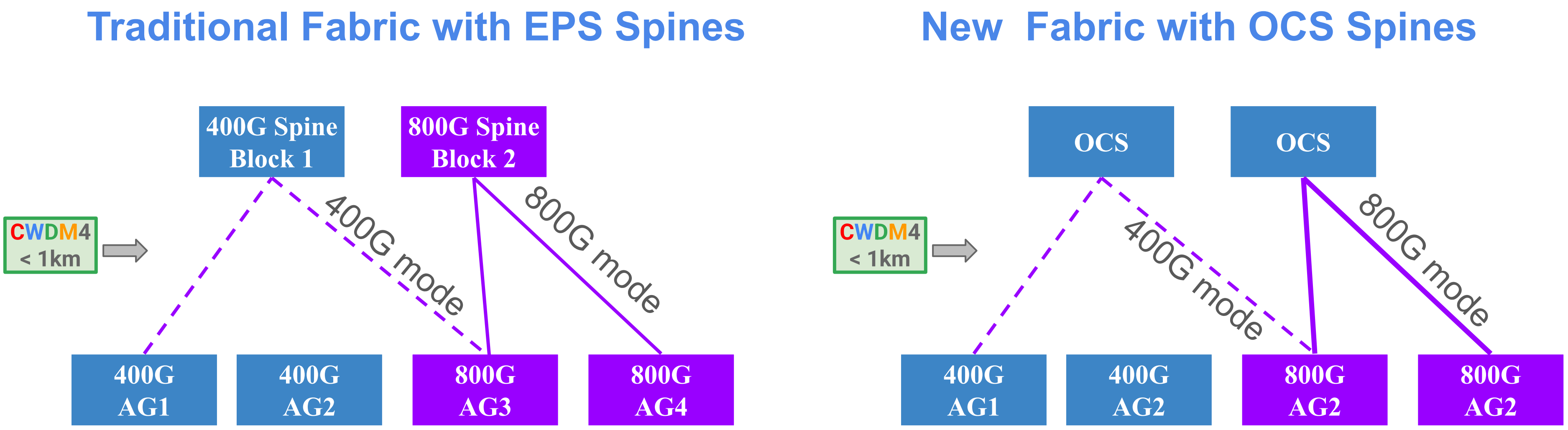
- Two types of optical interconnect technologies deployed
  - SR/PSM between TOR to Aggregation switch (<250m)
  - CWDM4 between Aggregation to Spince/OCS (<1km)
- Same CWDM4 optics has been used for campus and fabric so far
- Campus networks are growing beyond 2km
  - More spectrally efficient optical technologies under consideration

What Drives DC Fabric Optical Technology Evolution?

- Match electrical Switch ASIC I/O bandwidth growth
  - Scale with Moore's Law
- Improved cost per bit
- Improved energy efficiency
- Improved IO bandwidth density
- Backward interoperability
- Maintain good serviceability
  - Pluggable preferable

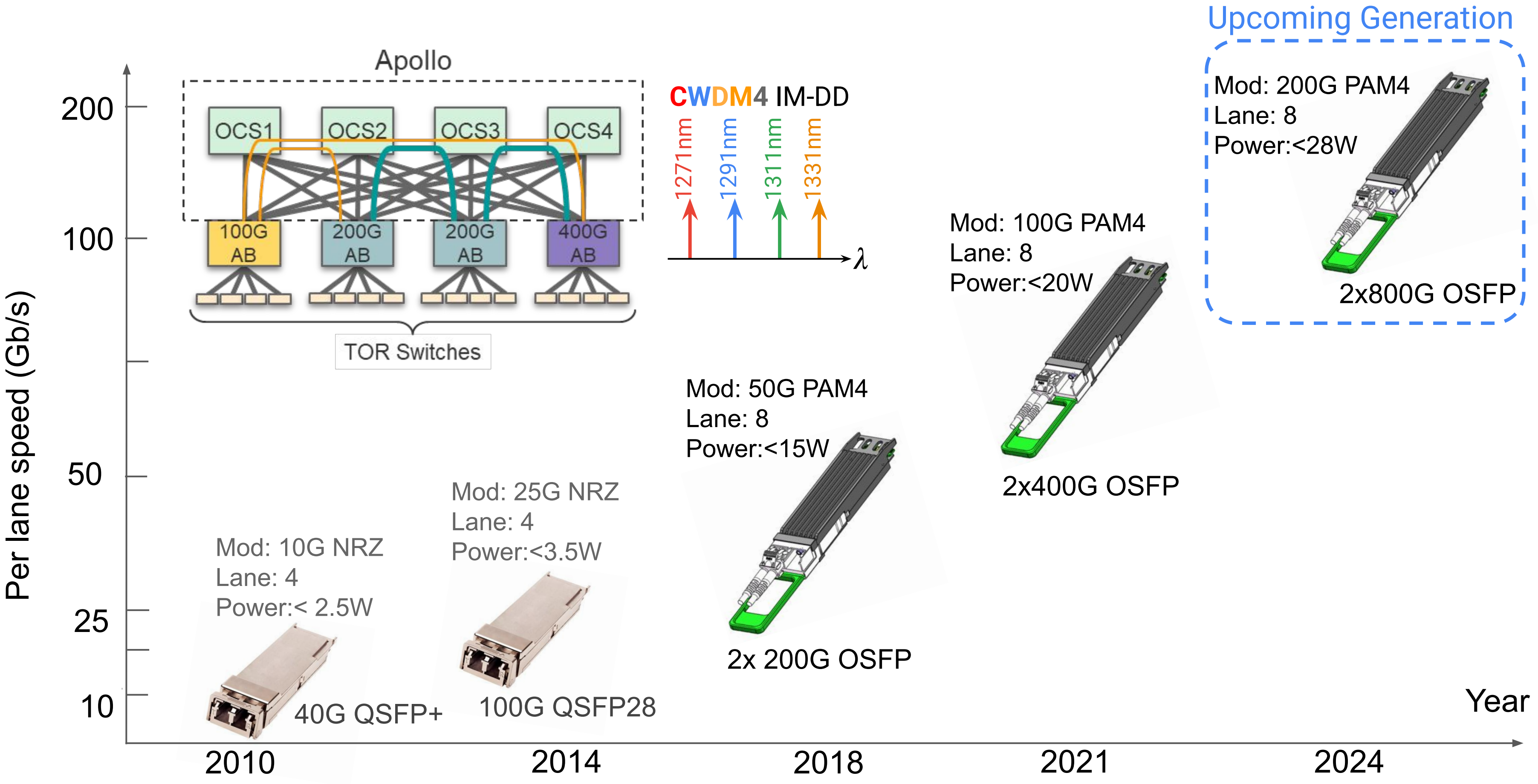


Why Backward Interoperability Desirable for DC Fabric



- Backward-interoperable optics enable smoother technology upgrades
  - Eliminate the need to forklift the entire pre-generation network
  - Eliminate the requirement for a technology refresh in the pre-generation switches

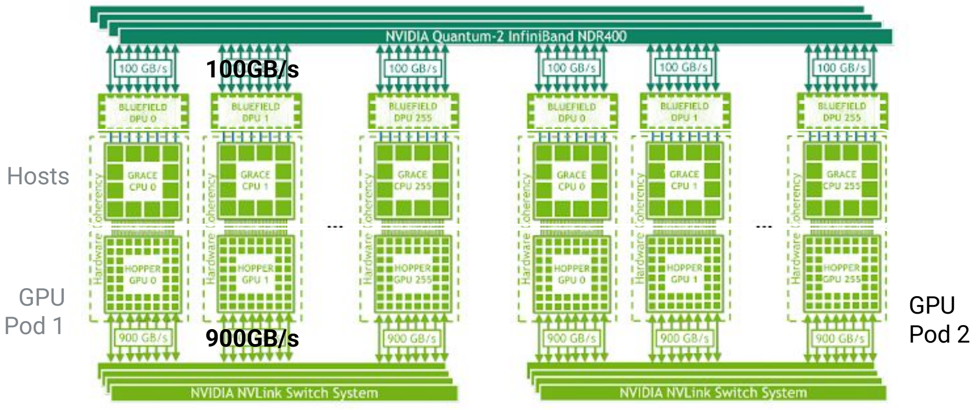
Generations of Google DC Fabric Optics Evolution



Modern ML Supercomputer Network Architectures

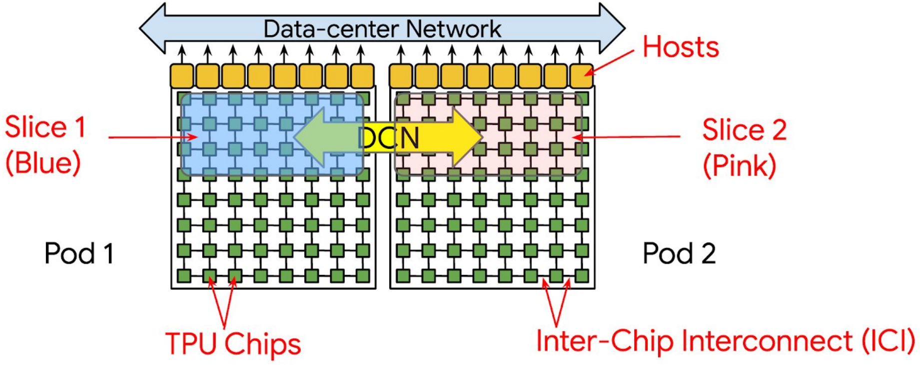
H200 GPU System

Datacenter Network



Source: Wheeler's Network,
https://www.wheelersnetwork.com/2023/06/nvidia-reveals-dgx-gh200-system.html
https://resources.nvidia.com/en-us-grace-cpu/nvidia-grace-hopper

Google's TPU System

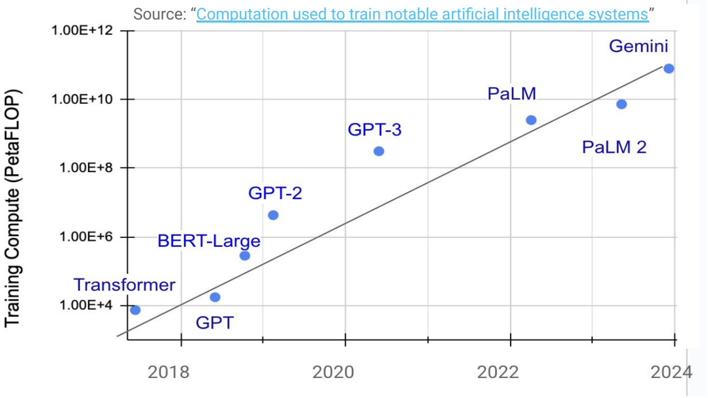


Source: Google Blog
https://cloud.google.com/blog/products/compute/using-cloud-tpu-multislice-to-scale-ai-workloads

- In addition to the host front-end and backend (scale-out) networks, accelerators are also connected with a high-bandwidth (scale-up) RDMA network
  - NVlink for Nvidia GPU systems
  - ICI network for TPU systems

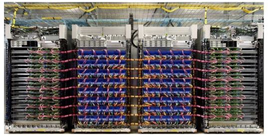
Google ML Supercomputer ICI Evolution

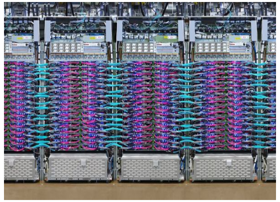
TPU Counts: 8192 (2^{13}), 4096 (2^{12}), 1024 (2^{10}), 256 (2^{8})



Copper (DAC) Only

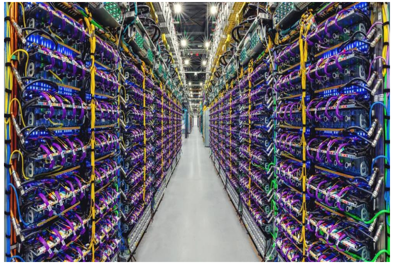
TPU v2 Pod
11.5 petaflops
4 TB HBM
2D Torus (256 chips)





TPU v3 Pod
100 petaflops
32 TB HBM
2D Torus (1024 chips)
SR Optics (AOC)
for wrap-around links

TPU v4 Pod - 2021
1 Exaflops
132 TB HBM
3D Torus (4096 chips)
OCS and 400G LR
Reconfigurable Superpod
(N. Patil, X. Zhou and A. Swing, US2020028552, 2019)

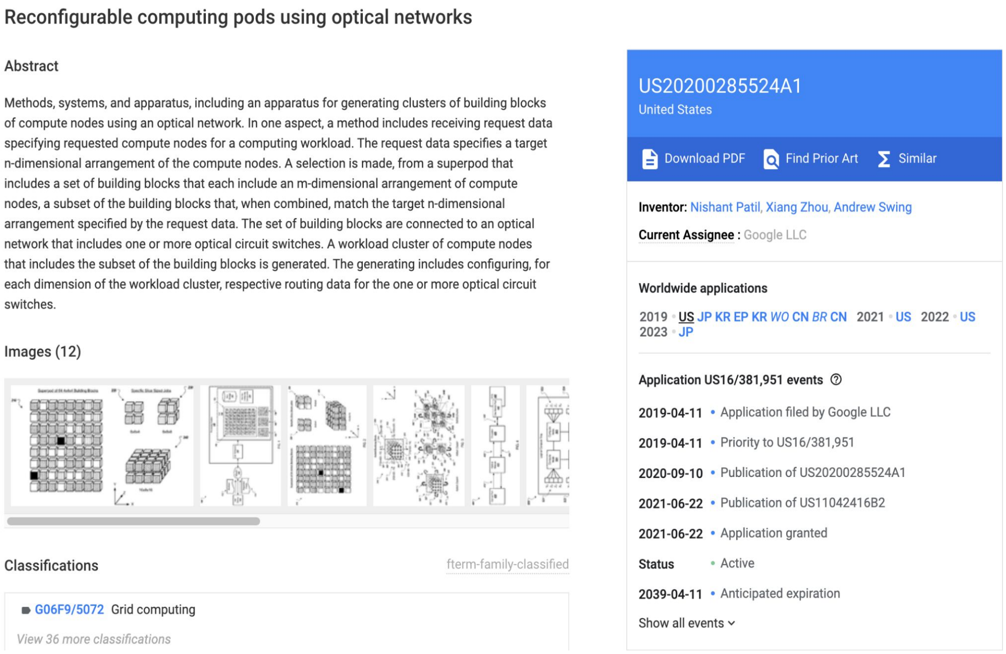


TPU v5p Pod - 2023
3.8 Exaflops
778 TB HBM
3D Torus (8192 chips)
OCS+ 800G LR optics
Reconfigurable Superpod

Year: 2017, 2018, 2019, 2020, 2021, 2022, 2023

Why OCS Introduced for ML Supercomputer

- Enable ML Supercomputer scaling beyond 1k TPUs (Superpod)
  - Address the scaling and availability constraints of pre-generation ICI networks with hard-wired Torus topologies
  - Significantly reduced cost and power compared to traditional flat-tree topologies based on electrical packet switches



Reconfigurable computing pods using optical networks

Abstract

Methods, systems, and apparatus, including an apparatus for generating clusters of building blocks of compute nodes using an optical network. In one aspect, a method includes receiving request data specifying requested compute nodes for a computing workload. The request data specifies a target n-dimensional arrangement of the compute nodes. A selection is made, from a superpod that includes a set of building blocks that each include an m-dimensional arrangement of compute nodes, a subset of the building blocks that, when combined, match the target n-dimensional arrangement specified by the request data. The set of building blocks are connected to an optical network that includes one or more optical circuit switches. A workload cluster of compute nodes that includes the subset of the building blocks is generated. The generating includes configuring, for each dimension of the workload cluster, respective routing data for the one or more optical circuit switches.

Images (12)

Classifications | fterm-family-classified

G06F9/5072 Grid computing

View 36 more classifications

US20200285524A1
United States

Download PDF | Find Prior Art | Similar

Inventor: Nishant Patil, Xiang Zhou, Andrew Swing

Current Assignee : Google LLC

Worldwide applications

2019 · US JP KR EP KR WO CN BR CN 2021 · US 2022 · US 2023 · JP

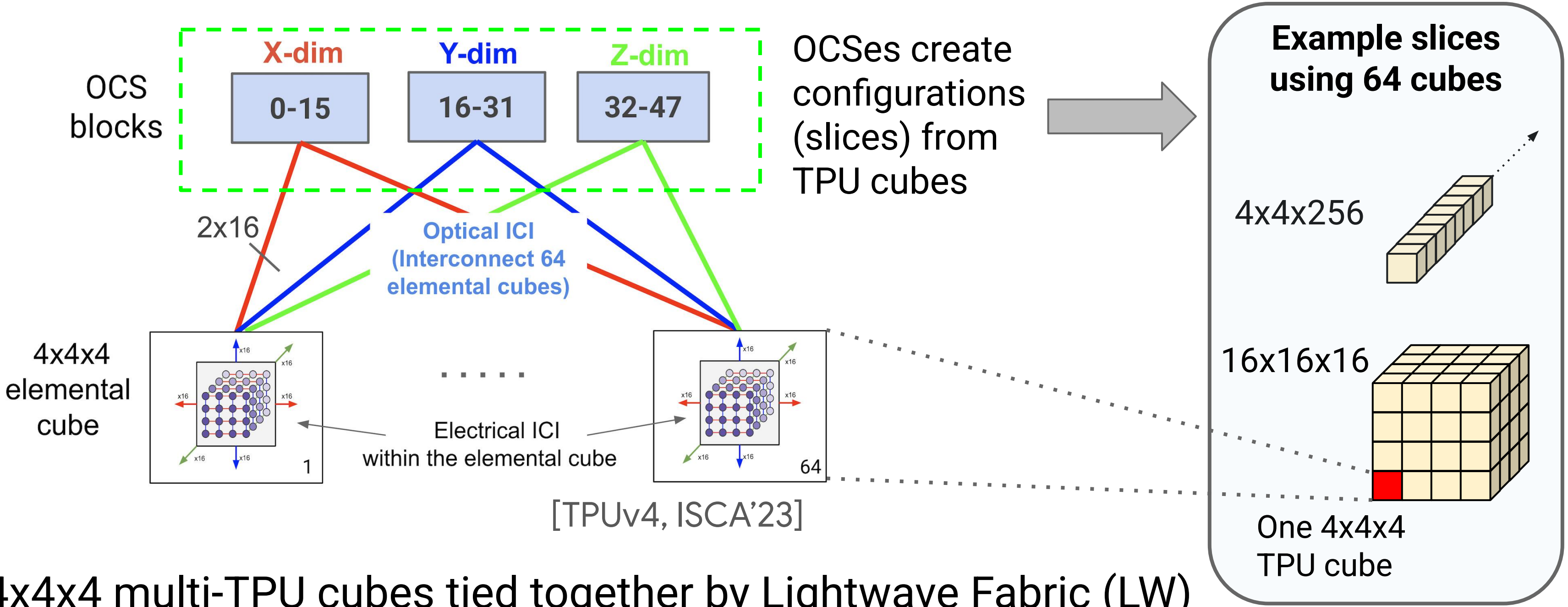
Application US16/381,951 events

2019-04-11	Application filed by Google LLC
2019-04-11	Priority to US16/381,951
2020-09-10	Publication of US20200285524A1
2021-06-22	Publication of US11042416B2
2021-06-22	Application granted
Status	Active
2039-04-11	Anticipated expiration

Show all events

Google's Reconfigurable ML Supercomputer System

TPUv4 as an example

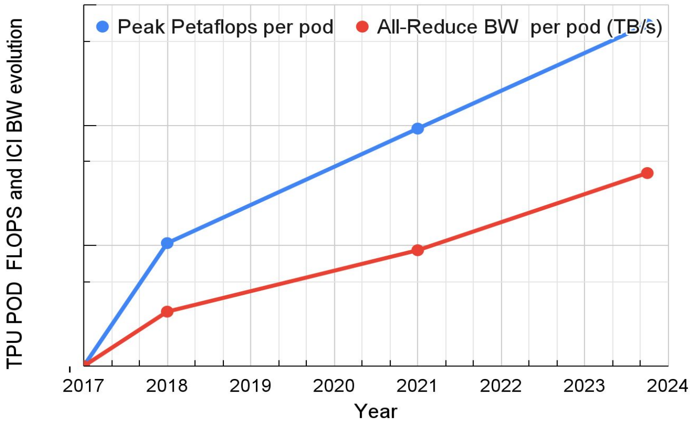


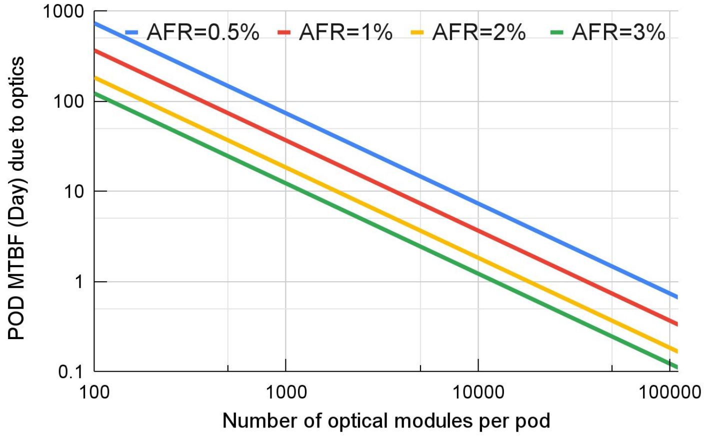
[TPUv4, ISCA'23]

- 4x4x4 multi-TPU cubes tied together by Lightwave Fabric (LW)
- Fabric enables reconfigurable interconnection between elemental cubes
  - Improved scale, availability, power, performance
  - Additional benefits: Utilization, modularity, deployment, security

What Drives ML ICI Optical Technology Evolution?

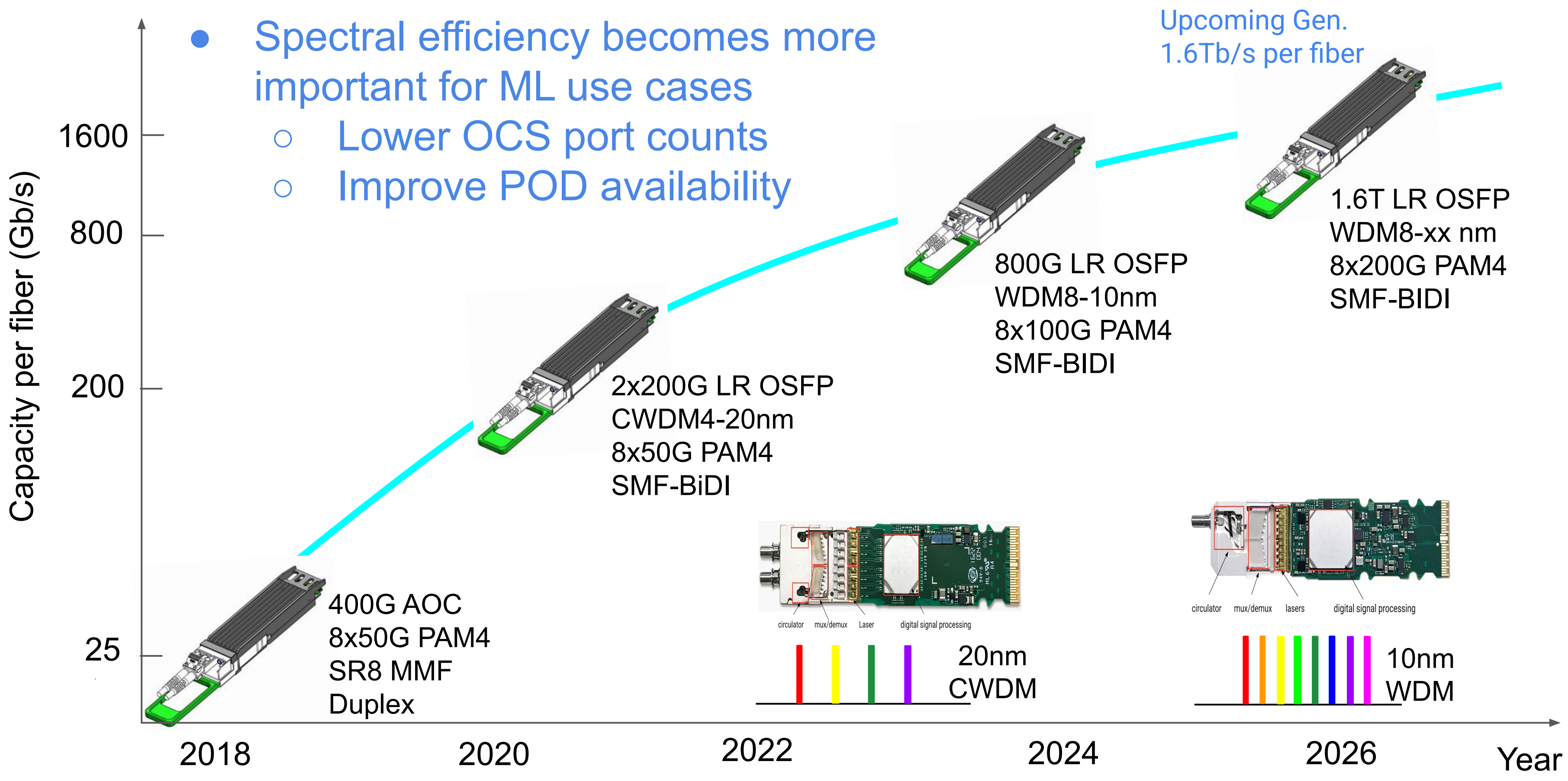
- Match the growth of ML computing and LLM model parameters
  - LLM very sensitive to ICI bandwidth
- High IO bandwidth density
  - Limited ML Chip I/O interface space
- High Reliability
  - Mean time between failures (MTBF)
  - Mean time to link flap (MTLF)
- Fast repairability
  - Pluggable preferable
- Low latency
- Improved energy efficiency
- Improved cost per bit
- Per fiber capacity (spectral efficiency) also matters for OCS-enabled Superpods



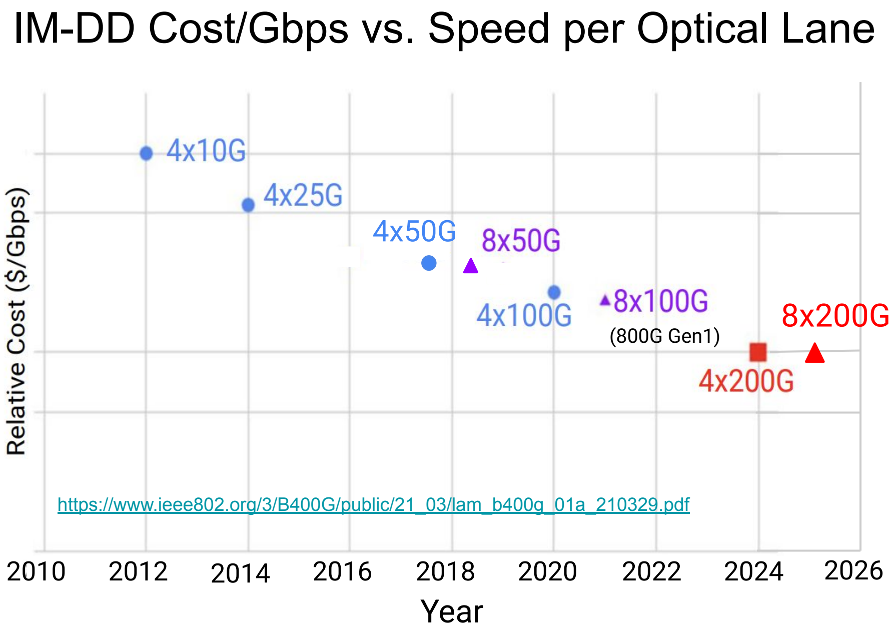


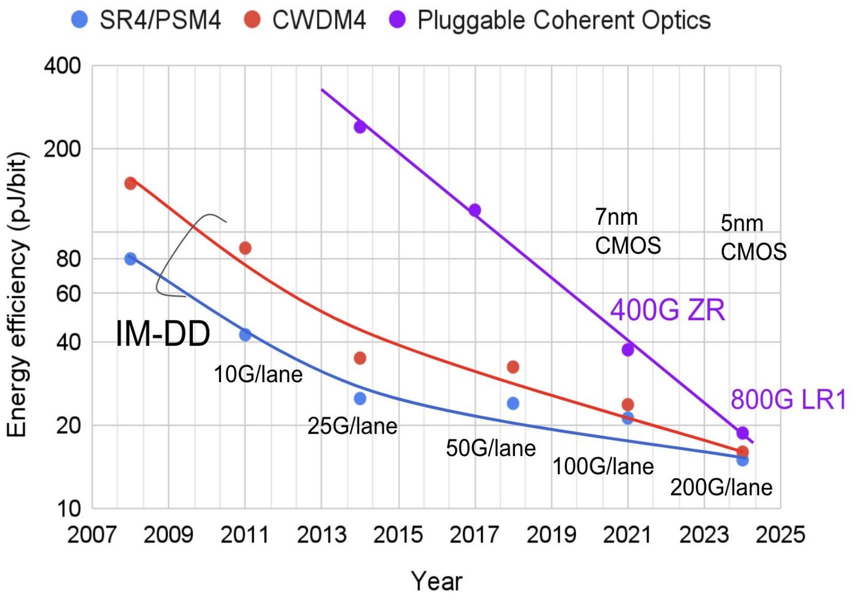
Google ML ICI Optics Evolution

- Spectral efficiency becomes more important for ML use cases
  - Lower OCS port counts
  - Improve POD availability



Technology Beyond 200G lane IM-DD ?





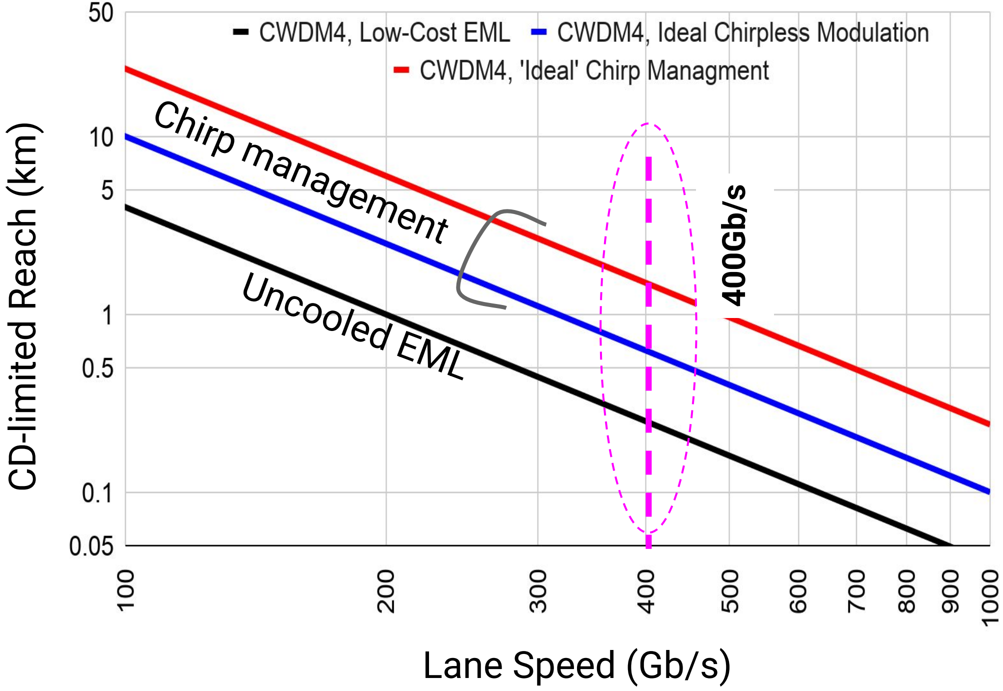
- Historically, increasing per lane speed with IM-DD offers lower lowest cost/power for DC Fabric and ML Supercomputer ICI
- Significant progress in lowering the power difference between Coherent and IM-DD
- 400G lane IM-DD and/or 400G per dimension coherent ?

IM-DD Scaling Challenges: Fiber CD-limited Reach

Assume CWDM4 optical bandwidth (1264.5nm to 1337.5nm)

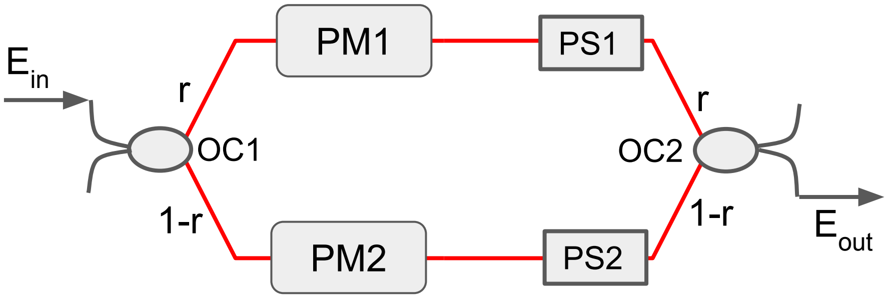
- CD Penalty ∝ (baud rate)^2
- Fiber CD puts an upper limit on the supported reach
- 10nm-spaced WDM8 (3.2T) or 20nm-spaced CWDM4 (1.6T)
  - ~0.2km with uncooled EML
  - <1km with ideal MZM
  - <2km with ideal (hypothetical) Chirp management
- Limited reach extension possible by more power-hungry MLSE
- Optical CD compensation faces size,loss and cost challenges

Assume low-power linear equalization, PAM4

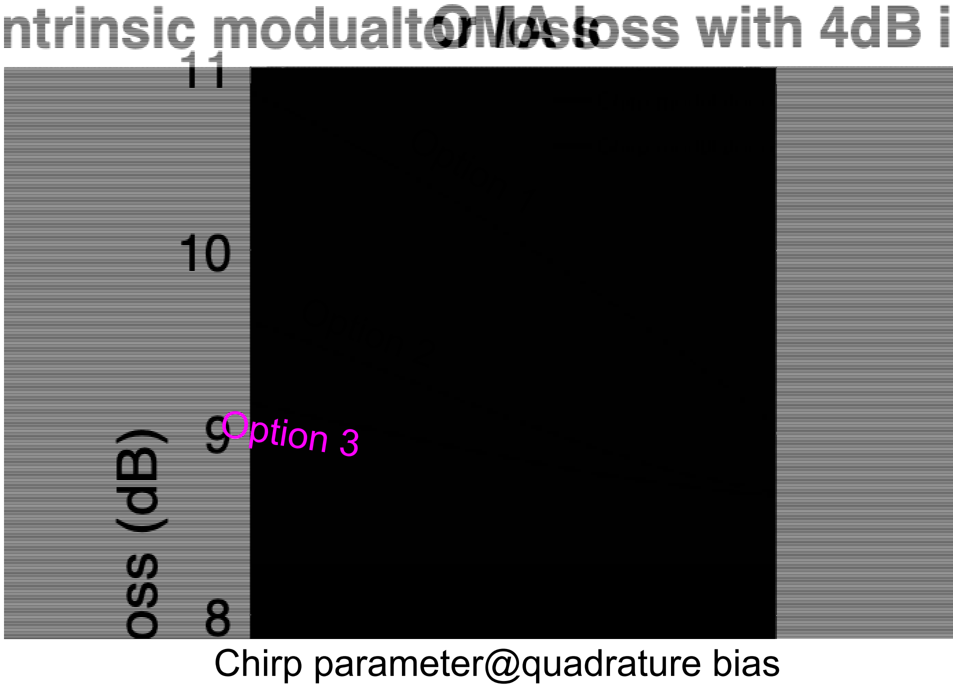


MZM Chirp Management Technology

Option 3

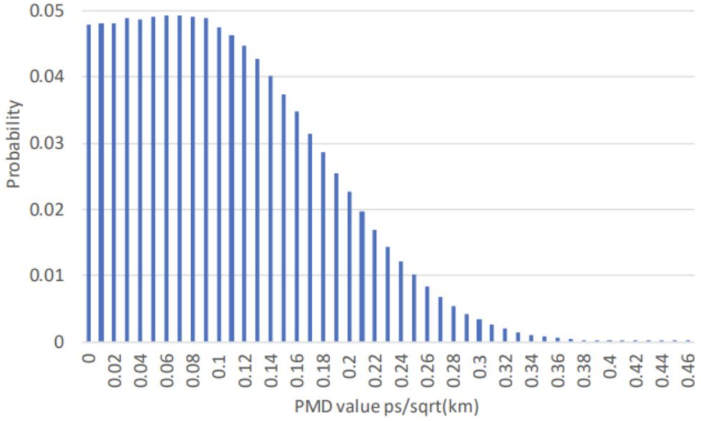


- PM: phase modulator
- PS: (thermal) phase shifter
- VOA: variable optical attenuator
- OC: optical coupler



- Introducing MZM chirp will reduce Tx OMA (optical modulation amplitude)
  - 0.3dB @chirp alpha=0.5
  - ~0.8dB@chirp alpha =1

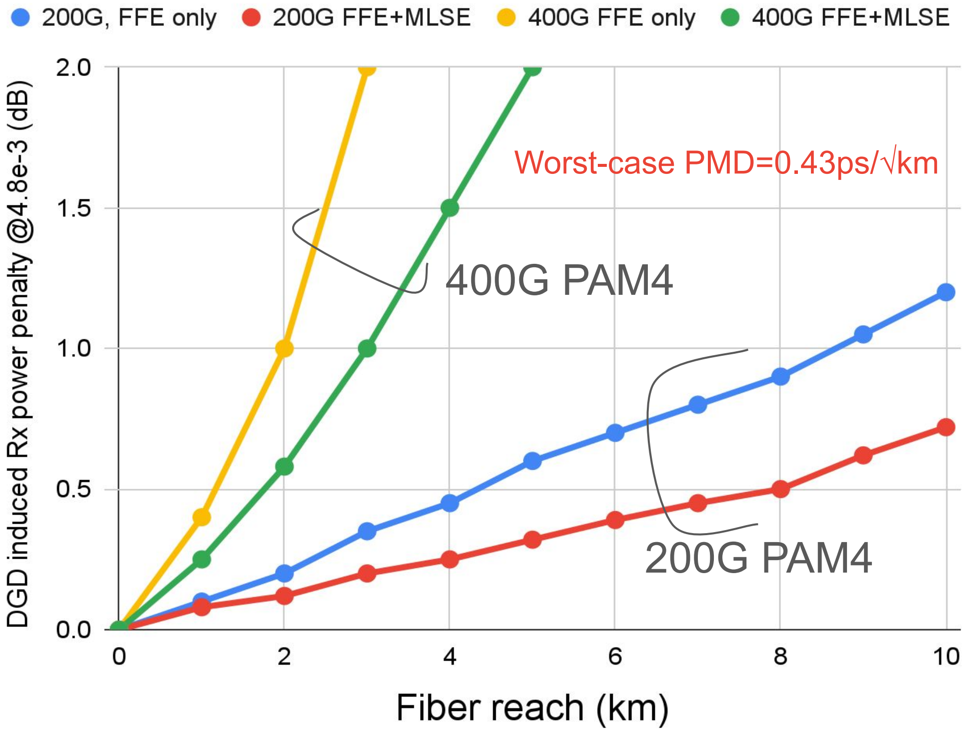
IM-DD Scaling Challenges: Fiber PMD Impact



Anslow_3cu_01_0519 *(slide 8)*

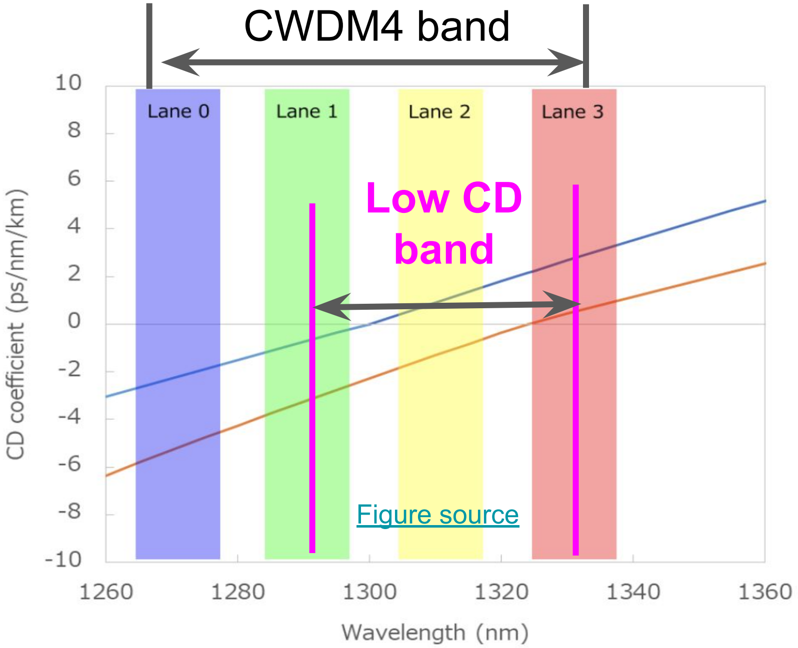
DGD_{mean} (LR-10km) = 0.43ps/√km * √10km = 1.36ps
DGD_{max} / DGD_{mean} ≈ 3.75
DGD_{max} (LR-10km) = 1.36ps *3.75 ≈ 5ps
DGD_{max} (LR-6km) ≈ 4ps

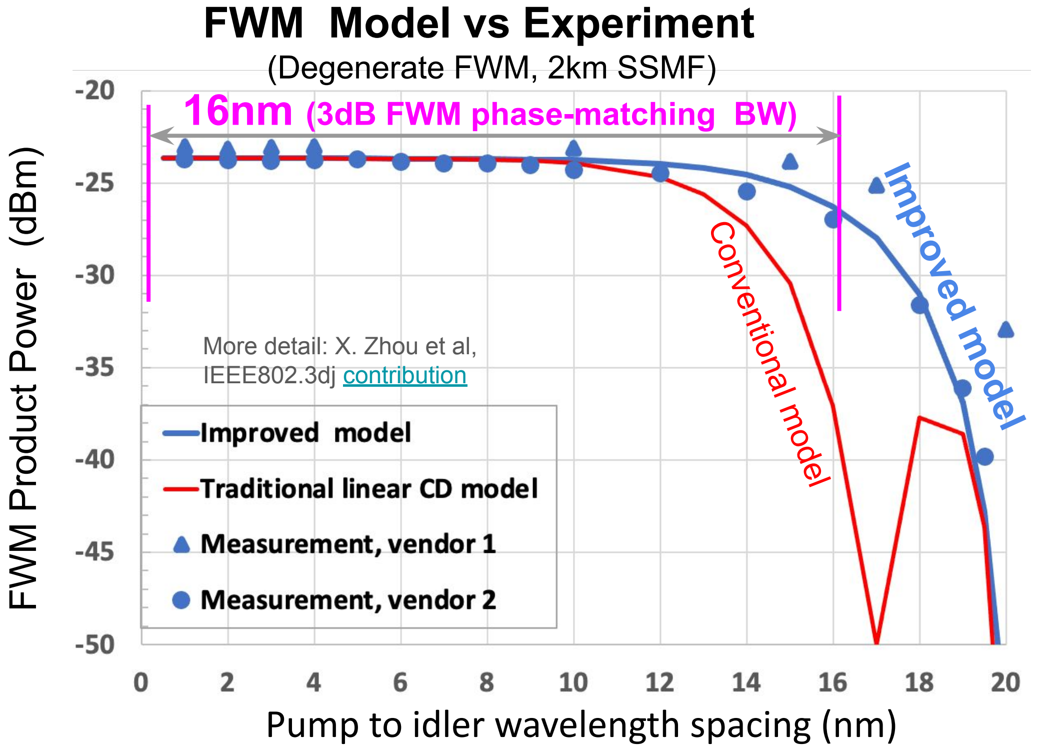
M. Kuschnerov et al, 800G LR4 DGD penalty and fiber specifications, iee802.3dj, 2022



- Fiber PMD can also be a performance-limiting factor for 400G lane IM-DD for >2km reach

How About Narrower CH Spacing to Lower CD Penalty

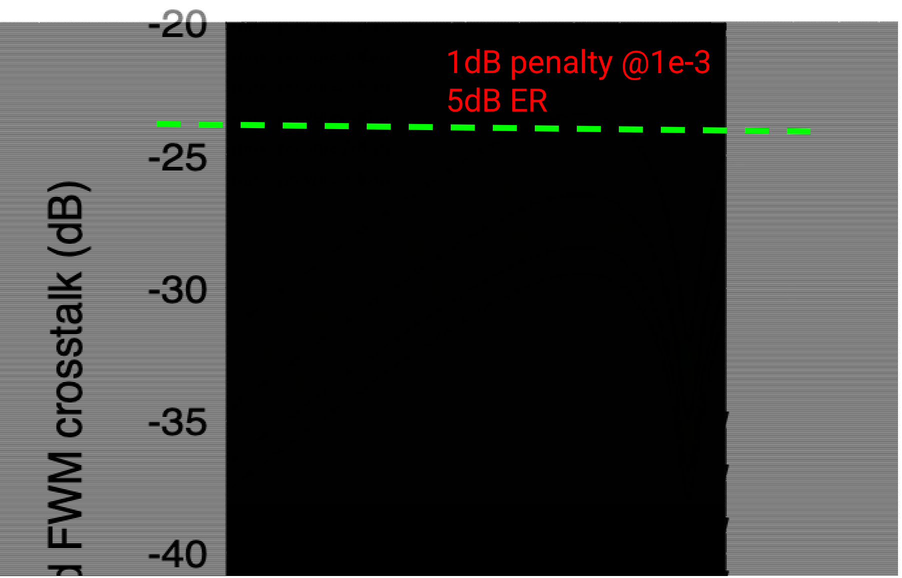




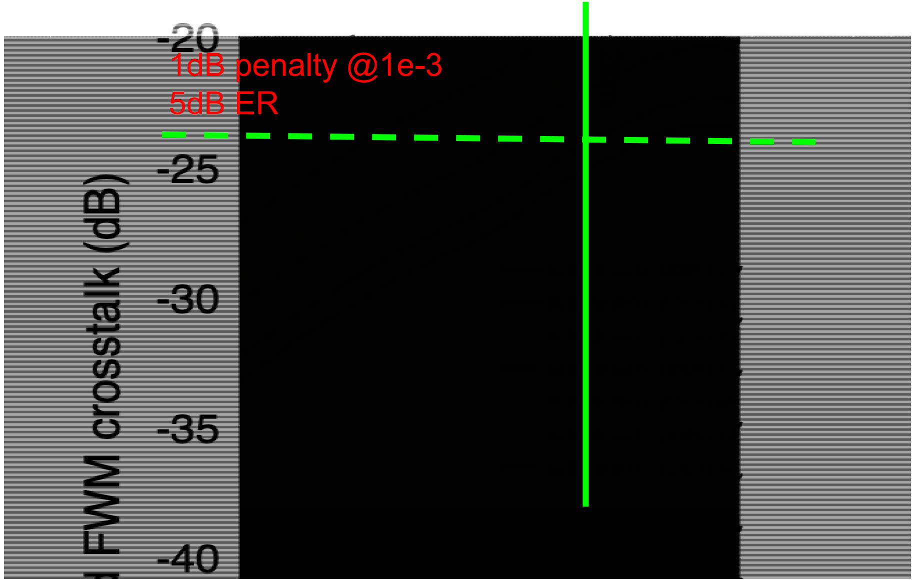
- FWM efficiency quickly increases as channel spacing reduces from 20nm
- Near perfect FWM phase matching observed when CH spacing <12nm @2km SSMF

IM-DD Scaling Challenges: Fiber FWM @O-band

20nm-spaced CWDM4, wavelength ±3nm

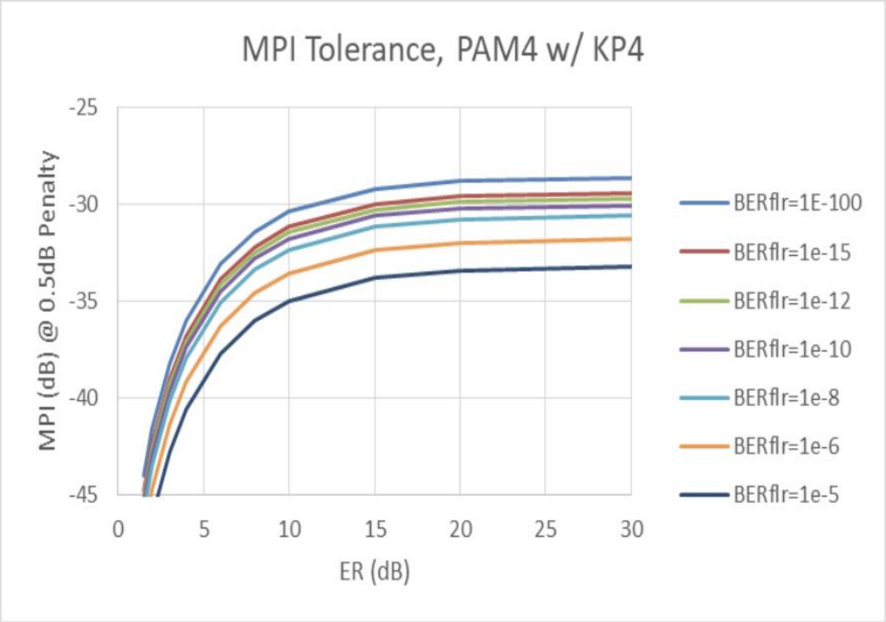


10nm-spaced WDM8, wavelength ±3nm

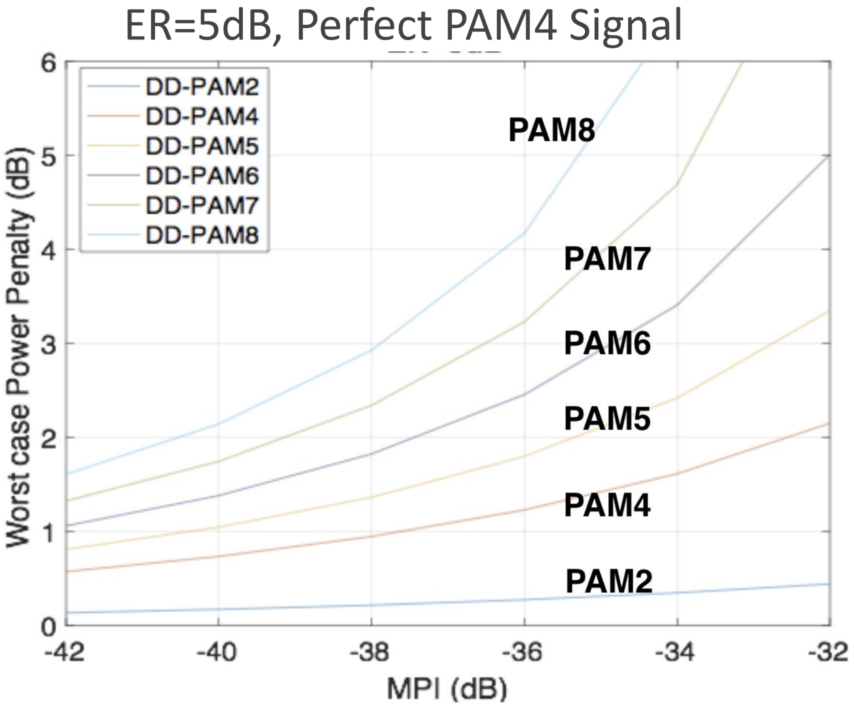


- FWM impacts depends on WDM wavelength grid, per channel launch power and fiber reach
- 20nm-spaced CWDM4: FWM still manageable (penalty <1dB@1e-3 over 10km at 7dBm Tx power)
- 10nm-spaced WDM8: FWM limits the reach to ~2km (penalty>1dB@1e-3 over 2km at 3dBm+ Tx power)

IM-DD Scaling Challenges: Inband Optical Interference

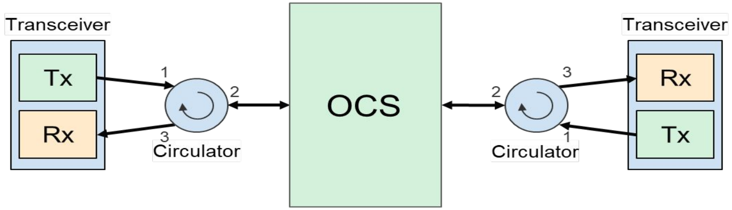


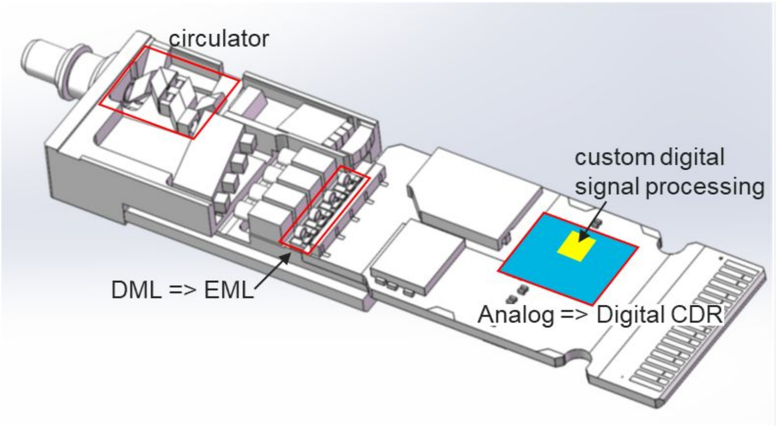
H. ZHANG, "[Modeling MPI penalty and its implication for next generation PAMx systems]", IEEE802.3dj, 2023

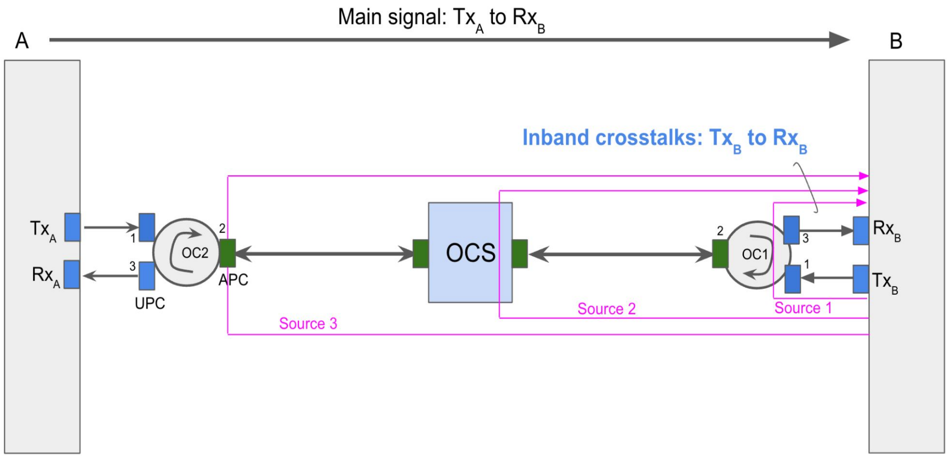


- Inband optical interference such as MPI can introduce significant system penalty, especially when the modulation order is greater than 2 and modulation ER is low

IM-DD Scaling Challenges: Inband Optical Interference

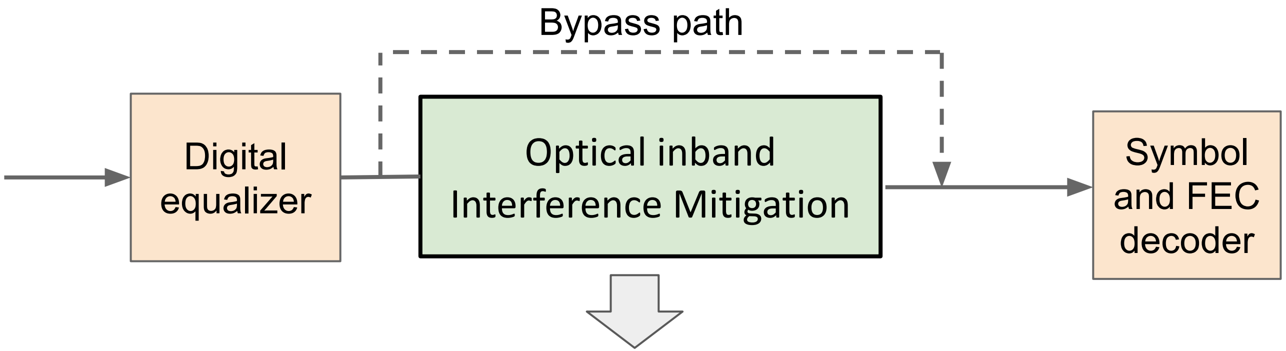






- Single optical reflection can cause inband optical interference for BiDi optical technology
- Mitigation of inband interference is needed even for PAM4 for practical transmission systems

IM-DD: Digital Mitigation of Inband Optical Interference

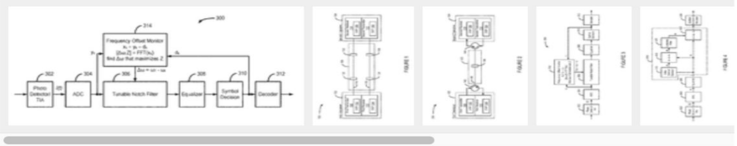


In-band optical interference mitigation for direct-detection optical communication systems

Abstract

This disclosure provides systems, methods, and apparatus for mitigating the effects of interference signals on optical signals received at a direct-detection optical receivers. The optical receivers are capable of attenuating interference noise signals resulting from the interference between a transmitted optical signal transmitted from a transmitter to the optical receiver and one or more additional signals received at the optical receiver. The interference can be due to multi-path interference or due to in-band interference. The receivers include a tunable filter for filtering the received optical signal to remove the interference. A frequency offset module processes the received optical signal to determine a frequency offset indicative of the difference between the carrier frequencies of a modulated optical signal and an interference optical signal. The offset frequency and a bandwidth determined by the frequency offset module can be used to adjust the tunable filter to remove the interference signal from the received signal.

Images (9)



US9998235B2
United States

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Inventor: Xiang Zhou, Ryohei Urata, Erji Mao, Hong Liu, Christopher Lyle Johnson

Current Assignee : Google LLC

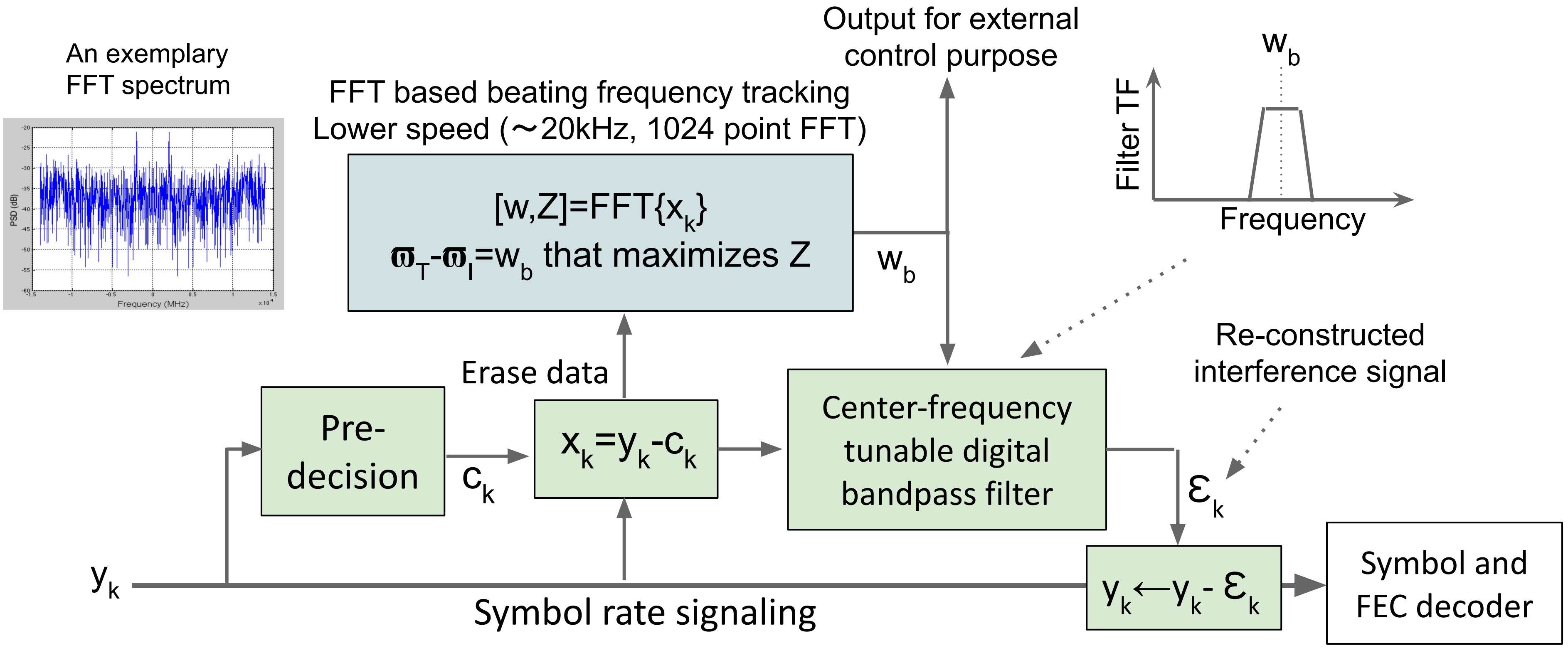
Worldwide applications

2016 • US AU WO KR EP SG JP DK KR DE DE CN GB CN TW
2018 • US 2019 • JP

Application US14/991,826 events

- First worldwide family litigation filed
- **2016-01-08** • Application filed by Google LLC
- **2016-01-08** • Priority to US14/991,826
- **2017-07-13** • Publication of US20170201330A1

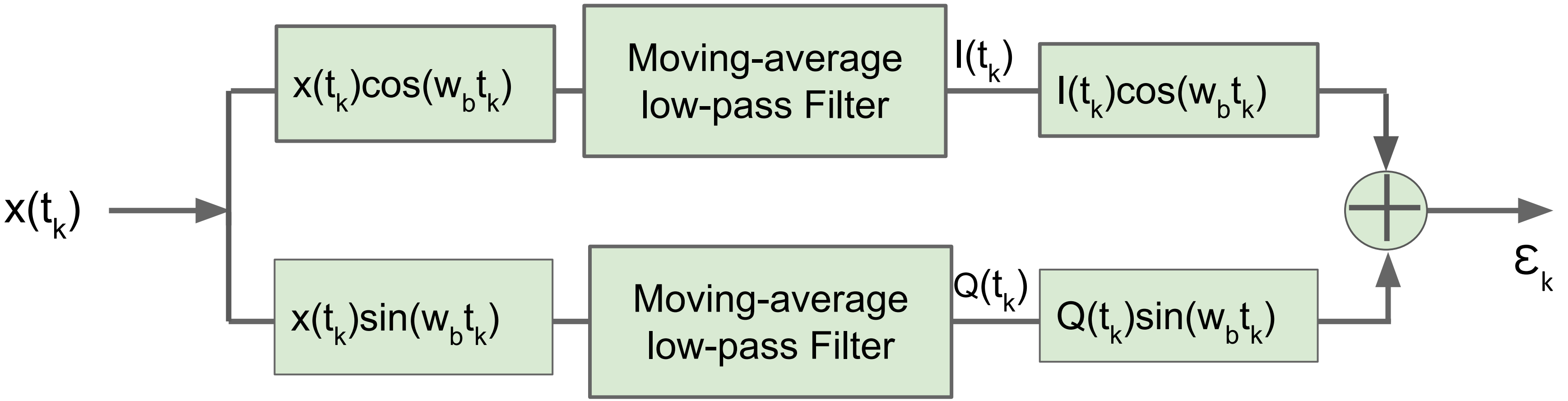
IM-DD: Optical Interference Mitigation (OIM) Algorithm



ϖ_T: Original optical signal frequency (angular); ϖ_I: Interfering signal frequency

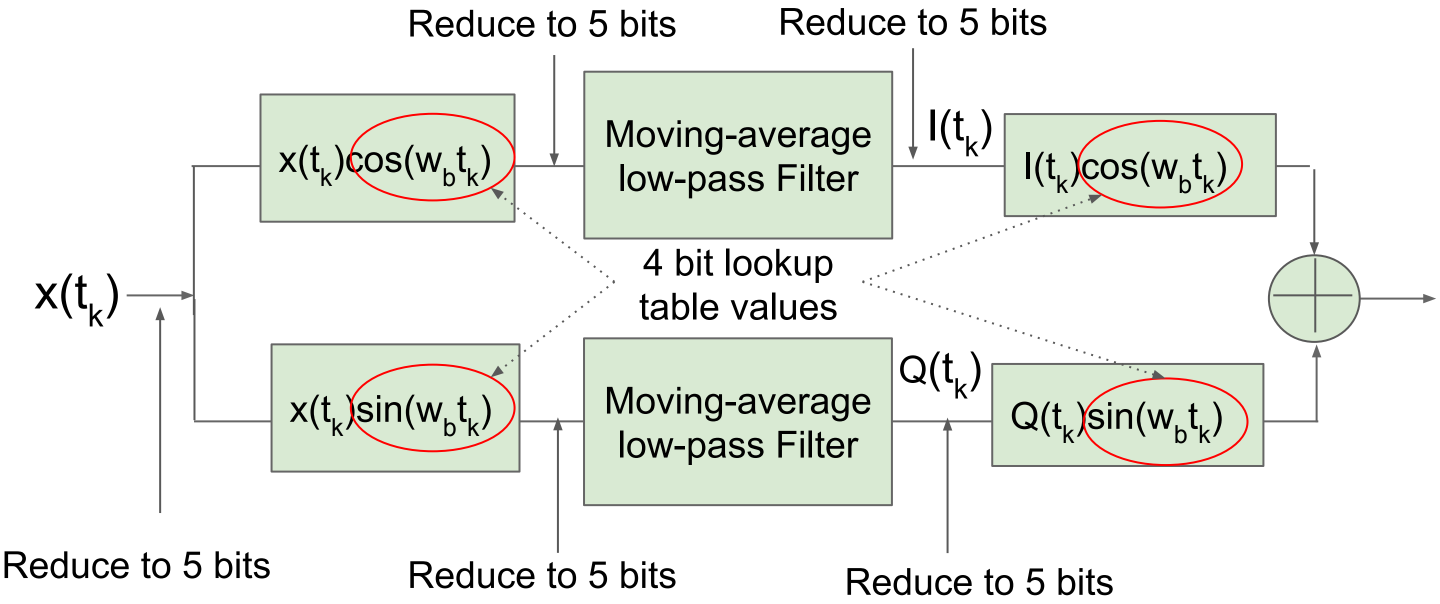
OIM: Low-Power Tunable Bandpass Filter Design

w_b: Passband center (angular) frequency



- Transform the passband signal-interference beating noise to baseband
- Using hardware-efficient low-pass moving-average filters to extract beating noise
- Transform the extracted beating noise back to passband

OIM: Low-Power Tunable Bandpass Filter Design

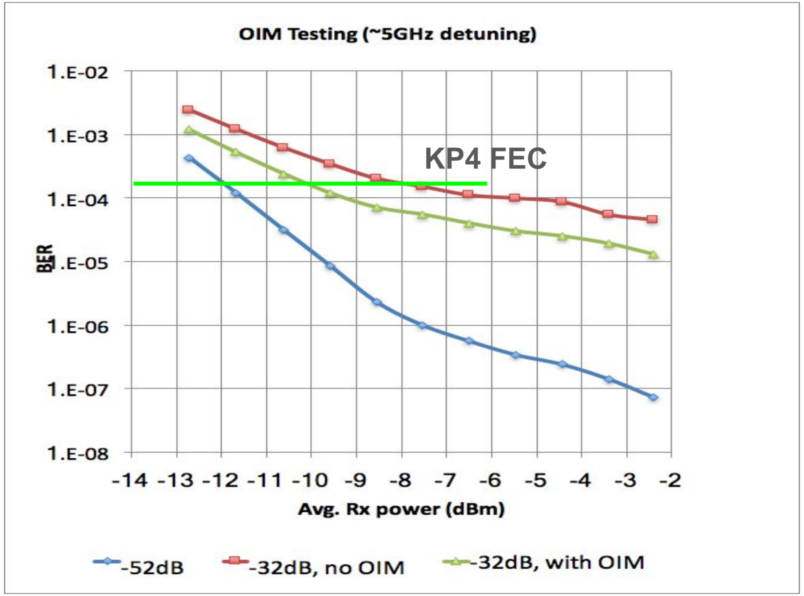


- Reduced digital resolution after each arithmetic operation
- OIM power <6% of total PAM4 DSP ASIC@ 5nm
  - Significantly lower than CORDIC based design

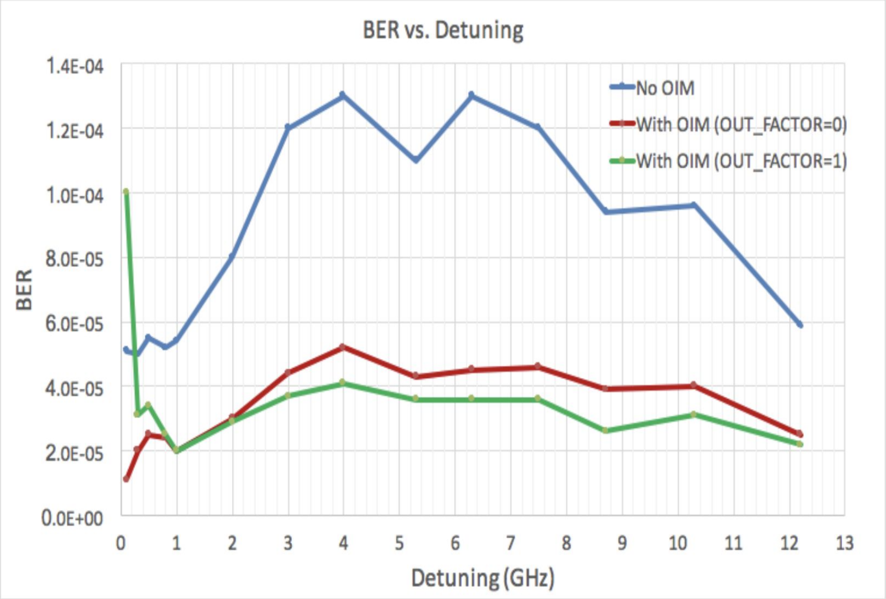
Effectiveness of Optical Interference Mitigation (OIM)

Measured 56Gb/s PAM4 with Gen 1 production PAM4 DSP, modulation ER=5dB

BER vs power at beating freq=5GHz

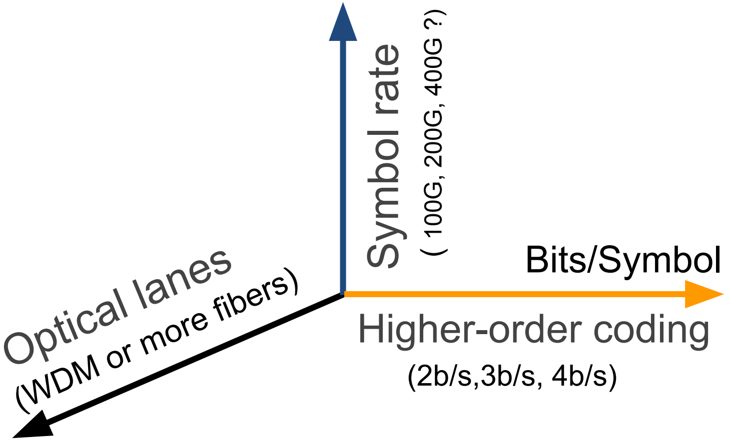


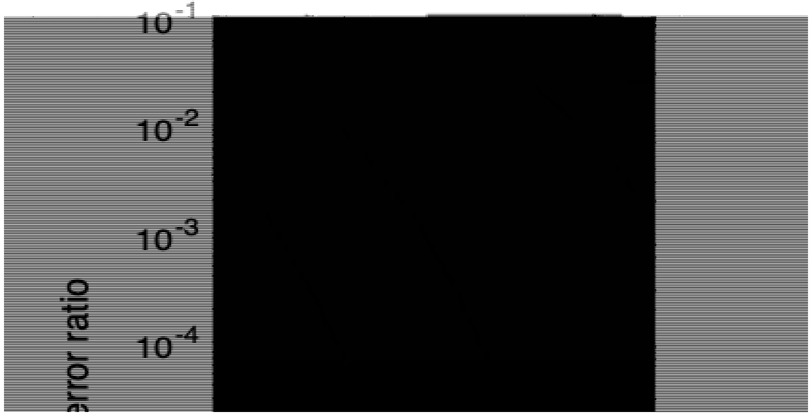
BER vs Beating freq at fixed Rx power



- At -32dB and df=5GHz, OIM reduces penalty from 3.5dB to 1.6dB at BER 2e-4

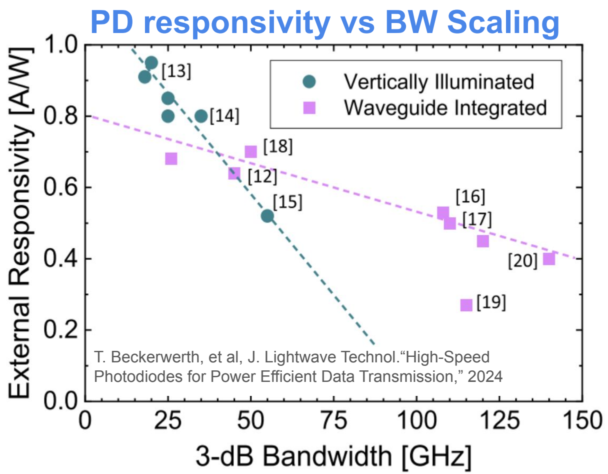
IM-DD Scaling Challenges: Link Budget

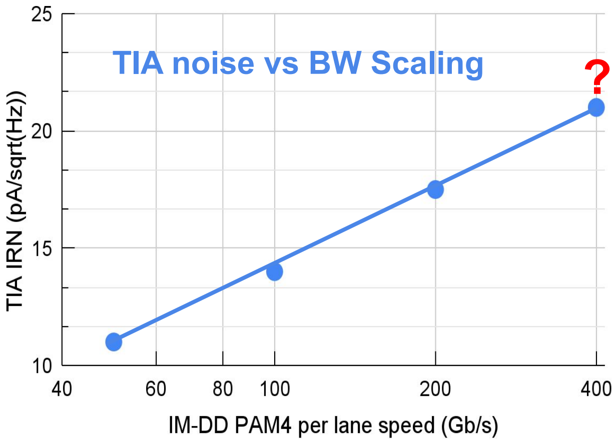


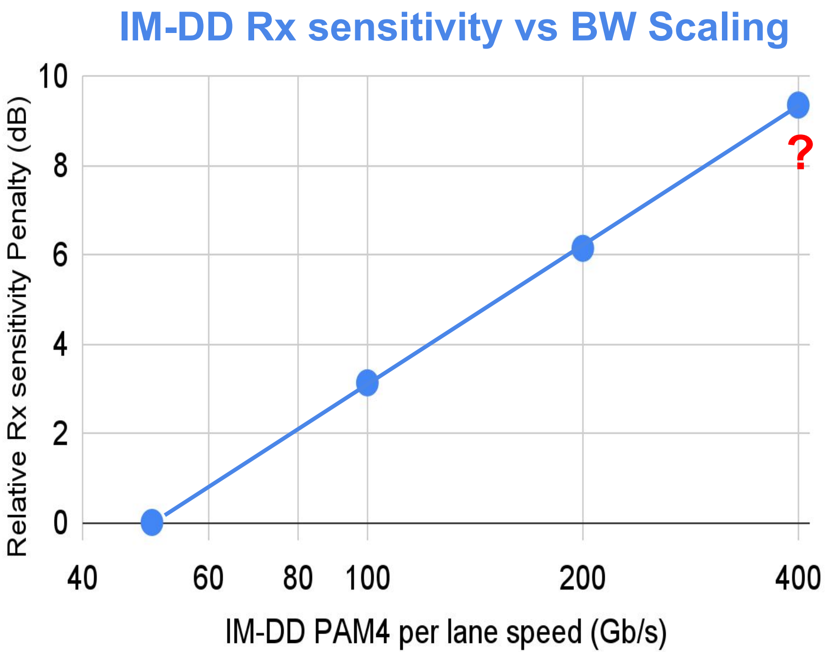


- Doubling the symbol rate doubles the noise bandwidth, reducing the SNR by 3 dB
- Higher-order coding introduces an additional SNR penalty
- Photodiode responsivity typically decreases as bandwidth increases
- TIA input-referred noise (IRN) density typically increases with bandwidth
- Plus additional CH impairments
    - CD/PMD
    - Optical interference
    - FWM nonlinear effects
    - Component bandwidth constraints

IM-DD Scaling Challenges: Receiver Sensitivity (PD/TIA)



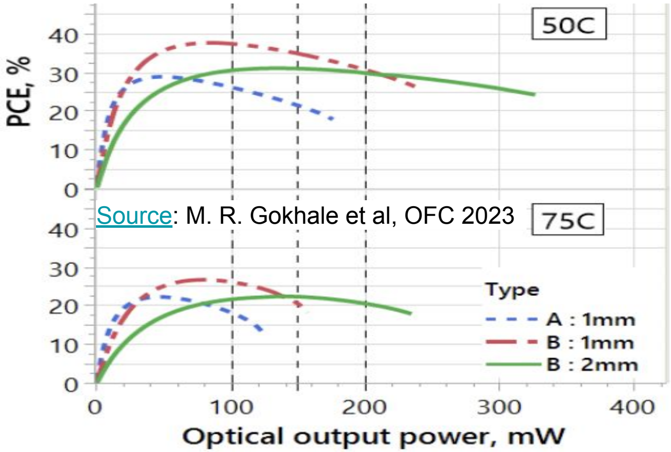




- Receiver sensitivity decreases by roughly 3 dB for each doubling of lane speed

IM-DD Scaling: Solutions to Improve Link Loss Budget

State -of-the-art O-band DFB

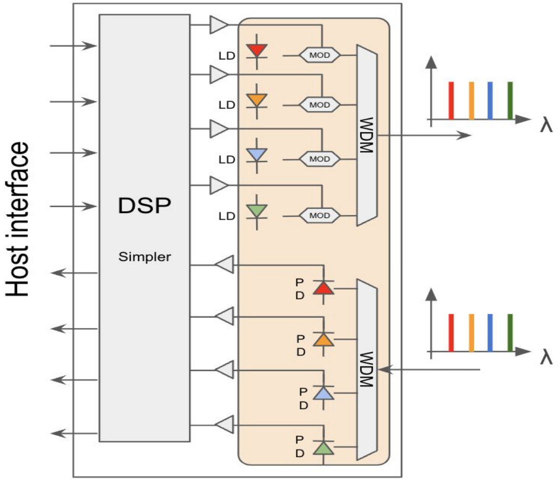


Source: M. R. Gokhale et al, OFC 2023

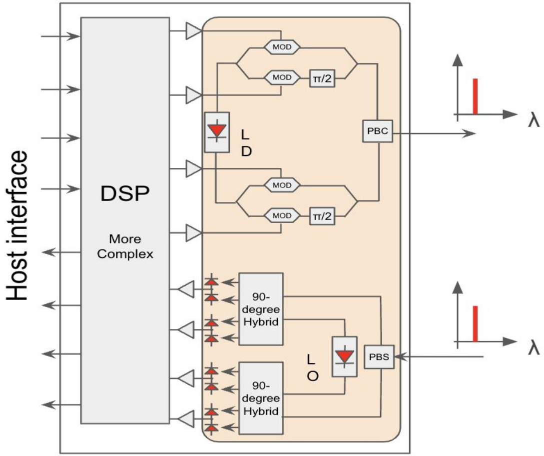
- **Higher launch optical power**
  - Limited by DFB power conversion efficiency, reliability and fiber link nonlinearity (such as FWM)
- **Higher modulation ER**
  - More efficient modulator technology
  - 2 to 3 dB potential upside
- **Compact optical amplifiers (SOA) ?**
  - Cross-gain modulation crosstalk
  - Polarization dependency
- **Higher Gain FEC ?**
  - Less effective for IM-DD: 3dB coding gain only translates into 1.5dB link budget gain
  - Latency increases
- **Probabilistic constellation shaping ?**
  - Not effective for peak-power constrained (un-amplified) IM-DD systems (detail study refers to a JLT paper by D. Che, X. Chen, 2024)

Coherent vs IM-DD: A High Level View

4-Lane IM-DD transceiver



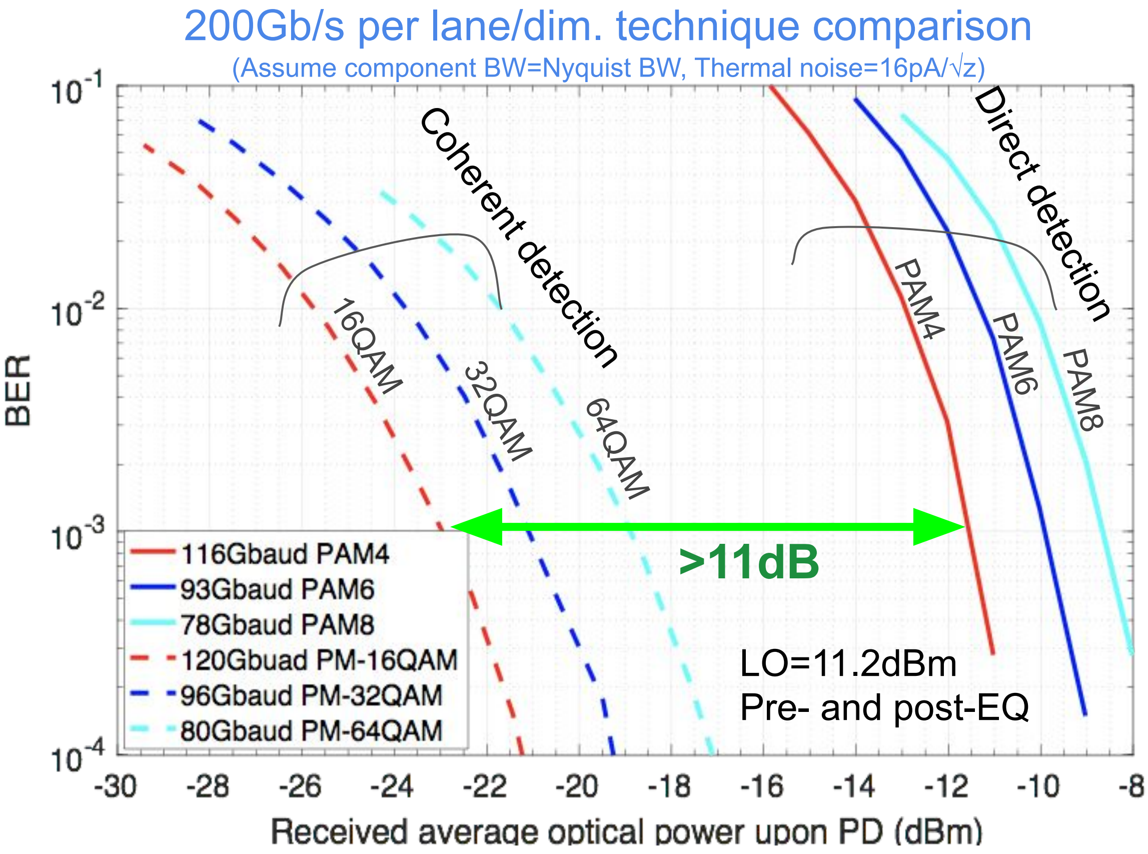
4-dim. coherent transceiver

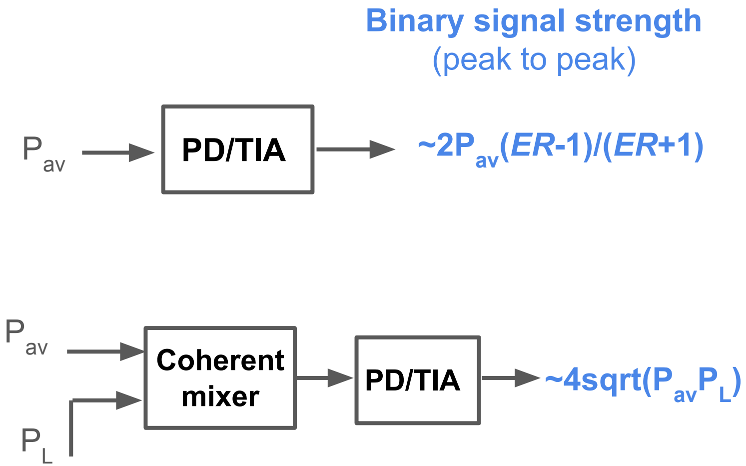


4-Lane IM-DD vs 4-dimension Coherent-Lite

- Share similar component bandwidth requirements and component counts (DAC/ADC, driver, MZM, etc.)
  - Coherent require less lasers, but impose more stringent frequency stability and phase noise requirements.
  - Coherent requires more powerful DSP and more complex modulator control
- With enough modulator drive swing, coherent can support larger link budget
- Coherent systems are more tolerant of channel impairments (CD, PMD, FWM, MPI etc), supporting longer reach
- Coherent future scalable, but not backward compatible

Coherent vs IM-DD: Receiver Sensitivity Gain





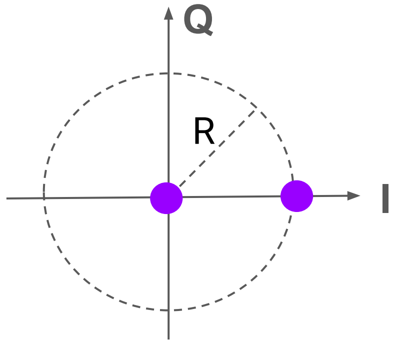
- Pav: average signal power
- ER: modulation extinction ratio
- PL: LO power

More details: X. Zhou et al, 'Beyond 1 Tb/s Intra-Data Center Interconnect Technology: IM-DD OR Coherent?' JLT 2019.

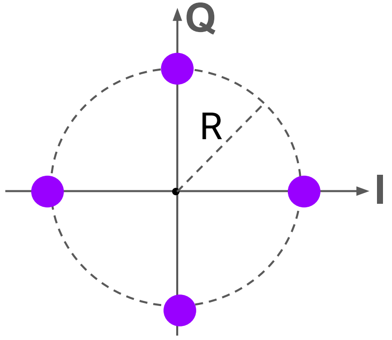
Coherent vs IM-DD: Transmitter Modulation Efficiency

- **Spectral efficiency**
  - IM-DD modulates over 1 dimension of the light (Amplitude)
  - Coherent allows modulation over four dimensions of the light: 4x spectral efficiency increase
- **Optical power efficiency**
  - Coherent enable bipolar modulation in the optical field, effectively ‘doubling’ constellation spacing (Euclidean distance) under identical peak optical power

IM-DD PAM-2

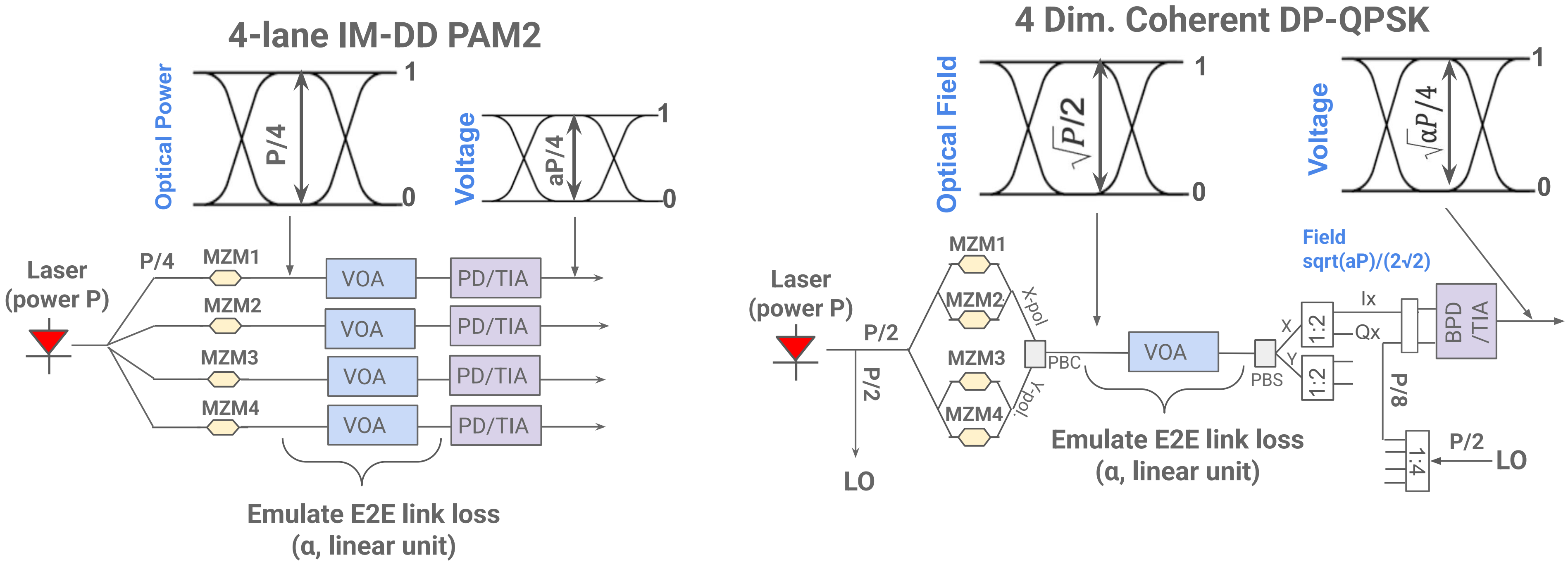


Coherent 4QAM



Coherent vs IM-DD: Fundamental Laser Power Efficiency

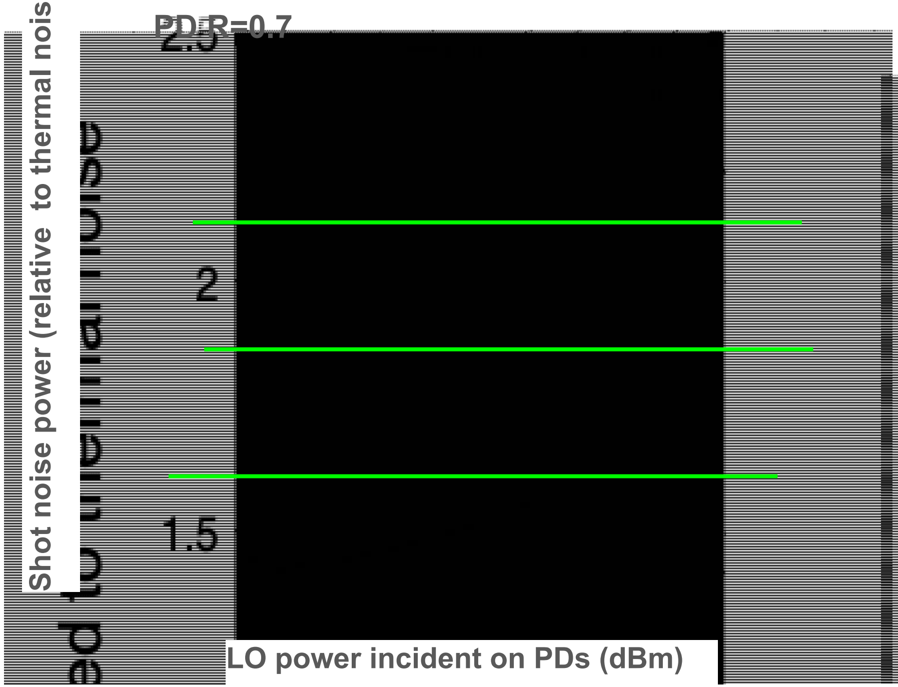
Theoretical Model Assuming Ideal Components



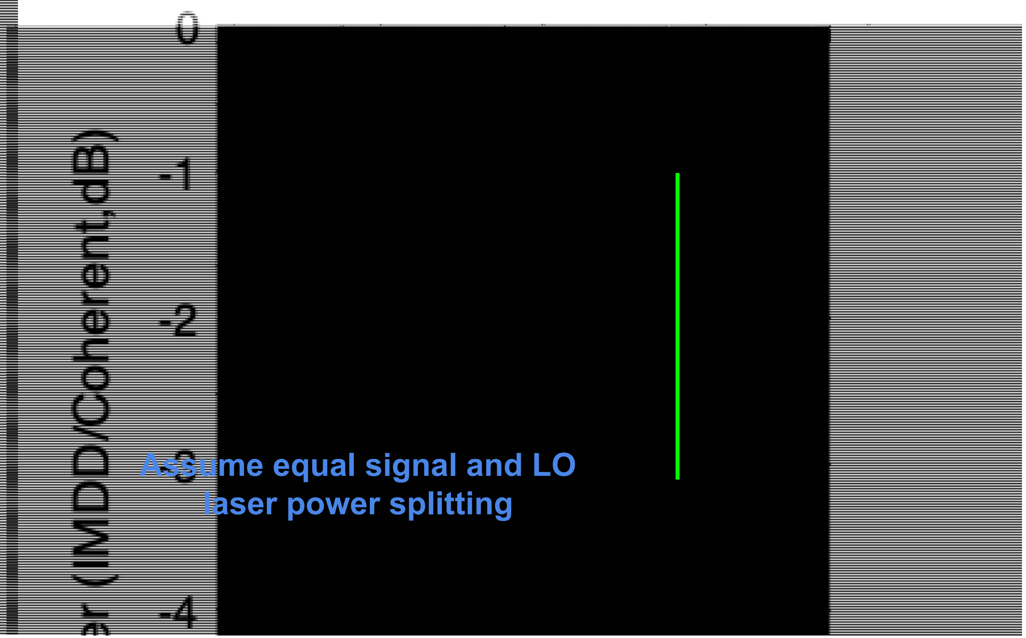
- To support the same E2E loss β dB: =-10log10(α), coherent requires β/2 dB less laser power
  - Assume TIA thermal noise dominates LO shot noise for the coherent system

Coherent vs IM-DD: Fundamental Laser Power Efficiency

Impact of LO Shot Noise

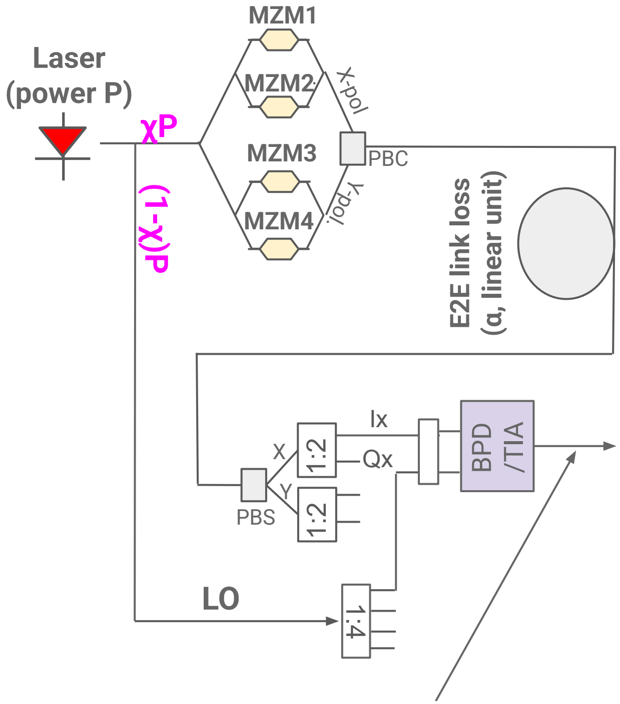


Required laser power of coherent systems relative to IM-DD systems versus end-to-end (E2E) optical link loss



- LO shot noise reduces coherent laser power efficiency improvement

Impact of LO Shot Noise on Optimal Signal/LO Splitting

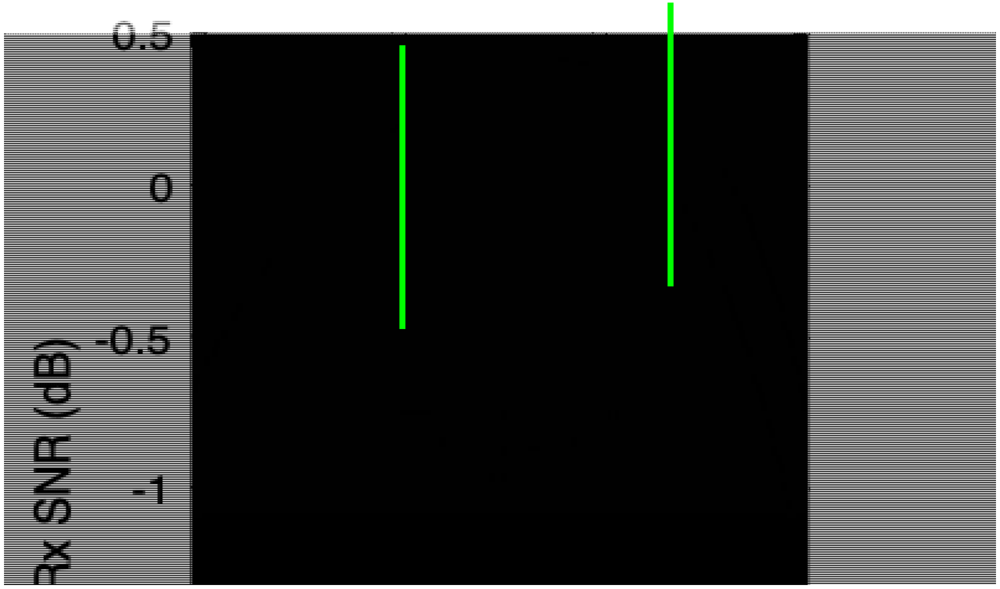


$$Signal\ Power = \chi(1-\chi)\alpha P^2/16$$

Noise variance=$Bi_{th}^2 + Bq(1-x)P/2$

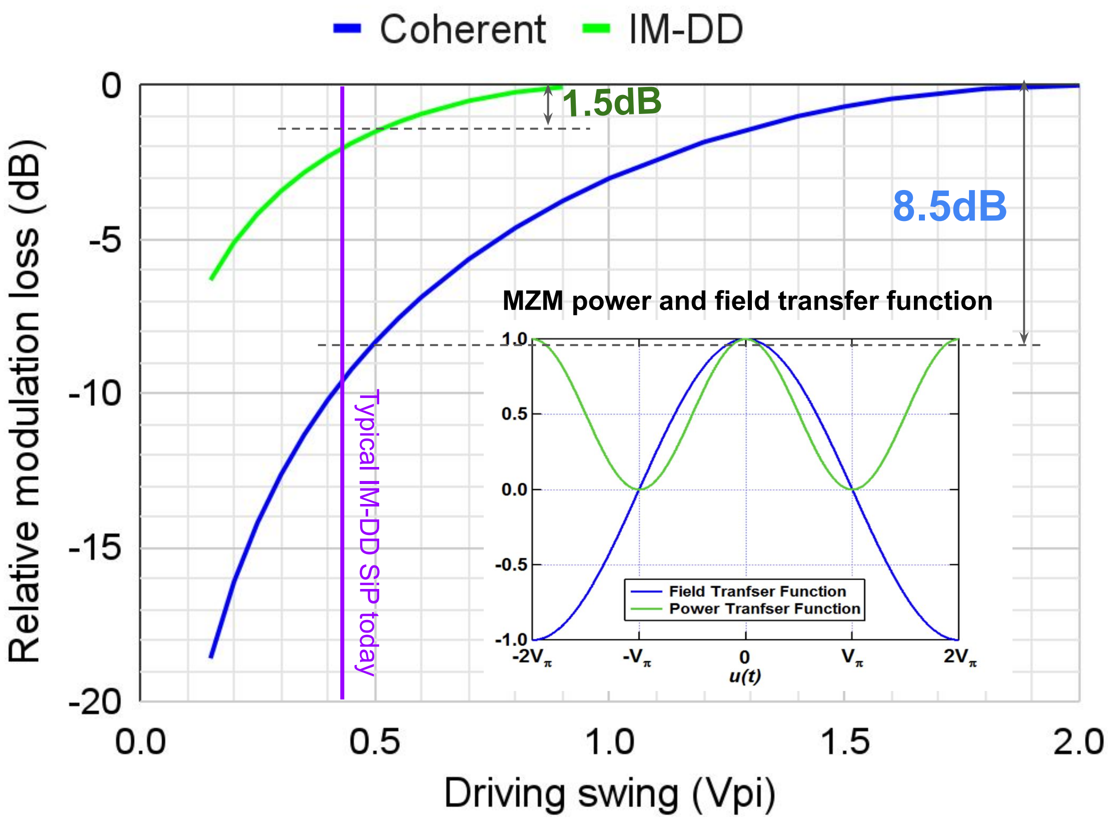
Thermal Shot noise

Assuming TIA thermal noise=20pA/sqrt(Hz)



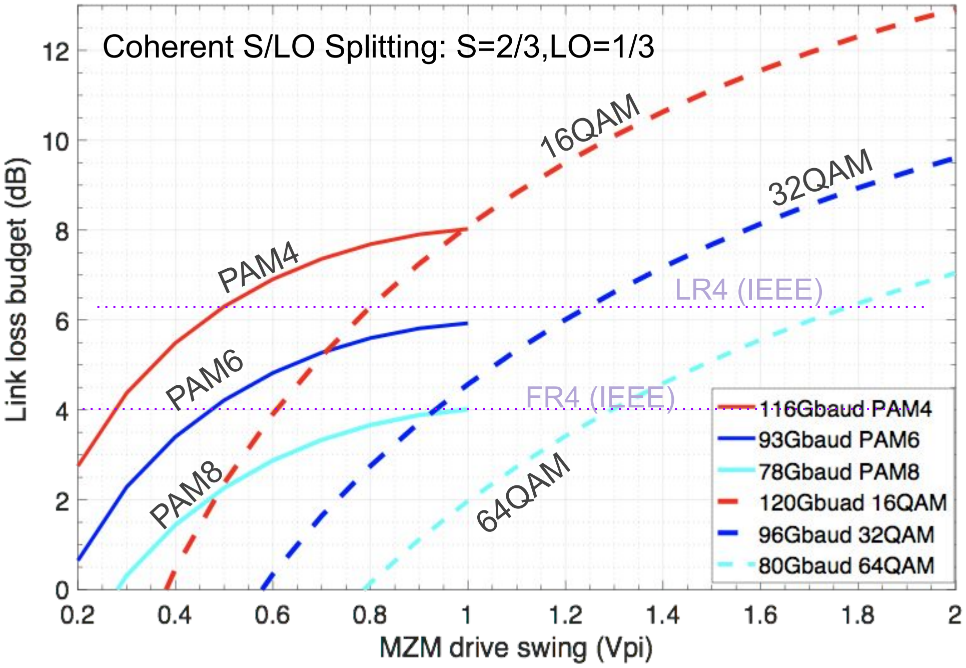
- The optimal signal/LO splitting ratio depends on LO power for constant TIA thermal noise

Coherent vs IM-DD: Modulation Loss



- Coherent requires to drive the modulator harder
  - Ideally 2Vpi for Coherent
  - Ideally 1Vpi for IM-DD
- Low-Vpi modulator holds the key
  - Improvement of modulator efficiency benefits coherent more than IM-DD

Coherent vs IM-DD: Achievable Link budget



An example

Item \ Technique	2x800Gb/s PM-QAM	8x200Gb/s (IM-DD) PAM
Laser number	2	8
Per Laser power (dBm)	16	16
MZM IL (dB)	4	4
Tx path loss(dB)	7.8[a]	4
Rx path loss (dB)	4	2
Mux+DeMux (dB)	1	4
Implement. penalty (dB)	5/5.5/6	4/4.5/5

[a]: include 1.8dB signal/LO splitting loss, additional 3dB I/Q modulation loss not included here

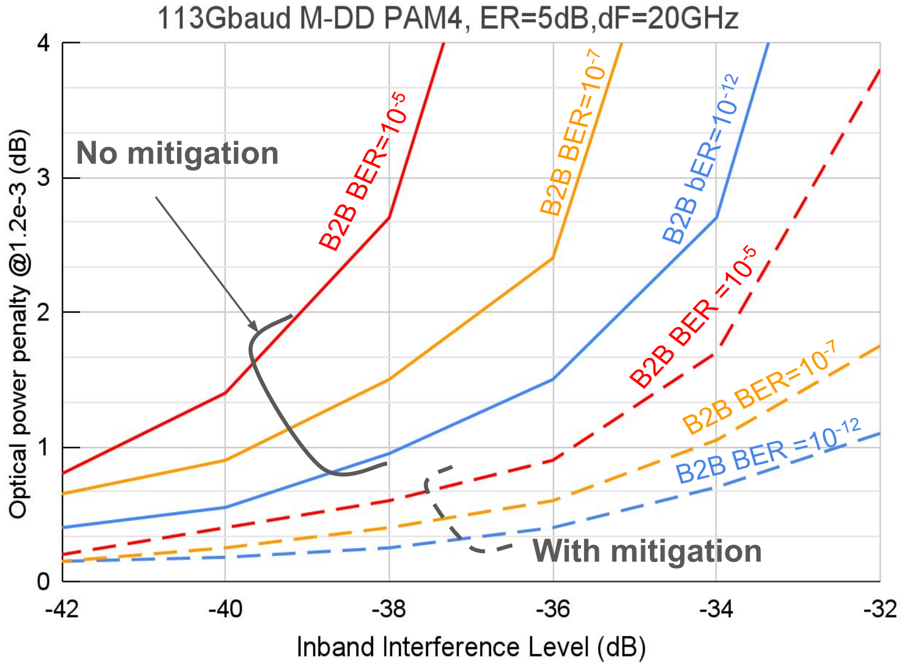
- At identical per laser power, coherent needs to drive the MZM harder to achieve a similar link budget
- At full drive swing, coherent can achieve about 5dB higher link budget

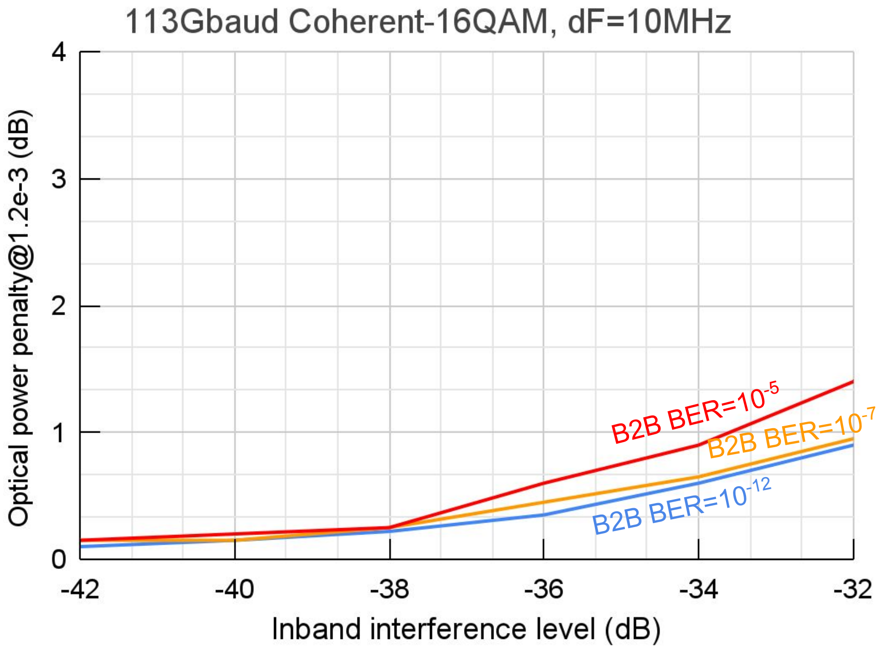
Coherent vs IM-DD: Optical Impairments Tolerance

	IM-DD	Coherent
Fiber CD	Limits the reach (~1km@400G Lane)	No limitations (can be fully compensated)
Fiber PMD	Limits the reach (~2km @400G lane)	No limitations (can be fully compensated)
Optical inband interference (OI, such as MPI)	Very sensitive to OI, especially when ER is low	Much more tolerable
Fiber nonlinear effects (Four-Wavelength-Mixing)	Limits the achievable reach and link budget (due to launch power constraints)	Much less an issue due to 1) ~10dB less optical power to support the same link loss 2) No DC optical components

Coherent vs IM-DD: Inband optical Interference Tolerance

Penalty derived from average BER under identical component bandwidth and implementation noise assumptions



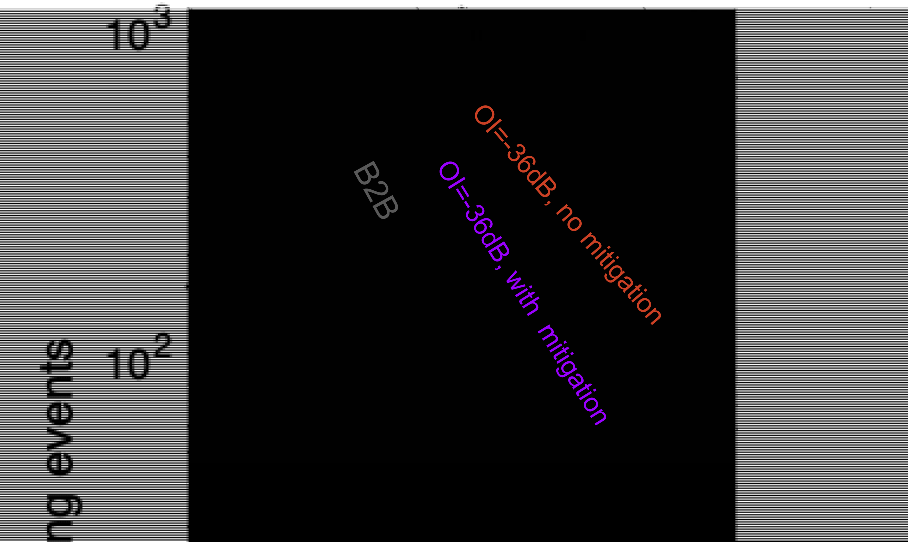


- **Coherent QAM is much more tolerant of optical in-band interference**

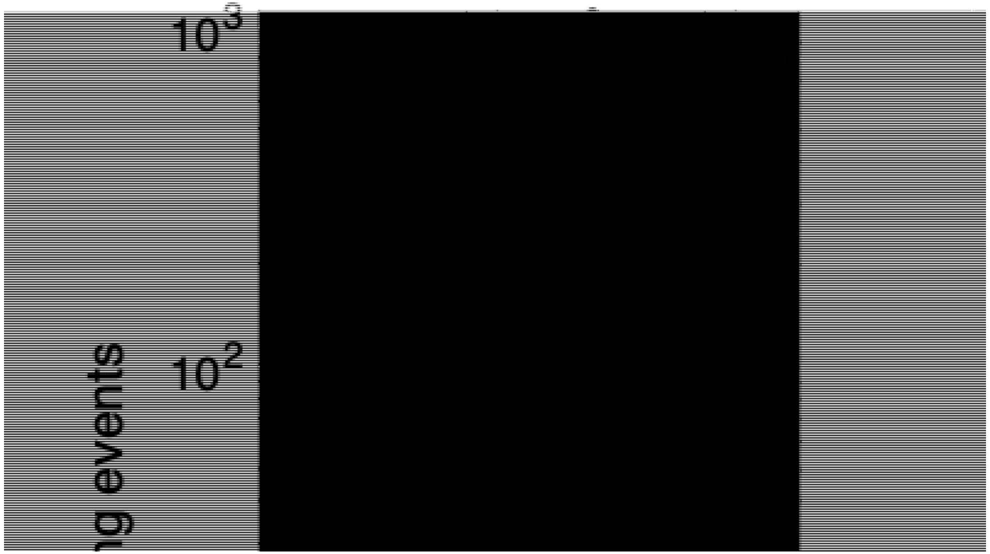
Coherent vs IM-DD: Inband optical Interference Tolerance

Burst Error Statistics (simulations)

IM-DD PAM4 KP4 FEC symbol error PDF (113Gbaud, Identical average BER ~1e-3)



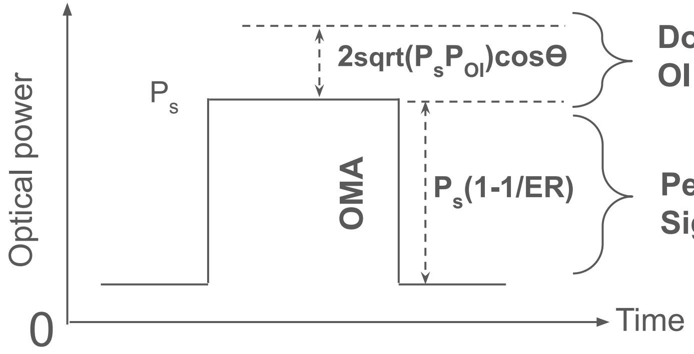
Coherent 16QAM KP4 FEC symbol error PDF (113Gbaud, identical average BER ~1e-3)



- Optical interference can result in significant burst errors in IM-DD systems
  - Penalties derived from average BER measurements may underestimate OI impacts
- Negligible burst errors are observed within coherent systems

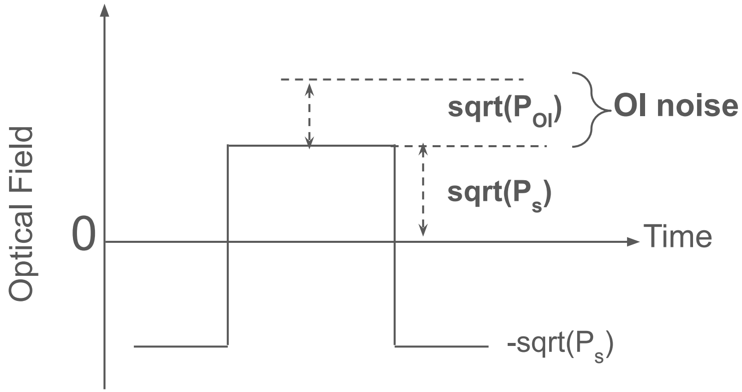
Why Coherent More Tolerant of Inband Interference ?

IM-DD PAM2



- Worst Rx (electrical) SNR due to OI
  - $\sim (1/4)(1-1/ER)^2(P_s/P_{OI})$

Coherent QPSK Inphase



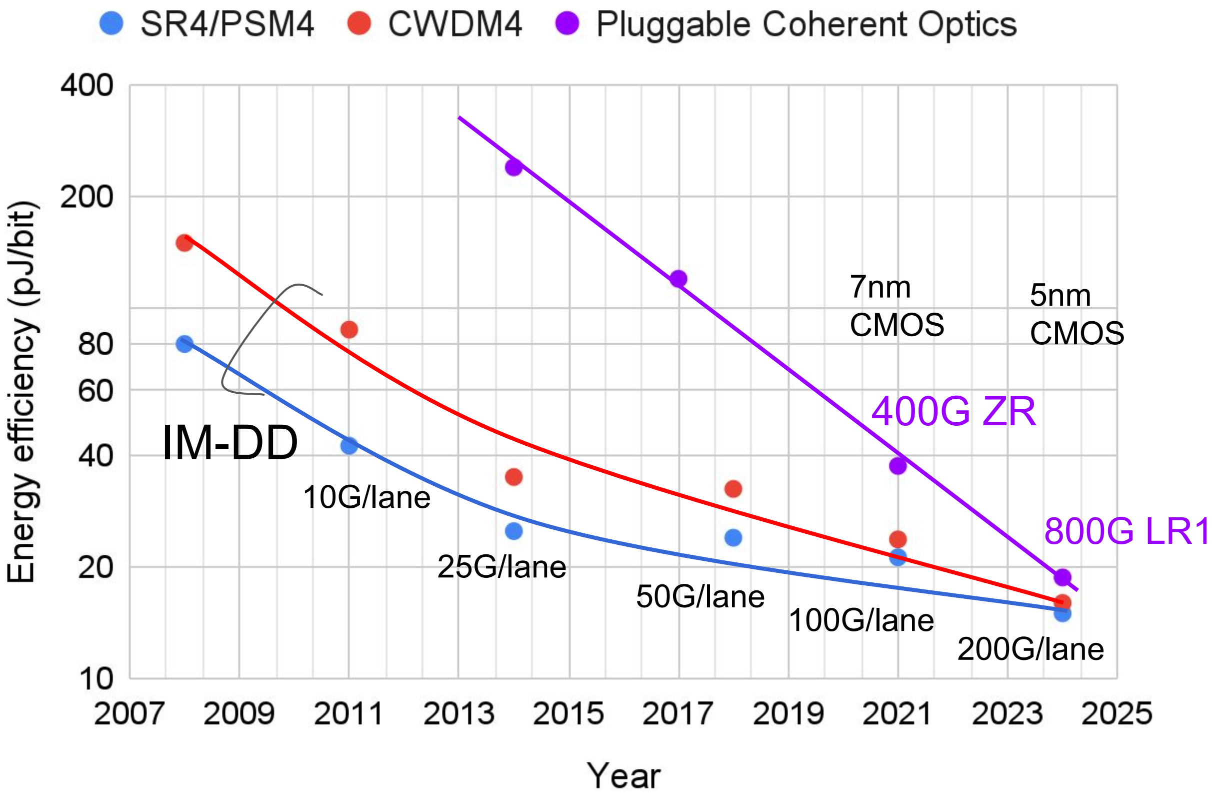
- Worst Rx (electrical) SNR due to OI
  - $\sim P_s/P_{OI}$

- Coherent detection reduces interfering noise by a factor of $\sim 4/(1-1/ER)^2$
  - 6 dB better than ideal IM-DD with infinite modulation extinction ratio (ER)

Challenges Facing Coherent for DC Uses

- Higher DSP power
  - Additional phase, polarization and timing/IQ skew control
  - Oversampling and fractional-spaced equalization
- Higher laser and modulator requirements
  - Lower phase noise and higher frequency stability
  - More efficient low-Vpi modulator to meet power/link budget
- Incompatible with pre-Gen IM-DD
  - Could be an issue for traditional heterogenous DC Clusters
  - Less a problem for Homogeneous ML ICI networks
- 4x higher breakout speed granularity
  - Limits certain breakout use cases that require finer speed granularity

Coherent vs IM-DD: Energy Efficiency Trend



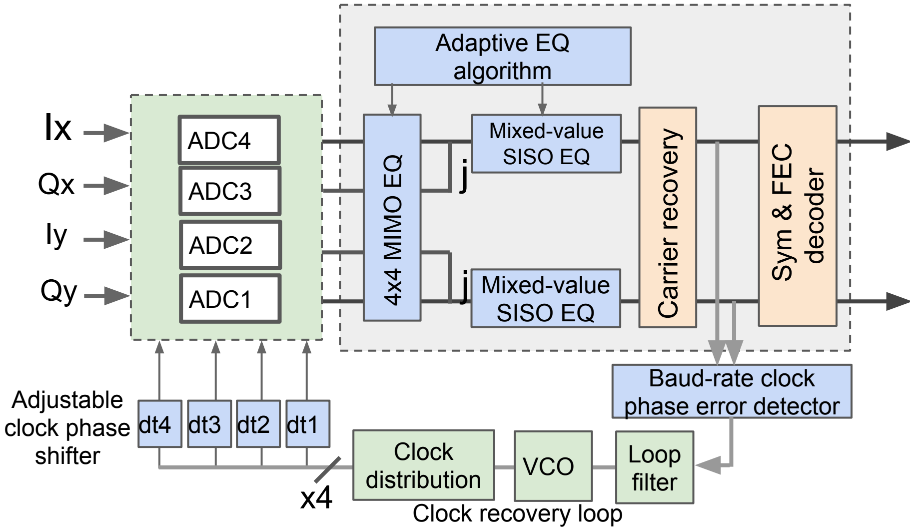
Gap between IM-DD and coherent is shrinking

- Optimizing coherent toward shorter reach (>1000km to ~100km)
- Coherent benefits more from CMOS advancement because more DSP required for coherent

Can Coherent DSP Power Approach IM-DD ?

- Remove independent CD compensation
  - Optimize toward <10km reach
  - C-band to O-band wavelength
    - |CD| <30ps/nm over 1291 to 1337 nm
- Separate polarization recovery from bandwidth (BW) equalization
  - A single- or few-tap 4x4 real-valued MIMO for joint polarization recovery, I/Q skew correction, and partial CD/BW equalization
  - Mixed-valued FFE for residual CD and bandwidth equalization
    - Complex-valued coefficients for CD+BW
    - Real-valued coefficients for BW only
- Develop lower-power baud-rate sampling and equalization technology

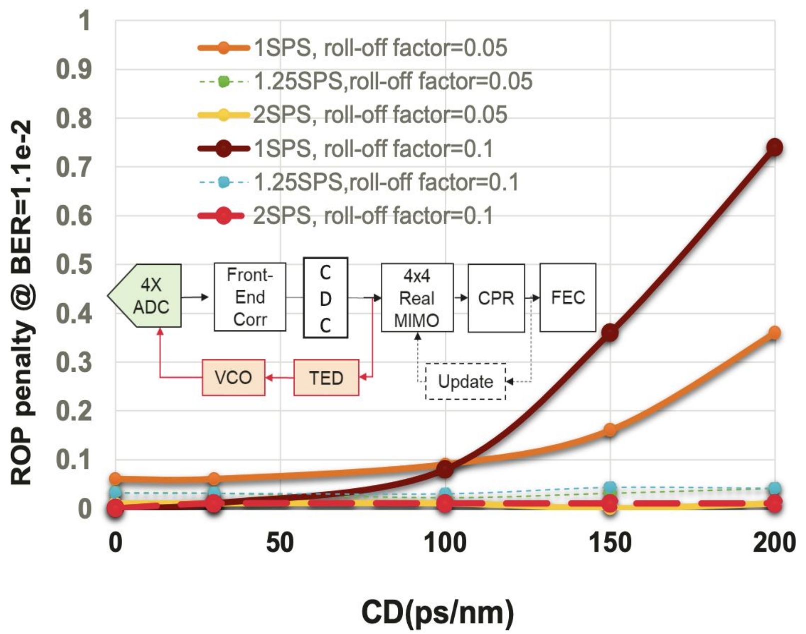
A low-power baud-rate coherent DSP architecture for <10km DC reach



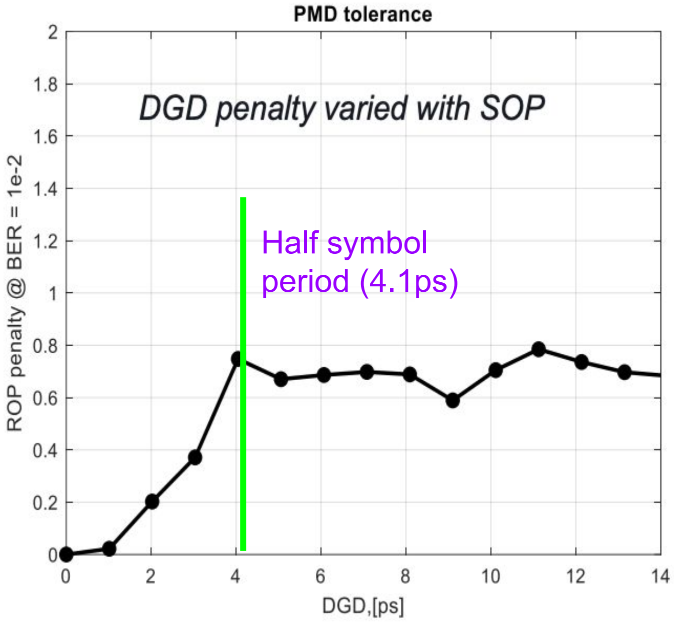
Details refer to Xiang Zhou et al, '[Beyond 1 Tb/s Intra-Data Center Interconnect Technology: IM-DD OR Coherent?]' JLT 2019.

Baud-Rate Sampling and Equalization Technology

CD and PMD Tolerance (122Gbaud PM-16QAM simulation results)



T. Gui et al, [Feasibility Study on Baud-Rate Sampling and Equalization (BRSE) for 800G-LR1](), 2023



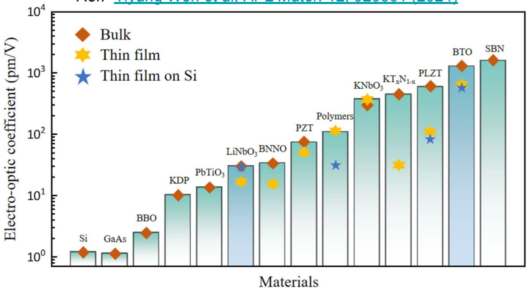
Or Vidal, IEEE802.3dj, [Updated PMD tolerance with synchronous Baud Rate Sampling and Equalization (BRSE) for 800GLR1](), 2023

Advancement in High-Efficient Modulator Technology

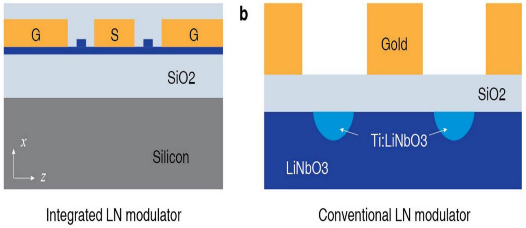
- **Thin-film LiNbO3 modulators**
  - >10x higher EO coefficient than Si
  - LN-on-insulator thin-film LN enable high-contrast waveguide with string optical confinements,overcoming voltage-BW-size trade-off of bulk LN
  - Simultaneous high bandwidth, low IL and low Vpi achievable
  - >100GHz BW, <2.4 V-cm Vpi and ~0.5dB/cm IL demonstrated
  - Single-ended drive so far, differential drive under development
  - Wafer-scale TFLN production
    - Not fully integrated into SiPh platforms

- **Thin-Film BTO modulators**
  - > 200x larger EO coefficient than Si
    - More compact than SiP and TFLN
  - Compatible with wafer-scale SiPh process
    - Feasibility of integration with a Si substrate and low loss hybrid BTO-Si passive elements
  - BTO used for both high speed and DC bias phase tuning
    - <1mW Ulta-low biasing power
  - BTO MZMs integrated on SiP platform demonstrated
    - VπL =4.8 Vmm; IL=1 dB/mm; 6dB BW ~45GHz
    - Biasing tuning power (~100 μW)
  - High dielectric constants make impedance matching more challenging

Ref: *Yiyang Wen et al. APL Mater. 12, 020601 (2024)*

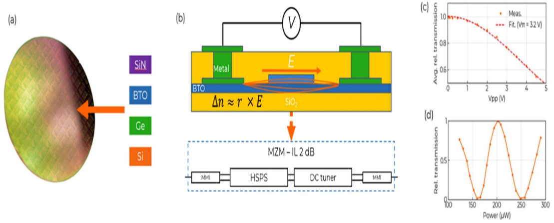


TFLN vs Bulk LN



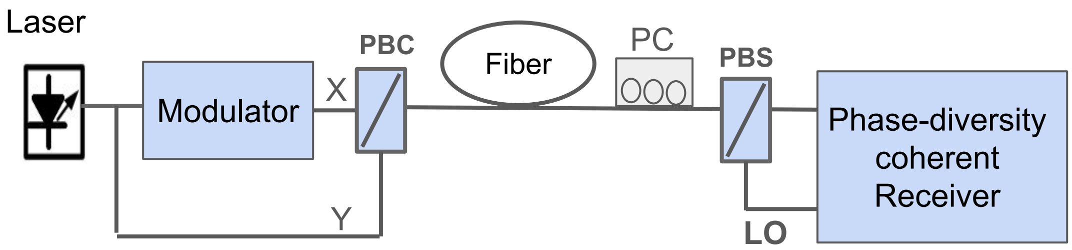
Ref: C. Wang *et al.*, Nature 2018

BTP on SiP



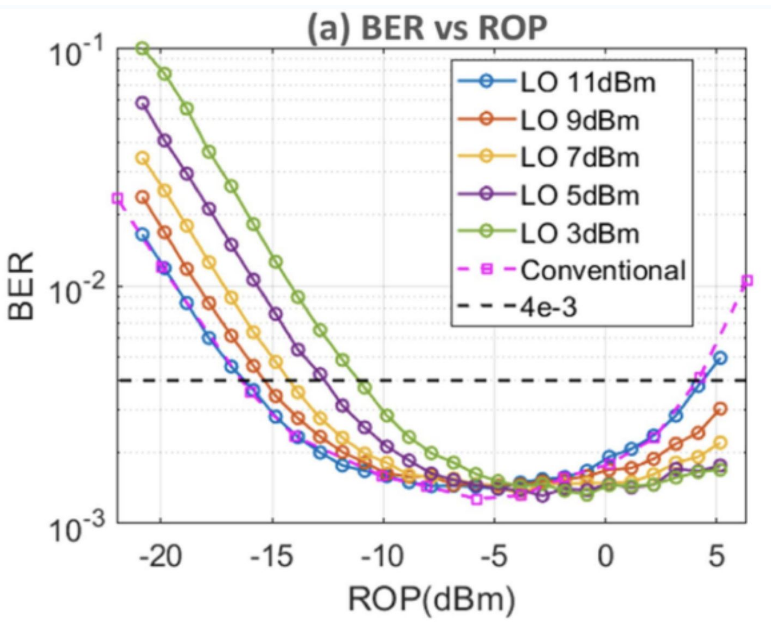
Ref: W. Li et al, JLT 2024

Reduce Laser Requirements: Self-Coherent Technology



- Advantages
  - Substantially reduce laser phase noise and frequency stability requirements
- Disadvantages
  - LO experiences the same link loss as the signal, degrading the fundamental receiver sensitivity advantage of coherent detection
    - 8dB lower LO ⇨ ~5dB less link loss budget
  - Require optical polarization recovery
    - Additional optical loss
- Other self-coherent techniques such as Stokes or KK receivers face similar link loss budget challenges for typical unamplified DC use cases

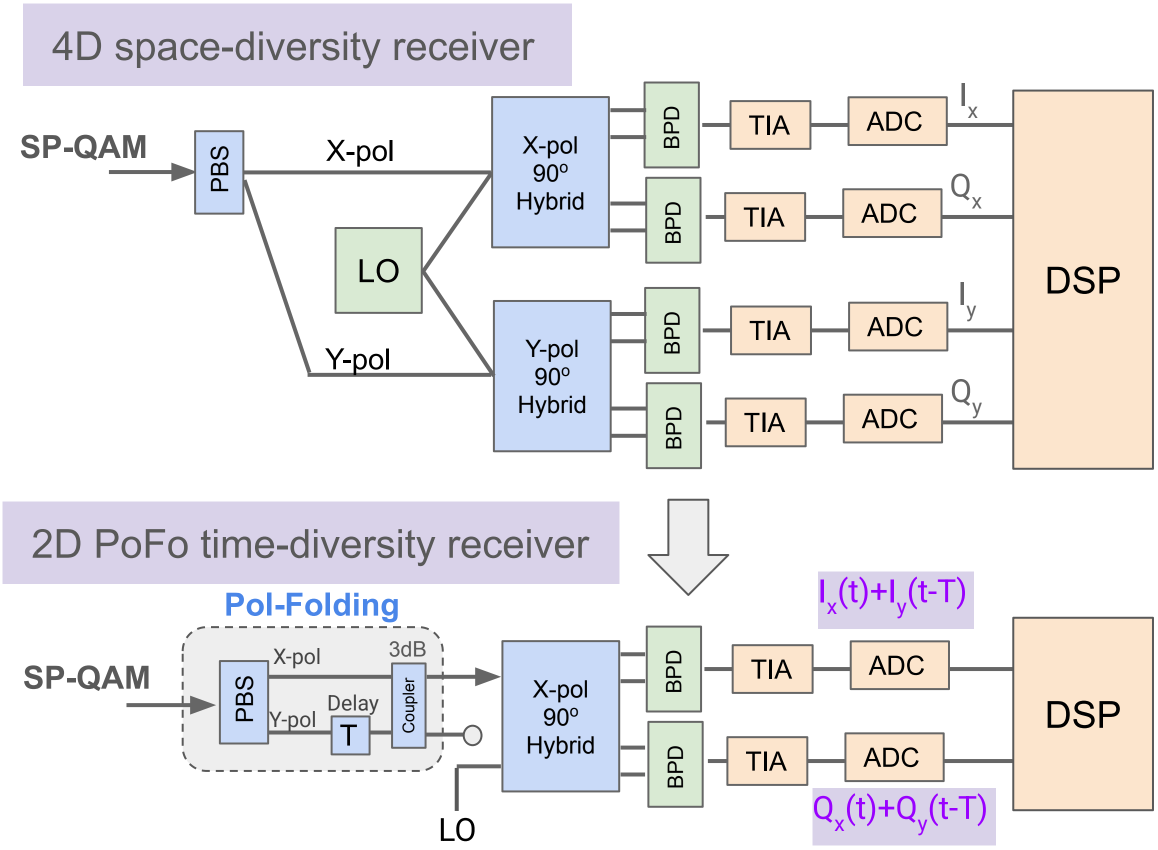
120Gbaud PM-16QAM Experiments



Source: R. Zhang et al, JLT 2023, "800G/λ Self-Homodyne Coherent Links with Simplified DSP for Next-Gen Intra-data centers"

Pol.-Folding (PoFo) Time-Diversity Coherent Technology

Improve components and power efficiency for single-pol. modulations

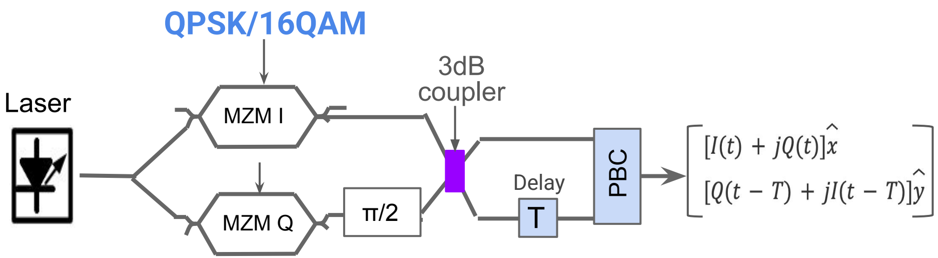


- **PoFo Time-Diversity Technology**
  - Detect the received X- and Y-pol. components at different time slots and then use a 1-tap MLSE to recovery the pol. in the digital domain
  - PoFo Time Diversity is realized by folding one polarization component into another, while introducing a time delay between them
  - Enables detection of single pol. modulation with half the optical and analog electrical components.
  - Source: Xiang Zhou, US 11689292 (2023), more details are to be published

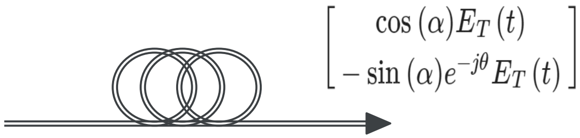
Pol.-Folding (PoFo) Time-Diversity Coherent Technology

An Improved Design

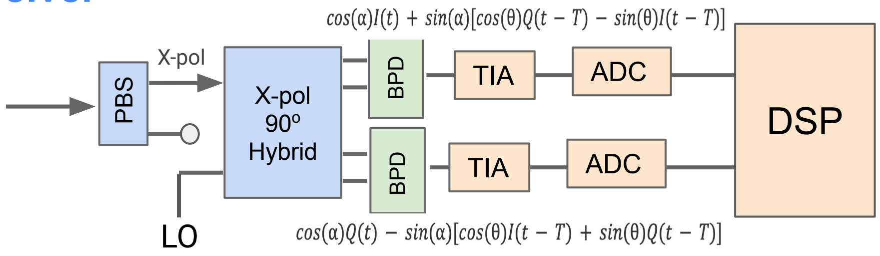
Transmitter



Tran. fiber

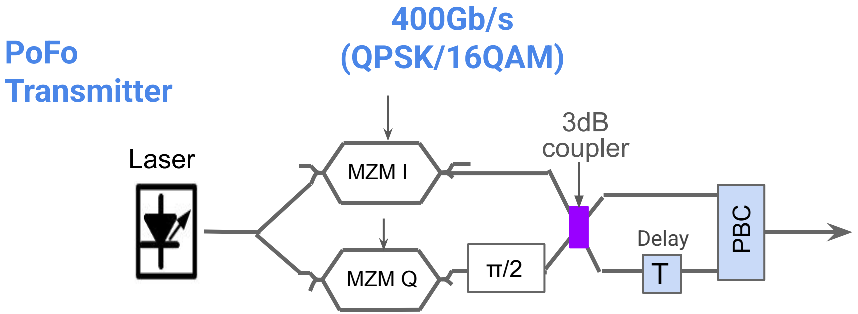


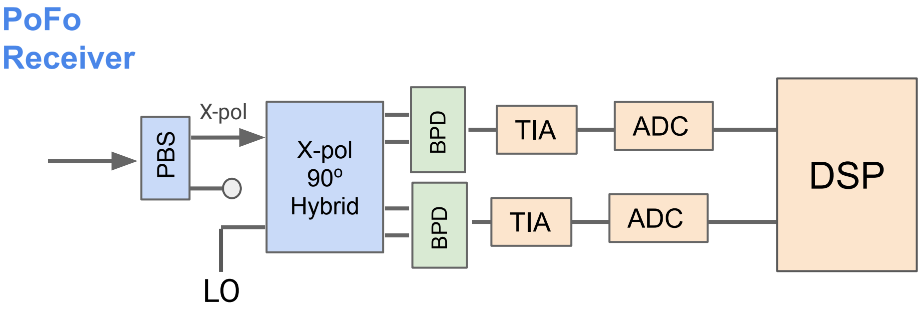
Receiver

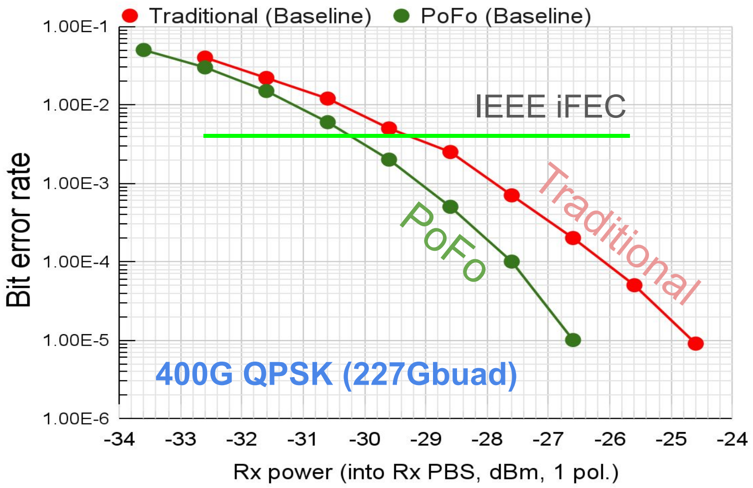


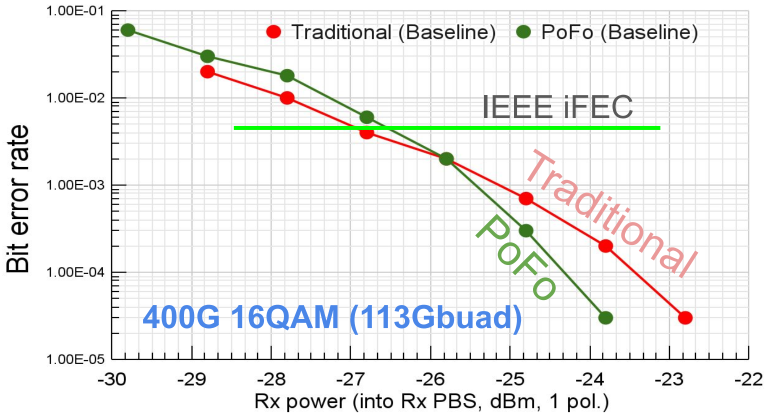
- 3dB link budget gain by a joint Tx and Rx PoFo Time-Diversity design
  - The transmitter transmits a redundant, T-delayed copy of the signal through orthogonal polarization, leveraging the signal disregarded by the I/Q combiner
  - The receiver uses a PBS to select a single polarization (X-pol.) component for phase-diversity detection
  - The selected single polarization component consists of both the original X-polarized and the delayed Y-polarized component

Performance of PoFo Time-Diversity Coherent Technology



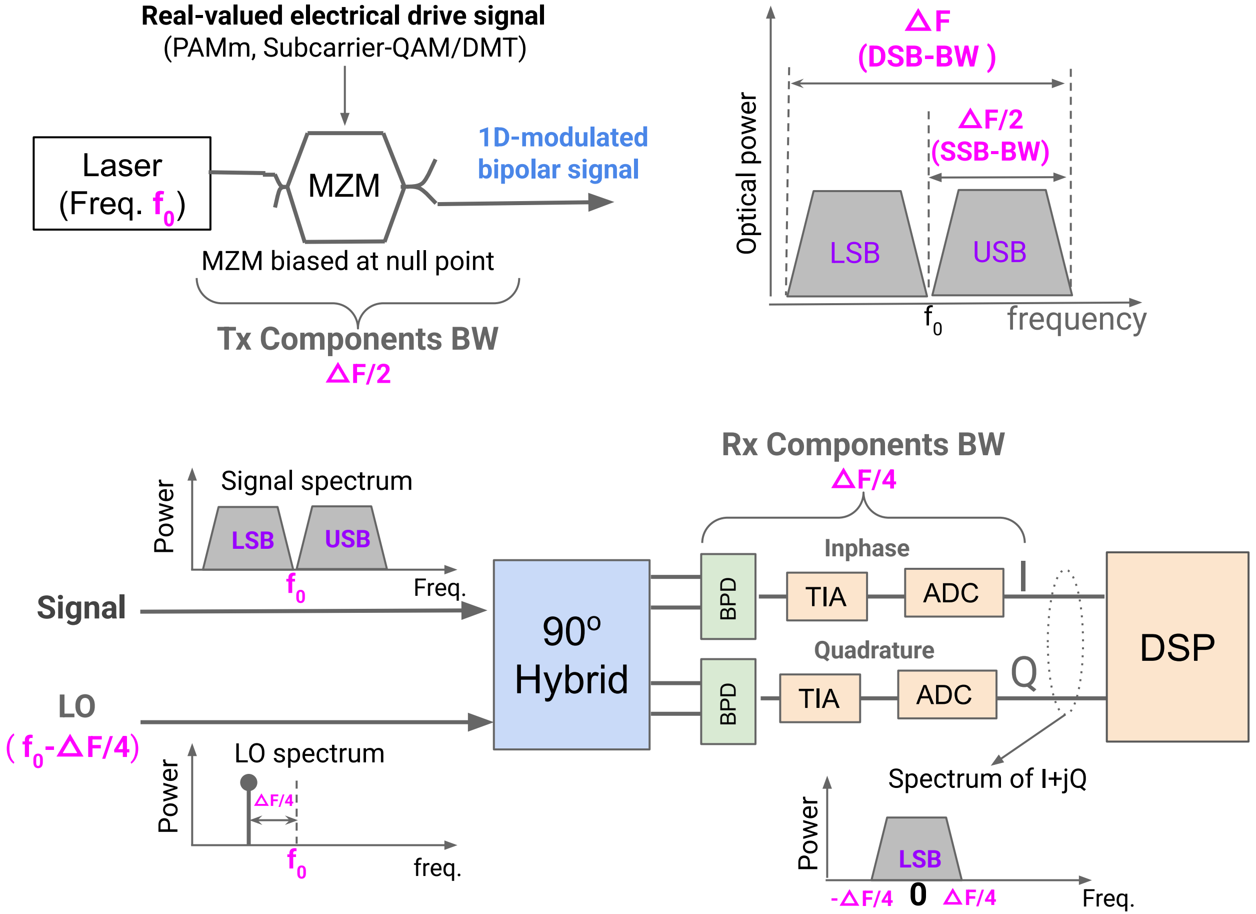






- For SP-QPSK and 16QAM, new PoFo coherent technology can achieve performance comparable to (or better than) traditional 4D coherent detection

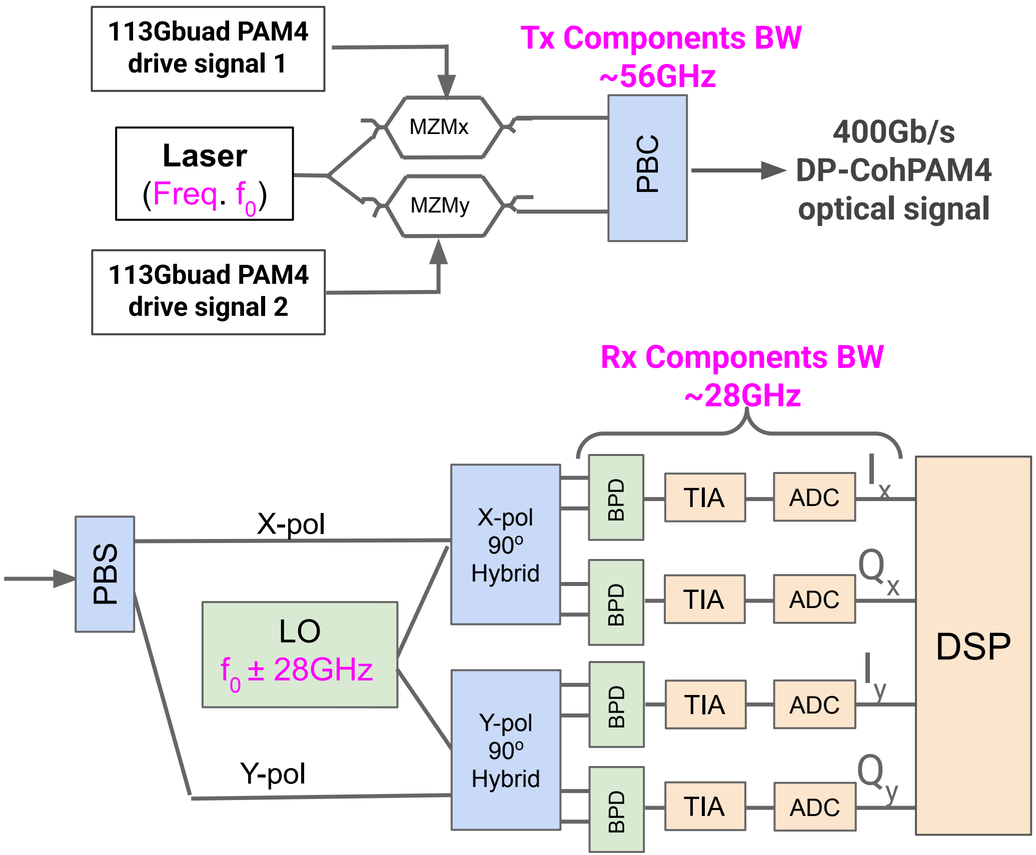
Single Sideband (SSB) Coherent Detection Technology



- SSB coherent detection for (1D) amplitude-modulated bipolar optical signals
  - Coherent PAMm
  - Subcarrier-QAM/DMT
- Offset the LO frequency by about one-half of the Nyquist bandwidth
- Reduce Rx front-end analog bandwidth (BW) by half
  - PDs, TIAs and ADCs
  - Lower power consumption
- Detected signal power is reduced by half, but the resulting Rx sensitivity penalty can be mitigated by improved PD responsivity and lower TIA noise, due to the lower bandwidth requirements
- More details are to be published

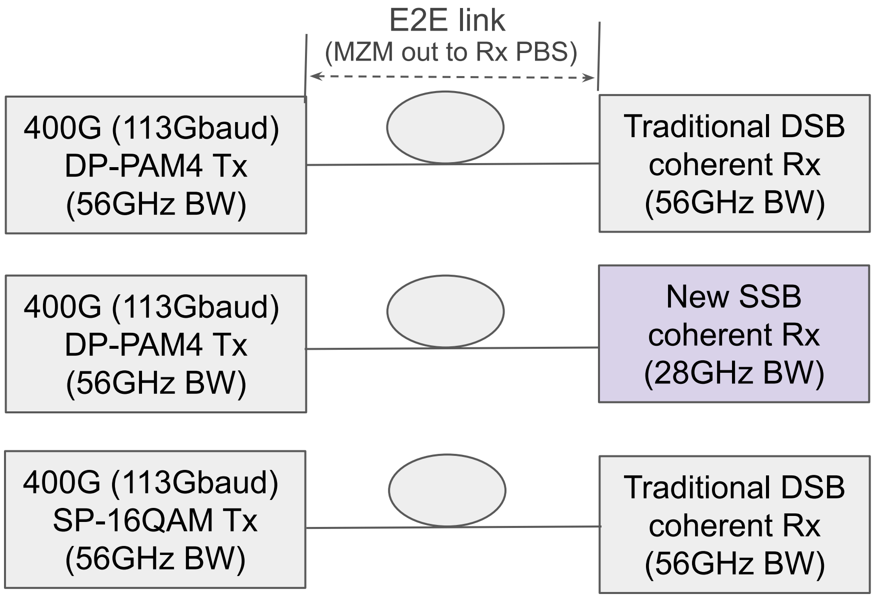
Single Sideband (SSB) Coherent Detection Technology

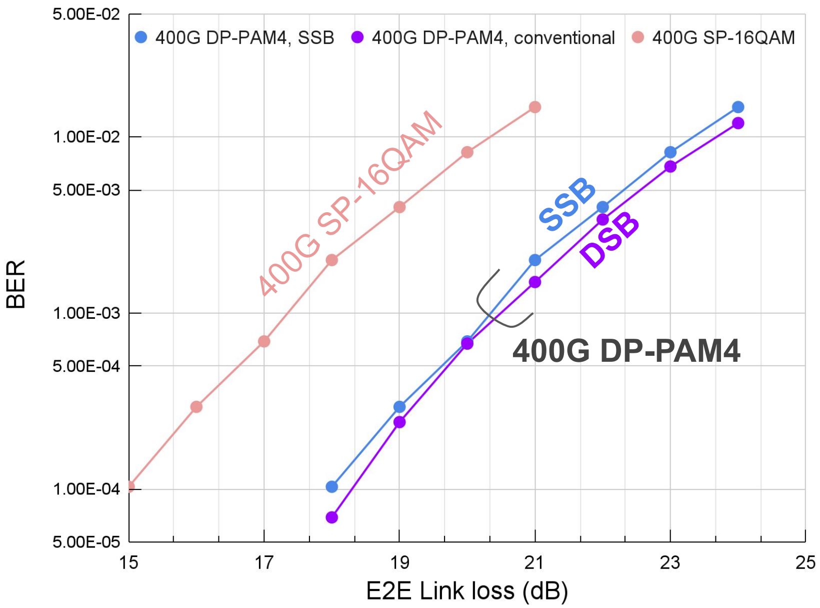
One exemplary use case



- **400G dual pol. (DP) PAM4 with SSB coherent detection**
  - Reduce Tx modulator and driver counts by half compared to traditional 400G DP-16QAM
  - Reduce coherent receiver front-end analog bandwidth and power consumption by half compared to traditional 4D coherent detection

Performance of SSB Coherent Detection Technology





Simulation assumptions

- Laser power: 15dBm, 3/4 for signal, 1/4 for LO
- MZM: 1Vpi drive swing; 4dB IL
- PD responsivity: 0.6@56GHz, 0.7@28GHz
- TIA: IRA=22pA/√Hz@56GHz; 17pA/√Hz @28GHz
- Tx pulse: Raised-Cosine with roll-off =0.7
- Rx Filter: Ideal low pass filter
  - 57GHz BW for DSB; 28.5GHz BW for SSB detection

- 400G DP-PAM4 with SSB detection can support
  - similar link budget as the conventional double sideband coherent detection technique
  - ~3dB higher link budget than 400G SP-16QAM

Conclusions

- Datacenter optical interconnect requirements continue to evolve
  - Higher per fiber capacity, low latency and high reliability more critical for homogeneous ML networks (ML ICI, dedicated ML clusters)
  - Lower cost per bit, backward interoperability and fan-out speed granularity matters more for general heterogeneous DC Clusters
- IM-DD faces significant reach and link budget scaling challenges beyond 200G lane
- Coherent optics potentially supports longer reach and a larger link budget, but it needs to close the power and cost gap
- Short reach (<10km) optimized coherent DSP and more efficient modulator technology are critical to bring coherent to DC
- Innovative coherent technology enabling finer per wavelength speed granularity without sacrificing components and power efficiency desirable for heterogeneous DC networks