# Data Center Links Beyond 100 Gb/s per Wavelength

**Joseph M. Kahn, Jose Krause Perin and Anujit Shastri**

Department of Electrical Engineering
E. L. Ginzton Laboratory
Stanford University

ee.stanford.edu/~jmk

OFC • March 12, 2020 • San Diego

## Abstract

- We review intra- and inter-data center link options, including those based on direct detection, digital or analog coherent detection, Stokes vector detection or Kramers-Kronig detection, comparing them in terms of spectral efficiency, optical power efficiency, complexity and power consumption.

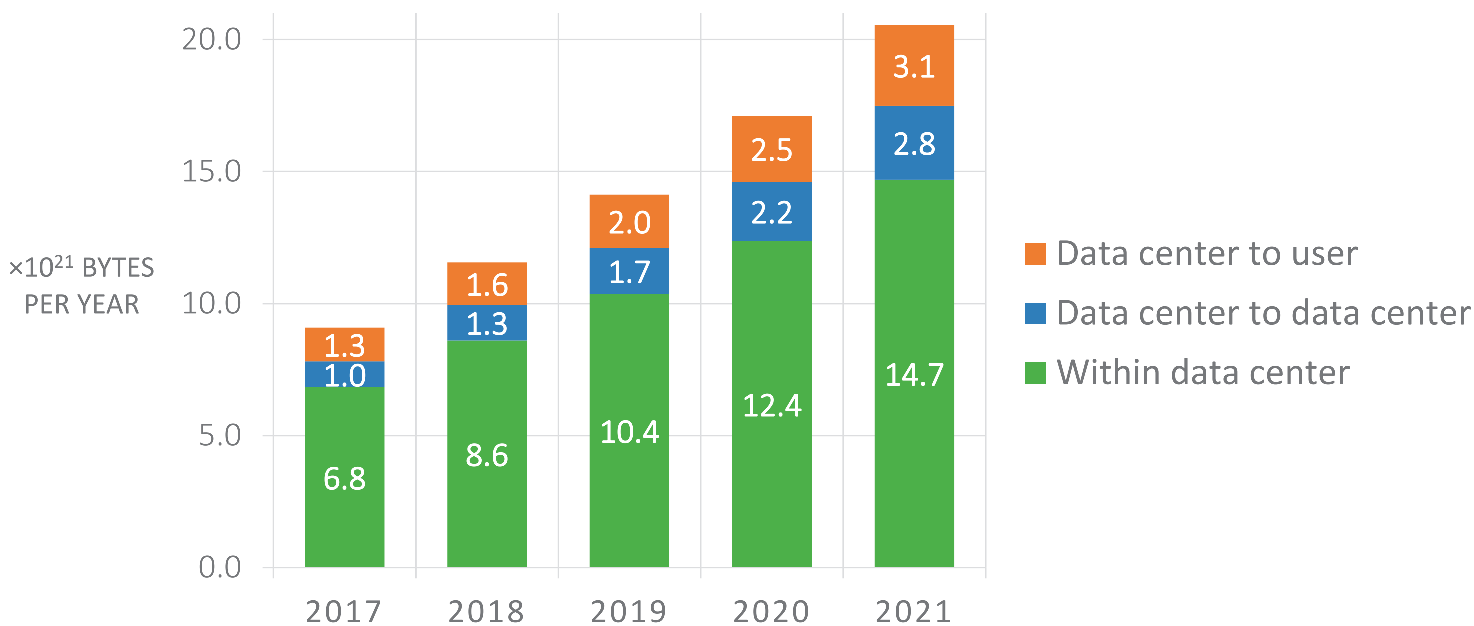
# Acknowledgments

We gratefully acknowledge the support of

- Maxim Integrated
- Google
- National Science Foundation ECCS-1740291



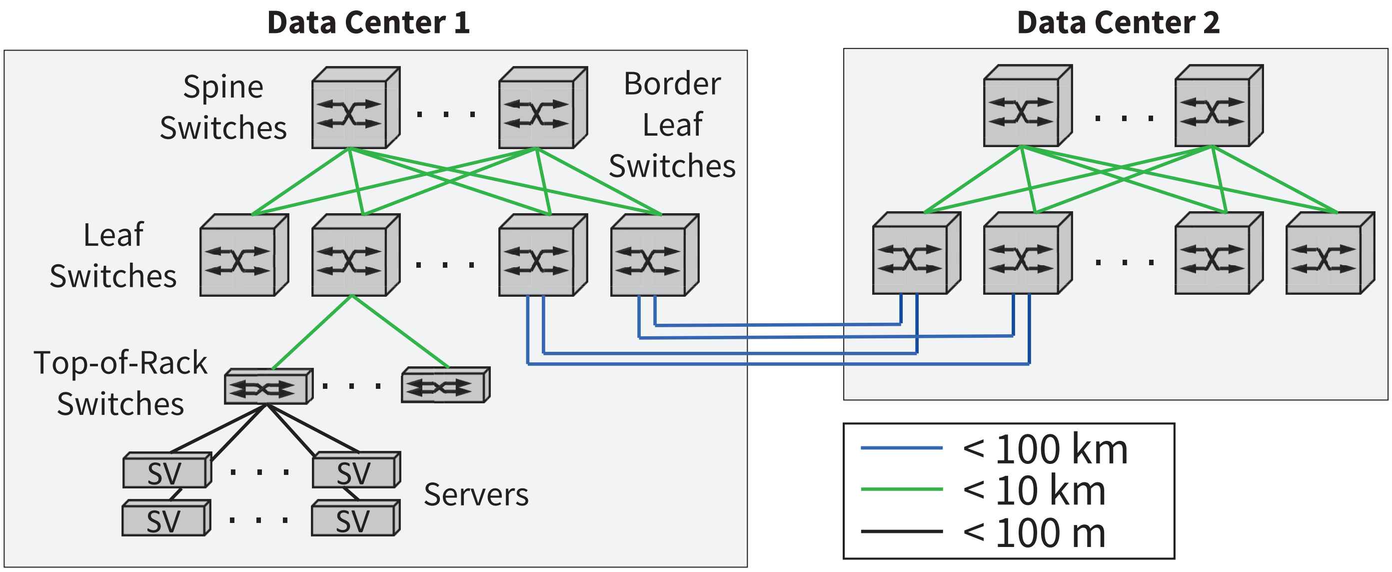
# Internet traffic growth




Source: Cisco forecast, 2016-2021

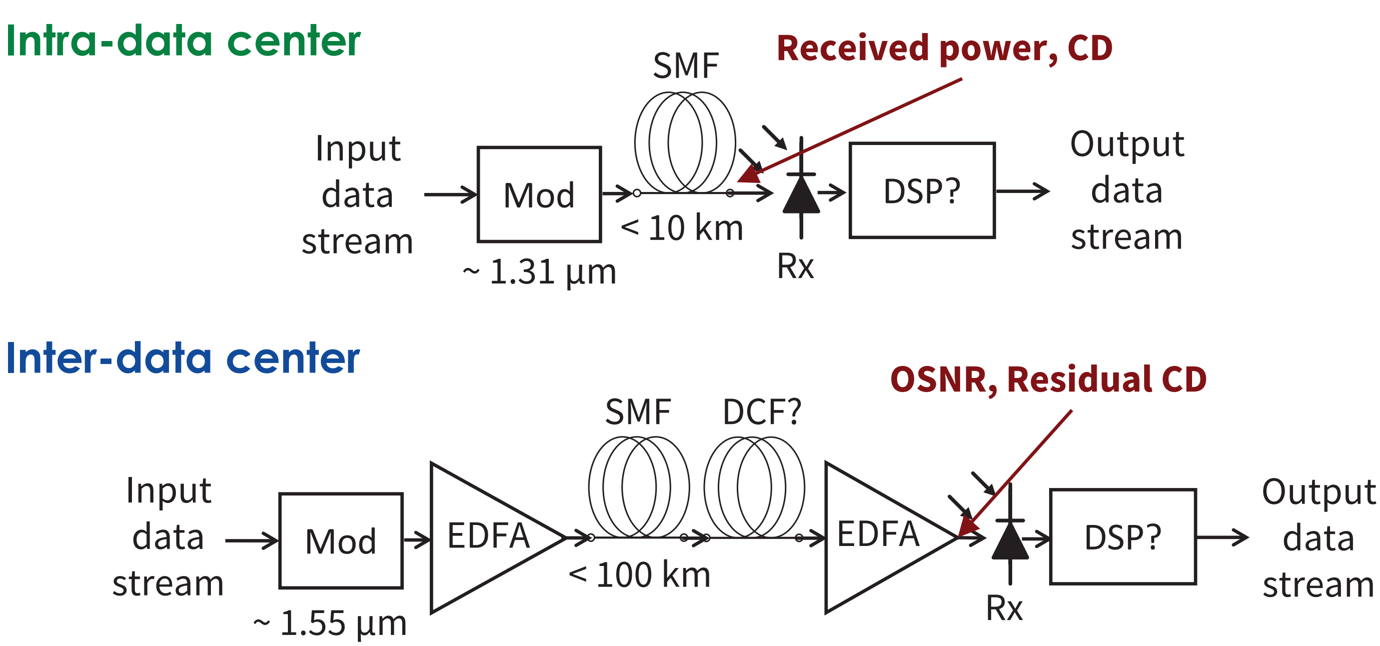
## Data center links

Example of two-tier topology

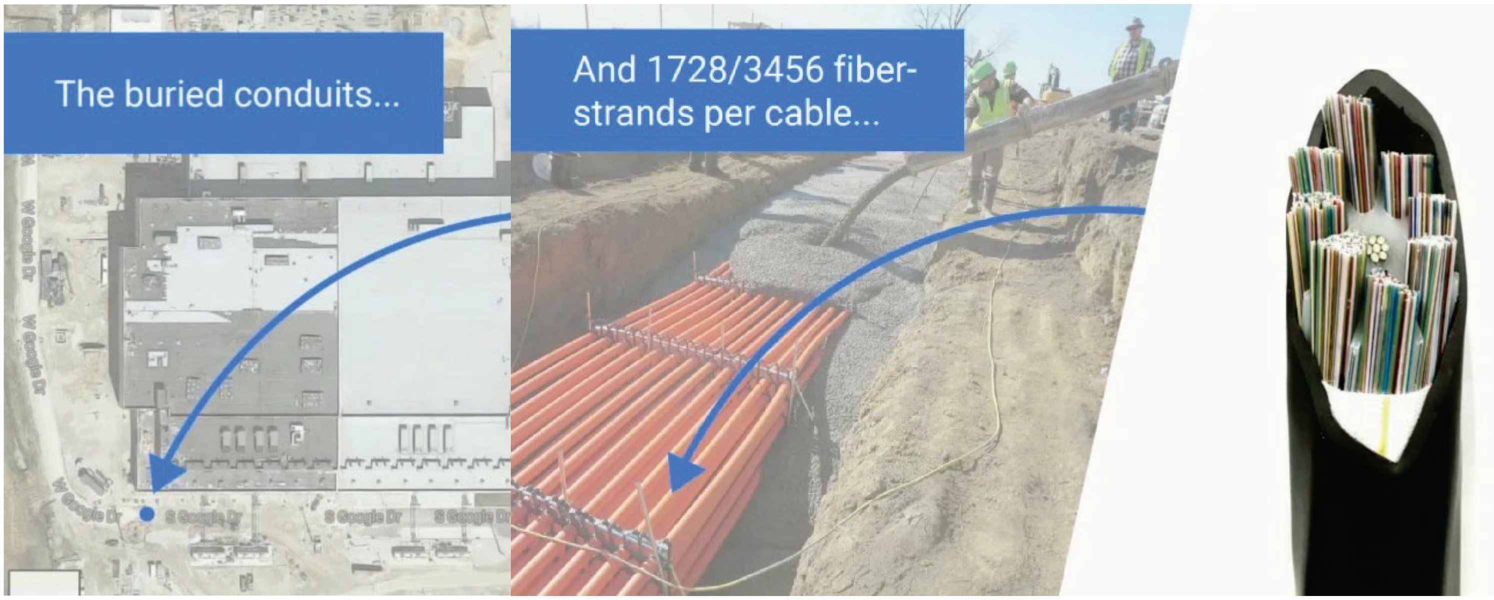





## Intra- vs. inter-data center links



# Example from a Google data center




Images:Urs Hoelzle, OFC 2017 plenary talk



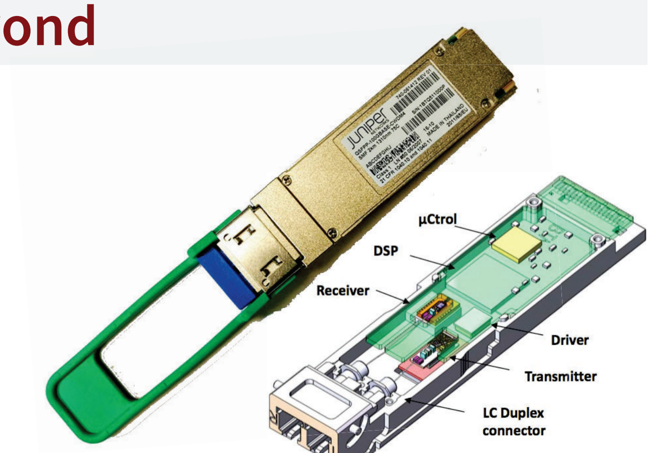
# Co-packaged optics: scaling density

- Current transceivers are pluggable.
  - Requires SERDES, electrical path from switch ASIC to front plate module.
- Co-packaging allows optical interconnects to be placed close to the switch ASIC, possibly via an interposer.
  - Significantly reduces power consumption.
  - More heat near optics, may require lasers to be placed further away.
- Key to meeting density and power consumption requirements for 25.6 Tb/s and 51.2 Tb/s switch fabrics.

Image: Luxtera

## 100 Gbit/s per wavelength and beyond

- IEEE has adopted 4-PAM for 400 Gbit/s links:
  - 4 ×100 Gbit/s 4-PAM
  - 8 ×50 Gbit/s 4-PAM
- Need improved receiver sensitivity:
  - Avalanche photodiodes
  - Semiconductor optical amplifiers
- Need still higher sensitivity to accommodate: higher fiber losses, more wavelengths, and possibly optical switching.
- Difficult to increase bit rate beyond 100 Gbit/s per laser using intensity modulation and direct detection.
- **Must exploit more degrees of freedom.**



Images: Juniper Networks and Oclaro



## 400 Gbit/s: intra- and inter-data center ports converge

- Intra-data center ports
  - 400 Gbit/s-DR4 (500 m), -FR4 (2 km) and -LR4 (10 km) can bring 4 × 100 Gbit/s 4-PAM in QSFP-DD form factor (~7 W).
- Inter-data center ports
  - 400 Gbit/s-ZR (100 km) can bring 400 Gbit/s 16-QAM over a single wavelength in QSFP-DD form factor (~15 W).
- 7 nm CMOS key enabler to bringing DSP power consumption down.
- 5 nm or 3 nm CMOS may allow doubling baud rates, enabling 800 Gbit/s.
  - Significantly higher development costs.
  - Extremely challenging to scale further by increasing baud rates.

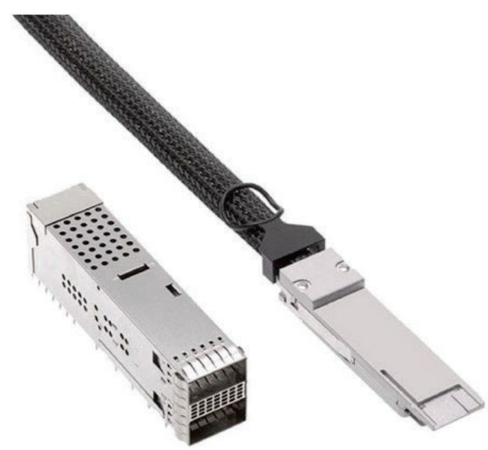


Image: qsfpdd.com

# Outline

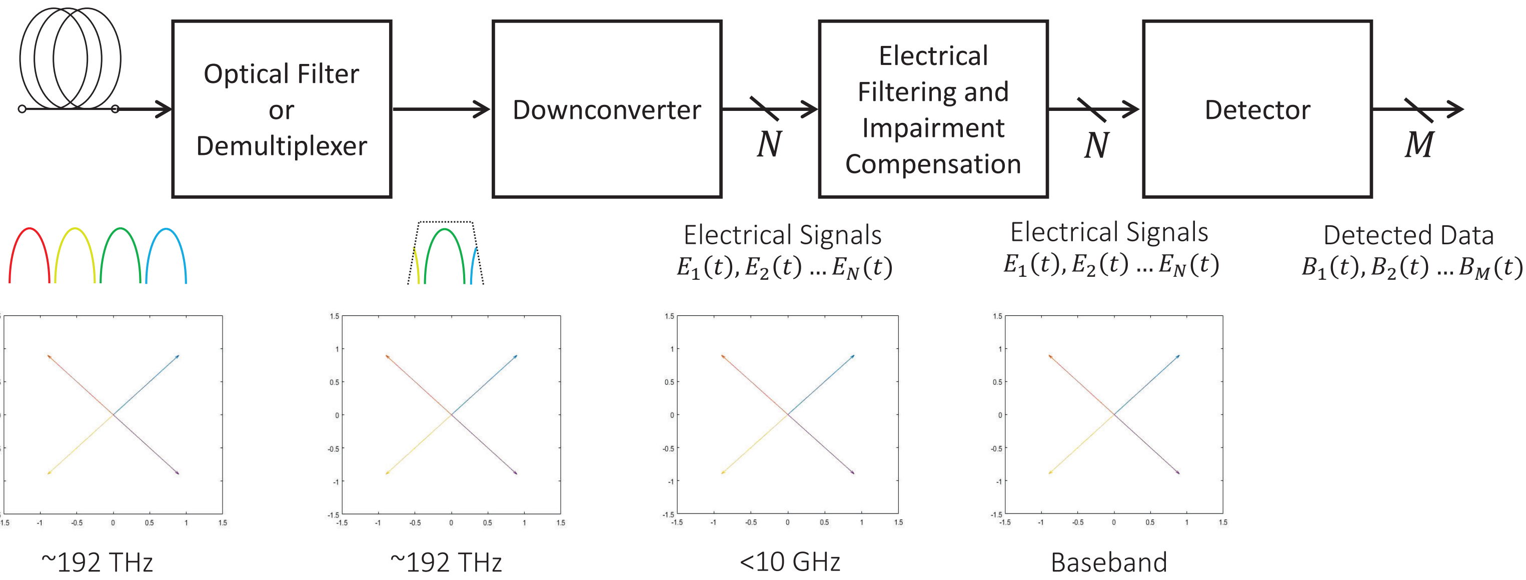
- Optical receiver functions
- Detection methods
- Methods compatible with direct detection
  - M-PAM
  - SSB-OFDM
  - Kramers-Kronig
  - Stokes
- DSP-based vs. DSP-free coherent detection
- Power consumption considerations
- Conclusions



# Outline

- Optical receiver functions
- Detection methods
- Methods compatible with direct detection
  - M-PAM
  - SSB-OFDM
  - Kramers-Kronig
  - Stokes
- DSP-based vs. DSP-free coherent detection
- Power consumption considerations
- Conclusions

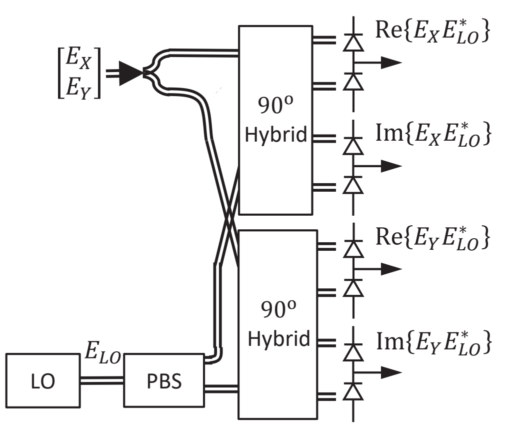
# Optical receiver functions





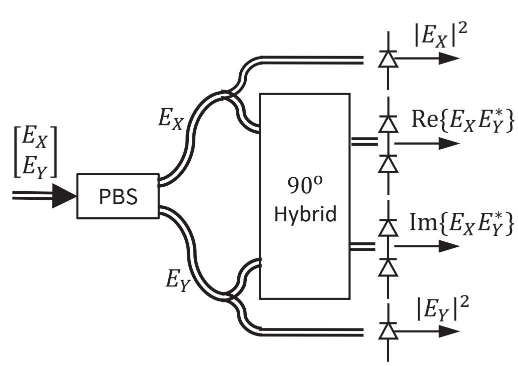

# Downconversion

**Dual-polarization homodyne downconverter**



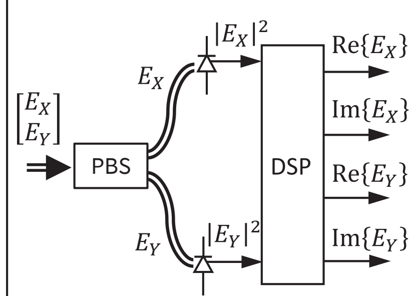

- Signal is amplified by strong LO.
- Uses all four signal dimensions efficiently.
- Enables electronic CD/PMD compensation.
- May select desired channel by electric filtering after downconversion.

**Stokes vector downconverter**




- No LO gain.
- Uses three signal dimensions (different architecture can use four).
- To compensate for CD/PMD, unmodulated carrier must be transmitted.
- Must select desired channel by optical filtering before downconversion.

**Kramers-Kronig downconverter**




- No LO gain.
- Uses all four dimensions, but less efficiently.
- To compensate for CD/PMD, unmodulated carrier must be transmitted.
- Must select desired channel by optical filtering before downconversion.

# Outline

- Optical receiver functions
- Detection methods
- Methods compatible with direct detection
  - M-PAM
  - SSB-OFDM
  - Kramers-Kronig
  - Stokes
- DSP-based vs. DSP-free coherent detection
- Power consumption considerations
- Conclusions



# Detection methods

| | | **Noncoherent**<br>Measures energy in signal dimension | **Differentially Coherent**<br>Measures phase difference between signal dimensions | **Noncoherent & Diff. Coherent Hybrid** | **Coherent**<br>Measures field quadratures in signal dimensions |
|---|---|---|---|---|---|
| **Using LO** | **Typical embodiments** | **Envelope detector**<br>e.g., OOK, M-PAM, OFDM | **Delay and multiply**<br>e.g., M-DPSK | **PolSK detector**<br>e.g., M-PolSK | **Synchronous detector**<br>e.g., M-QAM, OFDM |
| | **Pros** | • CD comp. by linear filtering.<br>• Amplification by strong LO. | • CD comp. by linear filtering.<br>• Amplification by strong LO. | • Uses all signal dims. (but less efficiently).<br>• CD comp. by linear filtering.<br>• Amplification by strong LO. | • Uses all signal dims. efficiently.<br>• CD comp. by linear filtering.<br>• Amplification by strong LO. |
| | **Cons** | • Uses just one signal dim.<br>• Complex optics (hybrid & LO). | • Inherent penalty of diff. det.<br>• Complex optics (hybrid & LO). | • Complex optics (hybrid & LO). | • Complex optics (hybrid & LO). |
| **Not using LO** | **Typical embodiments** | **Direct detection**<br>e.g., OOK, M-PAM, OFDM | **Delay interferometer + direct detection** | **Stokes receiver** | **Kramers-Kronig receiver** |
| | **Pros** | • Doesn't require unmodulated carrier.<br>• Simple optics (photodiodes). | • Doesn't require unmodulated carrier. | • Uses all signal dims. (but less efficiently). | • Uses all signal dims. (but less efficiently).<br>• Simple optics (photodiodes). |
| | **Cons** | • Uses just one signal dim.<br>• No amplification by LO.<br>• No CD compensation. | • No amplification by LO.<br>• No CD compensation. | • No amplification by LO.<br>• Complex optics (hybrid).<br>• Requires unmodulated carrier for CD comp. | • No amplification by LO.<br>• High-complexity DSP.<br>• Requires unmodulated carrier for CD comp. |

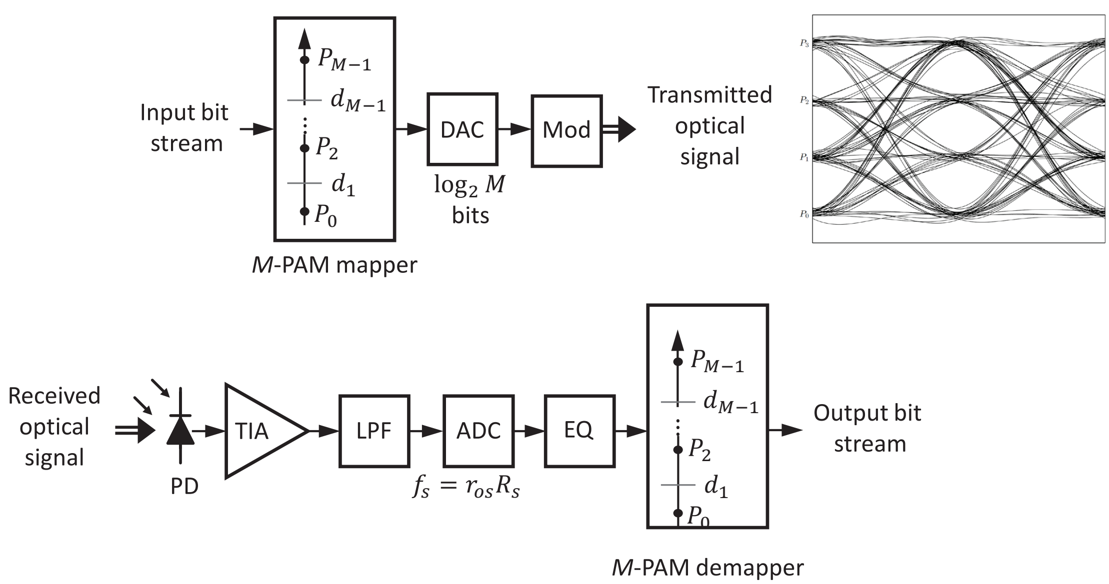
# Outline

- Optical receiver functions
- Detection methods
- Methods compatible with direct detection
  - M-PAM
  - SSB-OFDM
  - Kramers-Kronig
  - Stokes
- DSP-based vs. DSP-free coherent detection
- Power consumption considerations
- Conclusions



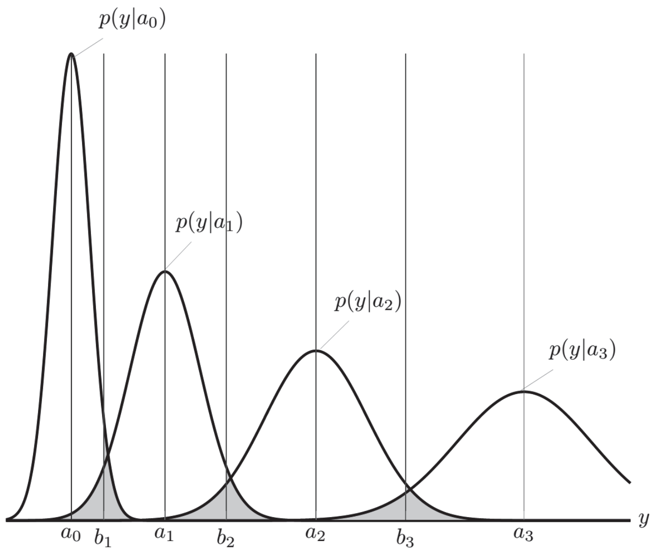
# M-PAM

- Information is encoded in intensity levels.
- Level spacing may be optimized when noise is signal-dependent.



# M-PAM

- Should optimize level spacing and thresholds for signal-dependent noise (APD, SOAs).




$$\xi = Q^{-1}\left(\frac{M\log_2 M \cdot BER_{target}}{2(M-1)}\right)$$

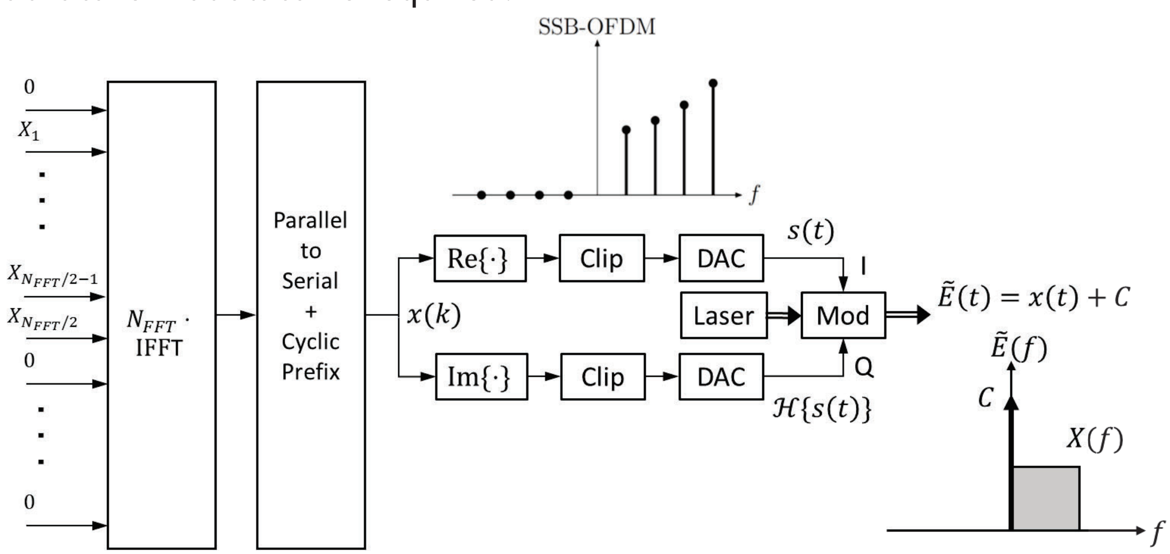
$$a_k = a_{k-1} + \frac{\xi}{GR}(\sigma_k + \sigma_{k-1})$$

K.-P. Ho and J. M. Kahn, U.S. Patent 6,690,894, February 10, 2004.



# SSB-OFDM

- Transmitted baseband signal is complex.
- A dual-quadrature modulator is required.



## SSB-OFDM

- After fiber propagation, amplification, and direct detection:

$$r(t) \approx \underbrace{\boxed{s(t) * g(t)}}_{\text{Signal}} + \underbrace{\boxed{\frac{1}{\text{CSR}}|x(t) * h(t)|^2}}_{\text{Interference}} + \underbrace{\boxed{\text{CSR} \cdot n(t)}}_{\text{Noise}}$$

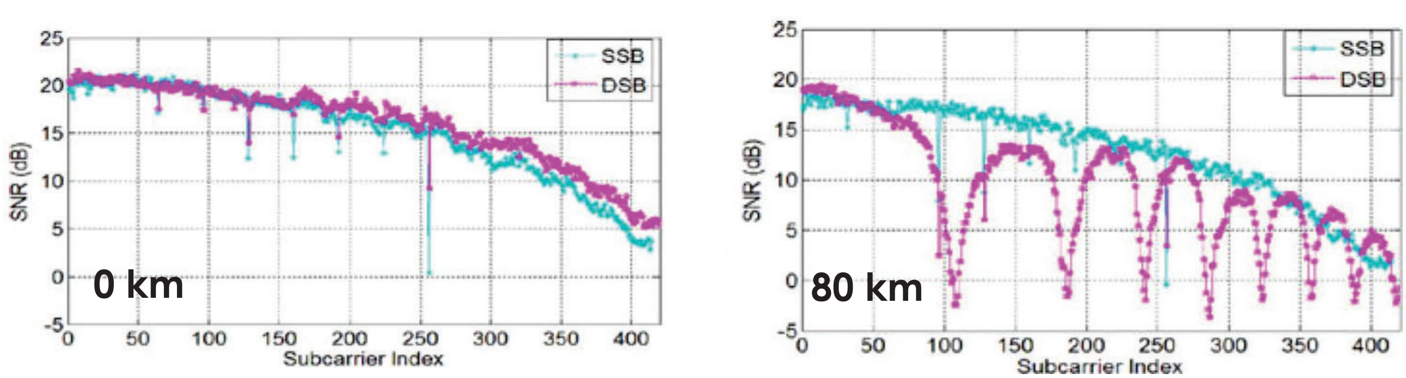
  - CSR = carrier-to-signal ratio
  - $\mathcal{F}\{h(t)\} = \exp(-j\beta_2\omega^2 L/2)$
  - $g(t)$ is the Hermitian-symmetric version of $h(t)$

- There is no amplitude distortion, but there is significant interference.
- Many techniques have been proposed for interference cancellation, including Kramers-Kronig detection.



## SSB-OFDM

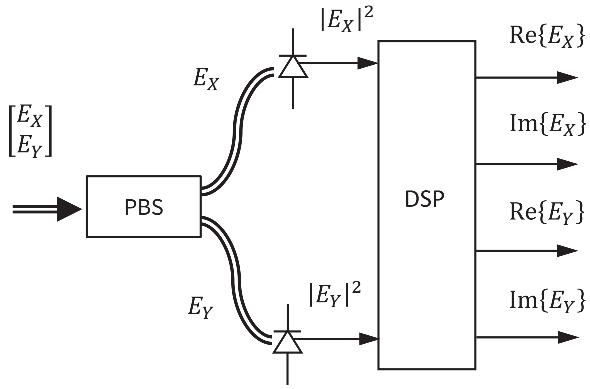
- Pros:
  - SSB-OFDM doesn't experience power fading caused by chromatic dispersion.
- Cons:
  - Unmodulated carrier is transmitted, impairing power efficiency.
  - Signal-signal interference must be cancelled.




L. Zhang, T. Zuo, Y. Mao, Q. Zhang, E. Zhou, G.N. Liu, X. Xu, Beyond 100-Gb/s Transmission Over 80-km SMF Using Direct-Detection SSB-DMT at C-Band, J. Lightw. Technol. 34 (2016) 723–729.

# Kramers-Kronig receiver

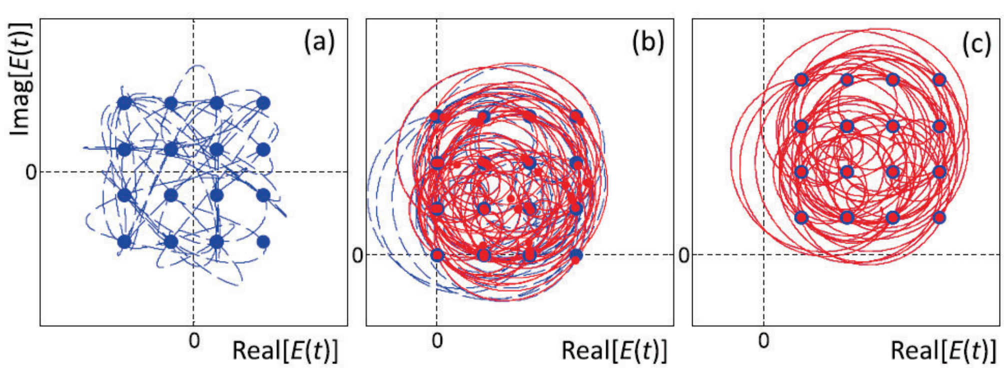
- After direct detection, electric fields quadrature information can be recovered by DSP if signal obeys the **minimum-phase condition.**






# Kramers-Kronig receiver

- To satisfy the minimum-phase condition, the time trajectory of the signal, as shown in the figure, cannot encircle the origin.
- This condition can always be satisfied by increasing the carrier component, as in (c).




Mecozzi et al, v. 3, n. 11, Optica, 2016

# 267 Gbit/s Kramers-Kronig receiver

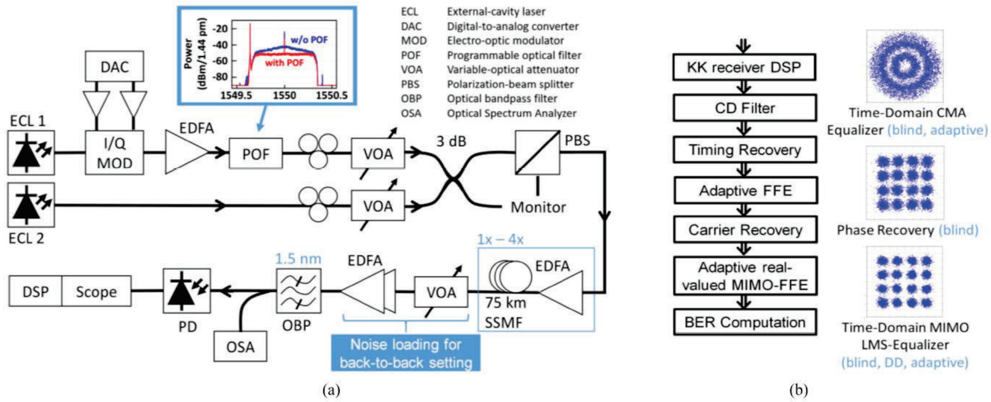


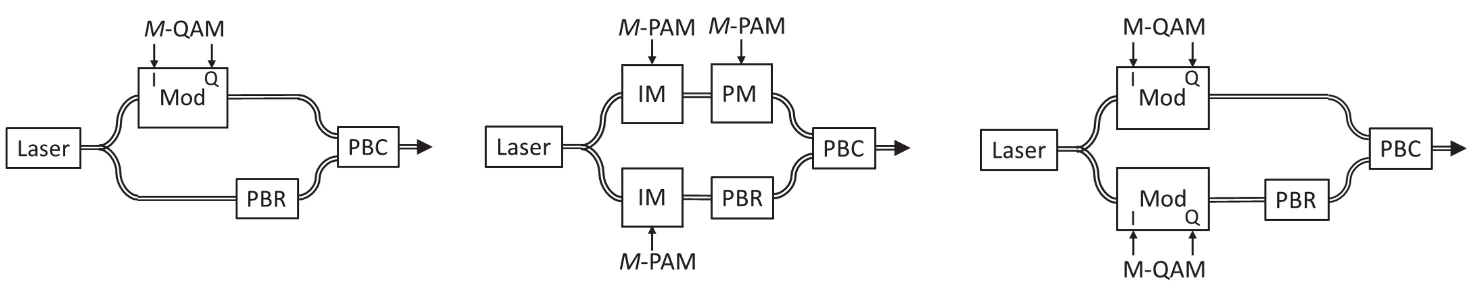

Fig. 10. (a) Experimental setup for the KK receiver experiment. In case of the back-to-back experiment, various OSNR levels are generated with the noise-loading block, whereas up to 300 km of SSMF are added for a transmission demonstration. (b) Coherent receiver DSP chain that follows the KK receiver implementation depicted in Fig. 2.

- Single-polarization, 80 Gbaud 16-QAM with 20% FEC overhead results in 267 Gbit/s over 300 km.
- Simplifies KK receiver complexity by using only 8 filter taps.

C. Fullner, M. M. H. Adib, S. Wolf, J. N. Kemal, W. Freude, C. Koos and S. Randel, Complexity Analysis of the Kramers-Kronig Receiver, J. of Lightw. Tech., Vol. 37, No. 17 (2019)



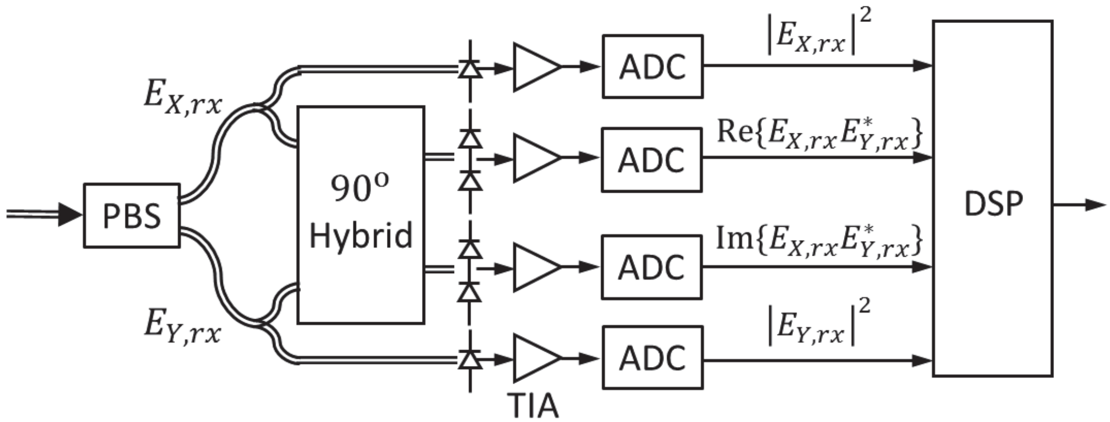
# Modulation formats for Stokes vector detection




**2D: *M*-QAM + carrier** **3D: DP-*M*-PAM + PM** **4D: DP-*M*-QAM**

## Stokes vector receiver

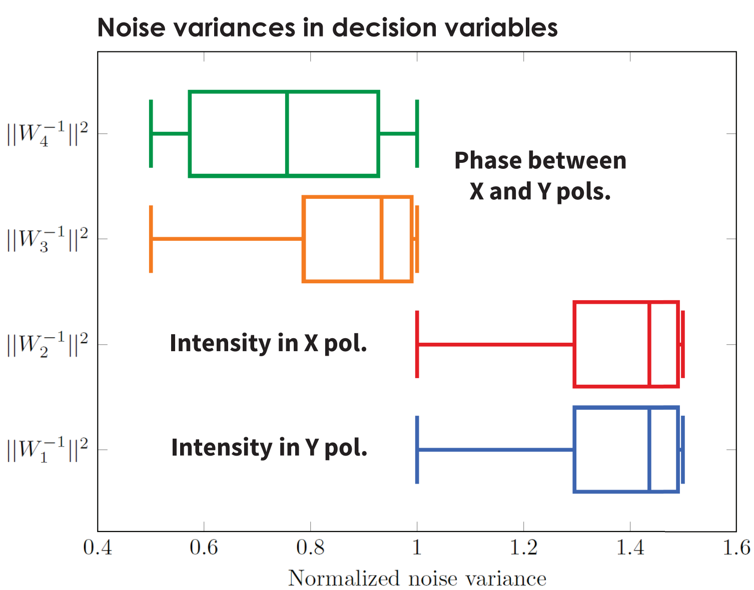
- Does not require local oscillator laser.
- Requires four ADCs and MIMO (or MISO) DSP.

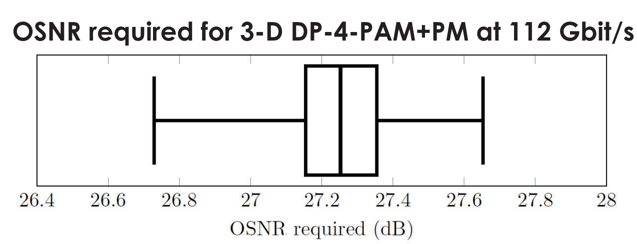





## Stokes vector detection

- Polarization rotation matrix for Stokes vector representation is not unitary.




(comparable to 4-PAM or 16-QAM SSB OFDM)

J. K. Perin, A. Shastri and J. M. Kahn, "Data Center Links Beyond 100 Gbit/s per Wavelength", *Optical Fiber Technol.* 44, 2018.

# 480 Gb/s Stokes Vector Receiver

- Exploits both quadratures and both polarizations by sending a digital tone with signals.

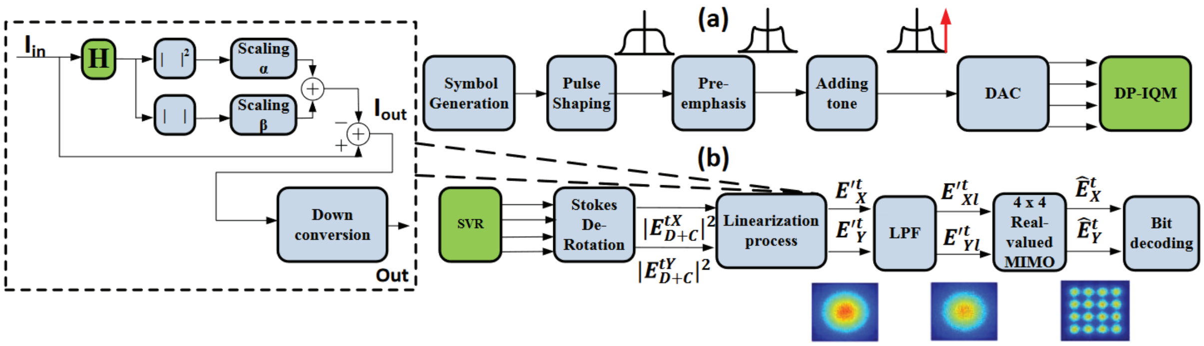



Fig. 1. Schematic diagram of the proposed 4D-PDM-DD system including (a) transmitter with DSP blocks to generate signals, and (b) receiver with DSP blocks after the SVR to recover PDM signals, and constellations of 60 Gbaud 16QAM signals after 80 km. H: Hilbert transform; LPF: Low pass filtering.

T. Hoang, Q. Zhuge, Z. Xing, M. Sowailem, M. Morsy-Osman and D. V. Plant, Single Wavelength 480 Gb/s Direct Detection Transmission Over 80 km SSMF Enabled by Stokes Vector Receiver and Reduced-Complexity SSBI Cancellation, W4E.7, OFC (2018)



# Summary of DD-compatible methods

- Modulation formats compatible with direct detection are extremely constrained beyond 100 Gbit/s.
  More degrees of freedom are needed.
- Stokes vector detection and Kramers-Kronig receivers can provide more dimensions.
- But they do not provide higher power efficiency than simple direct detection receivers.
- Power efficiency is reduced by transmitting unmodulated carrier, which is done to enable CD compensation and make signal minimum-phase.
- Scaling beyond 100 Gb/s per wavelength may be best achieved by using coherent detection, even for intra-data center links.

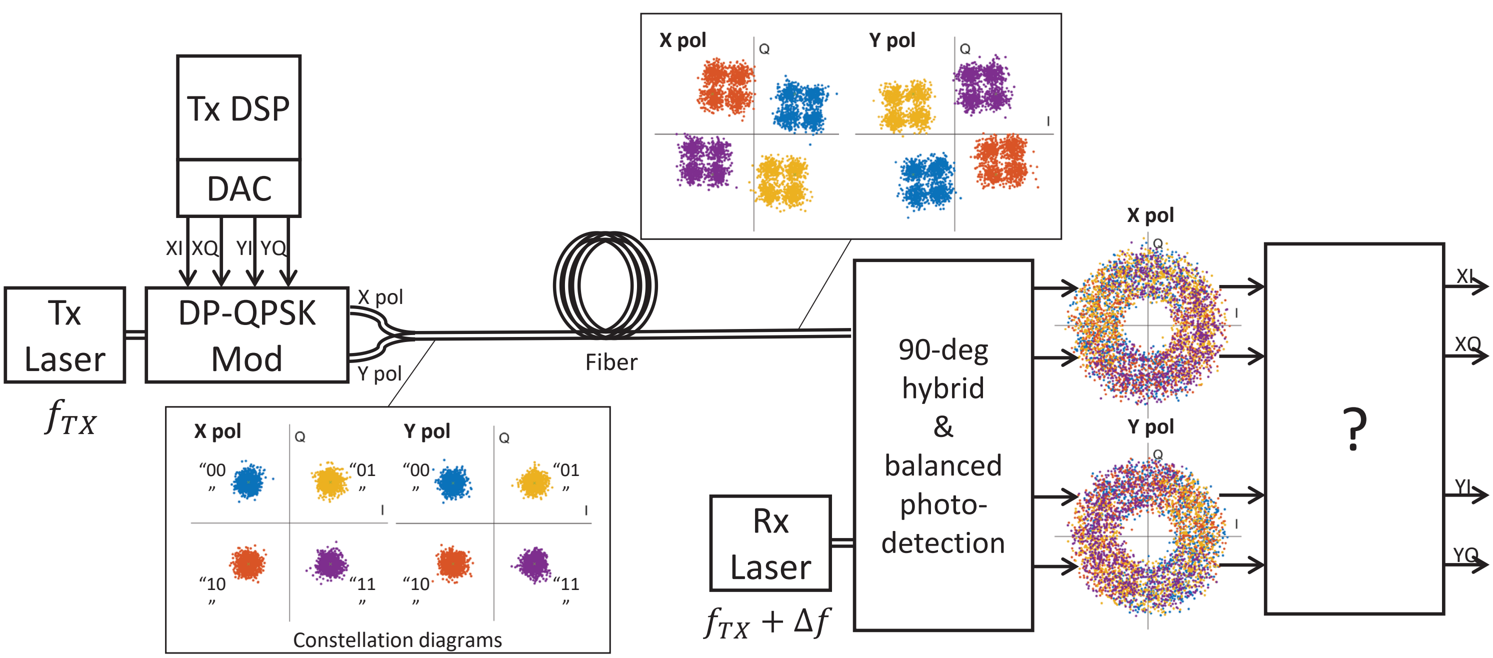
# Outline

- Optical receiver functions
- Detection methods
- Methods compatible with direct detection
  - M-PAM
  - SSB-OFDM
  - Kramers-Kronig
  - Stokes
- DSP-based vs. DSP-free coherent detection
- Power consumption considerations
- Conclusions



# Coherent detection

- Example for dual-polarization quadrature phase-shift keying (DP-QPSK).



# Functions performed by coherent receivers

| Function | Digital signal processing (DSP) implementation | Proposed DSP-free alternative |
|---|---|---|
| ADC | 4 high-speed (~ 50 GS/s) | Low-speed only (< 1 MS/s) |
| Polarization recovery | 2 × 2 MIMO equalizer | Cascaded phase shifters |
| CD equalization | Frequency-domain linear equalizer | None |
| Carrier recovery | Feedforward | PLL with XOR-based phase detector |
| Timing recovery | Gardner-type | Conventional clock data recovery (CDR) |

- Total DSP-based power consumption is expected to be ~15 W using 7 nm CMOS for 400 Gbit/s-ZR.
- Reach-independent: ADCs, carrier recovery, and timing recovery.

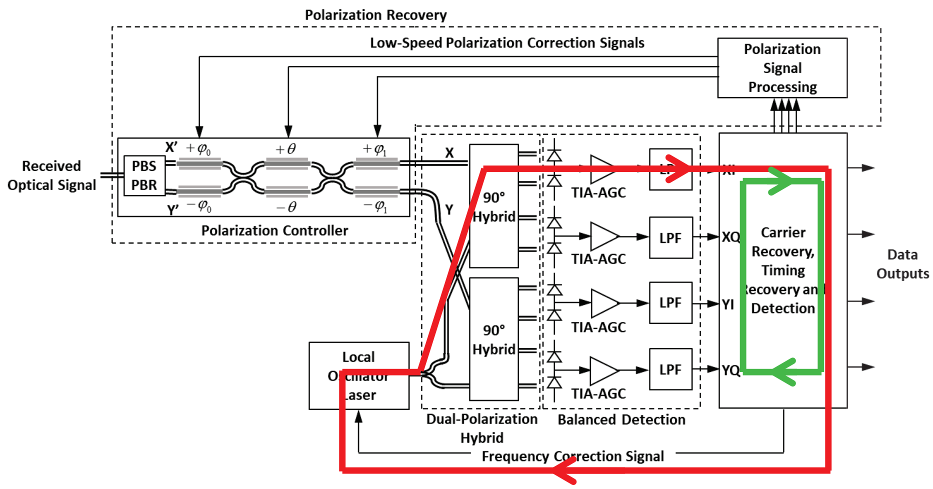


# Long-haul vs. data center links

| | Long-haul | Inter-data center | Intra-data center |
|---|---|---|---|
| **Maximum reach** | 1000s of km | 100 km | 10 km |
| **Wavelength** | 1550 nm | 1550 nm | 1310 nm |
| **Amplification** | Yes | Yes | No |
| **Fiber impairments** | CD, PMD, Kerr nonlinearity | CD | |
| **Design priorities** | Reach, bit rate | Bit rate, power consumption, density, and cost | Bit rate, power consumption, density, and cost |
| **Current technology** | Coherent detection: 33.3 Gbaud DP-64-QAM (DWDM) | Direct detection: 25 Gbaud 4-PAM (DWDM) | Direct detection: 25 Gbaud 4-PAM (LAN-WDM) |

- A 3 dB penalty halves the reach of long-haul links, but causes only a 3 dB loss of loss budget in data center links.
- Sacrificing performance to reduce cost and power consumption is reasonable in data center links.
- Fiber impairments are less severe.
- These key differences may favor low-power DSP-free coherent receivers.

# Proposed architecture for DSP-free coherent receiver




Expected to consume ~4 W at 200 Gbit/s using DP-QPSK

Three key synchronization functions:

**Polarization recovery**

- Use optical polarization control driven by detection of low-speed marker tones.

**Carrier recovery**

- Optical phase-locked loop: requires short delay around entire path shown.
- Electrical phase-locked loop: requires short delay only within electrical circuit.

**Timing recovery**

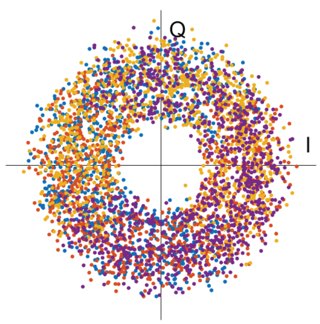
- Use conventional clock and data recovery for binary signals.

J. K. Perin, A. Shastri and J. M. Kahn, "Design of Low-Power DSP-Free Coherent Receivers for Data Center Links", *J. of Lightwave Technol.* 35, 2017.

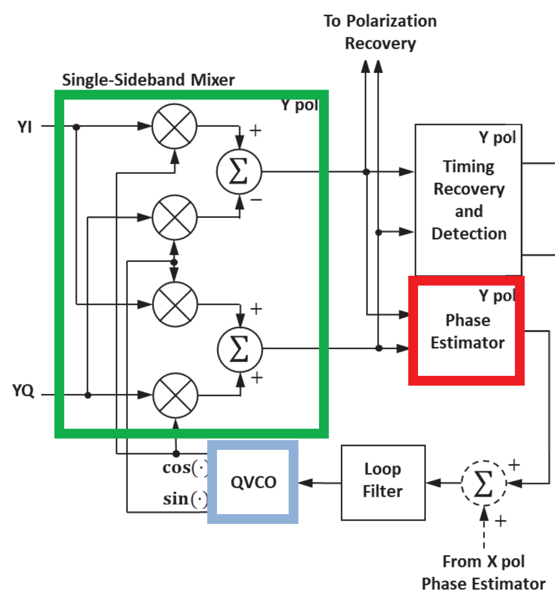


# Electrical phase-locked loop

**Received signal in Y pol**

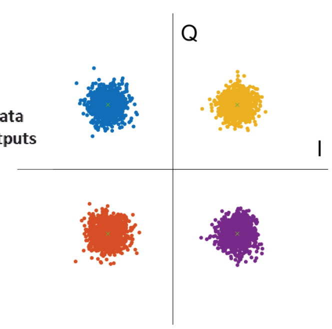



$$e^{j(\phi_{data}(t)+\phi_{noise}(t)+2\pi\Delta f t)}$$
$$\times\, e^{-j(\phi_{noise}(t)+2\pi\Delta f t-\phi_e(t))}$$
$$= e^{j(\phi_{data}(t)+\phi_e(t))}$$




**(one polarization shown)**

**After de-rotation**



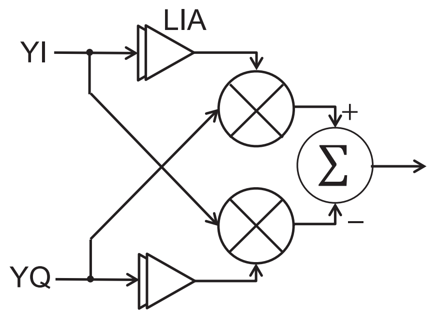

$$e^{j(\phi_{data}(t)+\phi_e(t))}$$

- Second moment of phase error $E(|\phi_e(t)|^2)$ can be computed analytically. It depends primarily on SNR and laser linewidth.
- The natural frequency $\omega_n$ of the loop filter $F(s) = 2\zeta\omega_n + \omega_n^2/s$ is chosen to minimize $E(|\phi_e(t)|^2)$.

# Phase estimators

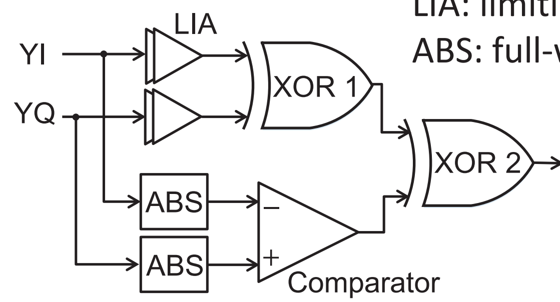
•Wipes off QPSK modulated data to estimate phase error

**Costas-type**




Estimates the phase error: $\hat{\phi}_e(t)$

**XOR-based**




LIA: limiting amplifier
ABS: full-wave rectifier

Estimates the sign of the phase error: $\operatorname{sgn} \hat{\phi}_e(t)$

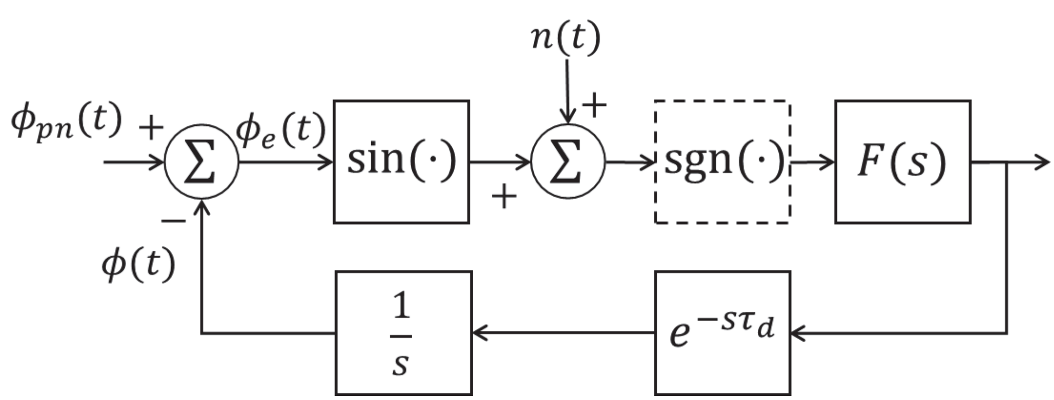
**Advantages of XOR-based phase estimator**

- Avoids wideband and linear analog multipliers.
- Lessens signal integrity requirements.



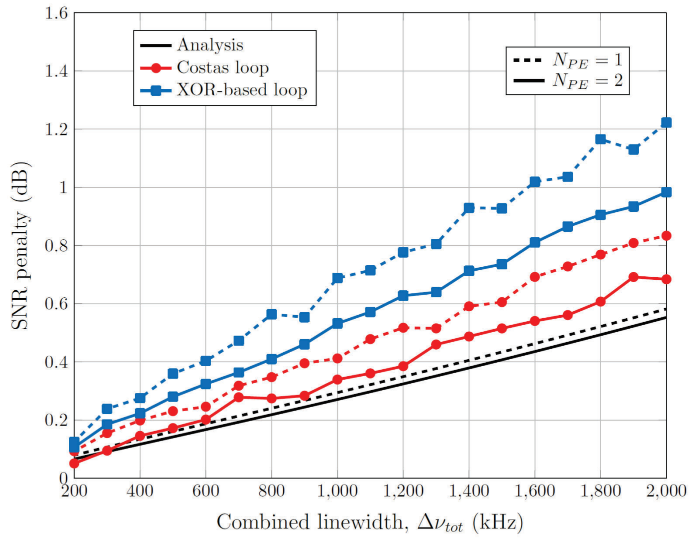
# Phase-locked loop analysis

- Multiplier-free phase estimator: include sgn(·) operation.
  Costas phase estimator: omit sgn(·) operation.
- Performance metric: $E(|\phi_e(t)|^2)$.



# Costas vs. XOR-based phase estimator

- Difference is less than 0.5 dB.
- Small SNR penalty for using only one polarization in phase estimation ($N_{PE} = 1$), since performance is limited primarily by laser phase noise.

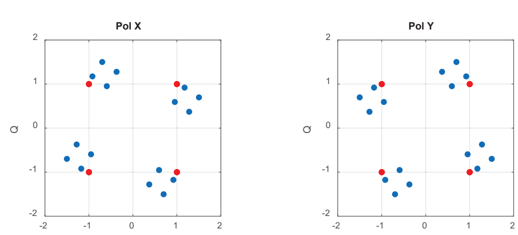





# Modeling polarization effects

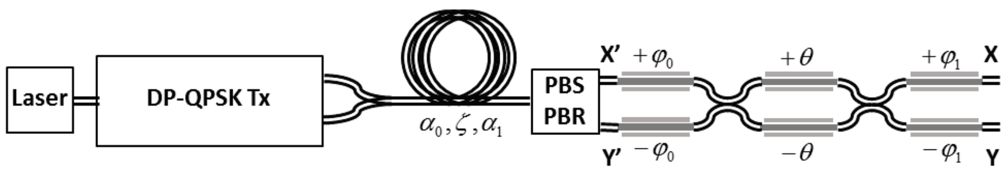
- PMD and PDL are weak in intra- or inter-data center links.
- Mean DGD in modern SMF: $E(\Delta\tau) \leq 0.1$ ps/$\sqrt{\text{km}}$ $\times \sqrt{100 \text{ km}} = 1$ ps.
- Propagation described by frequency-independent unitary Jones matrix with three parameters $\alpha_0, \varsigma, \alpha_1$:

$$T_{Fiber} = \begin{bmatrix} e^{j\alpha_1} & 0 \\ 0 & e^{-j\alpha_1} \end{bmatrix} \begin{bmatrix} \cos(\zeta) & -j\sin(\zeta) \\ -j\sin(\zeta) & \cos(\zeta) \end{bmatrix} \begin{bmatrix} e^{j\alpha_0} & 0 \\ 0 & e^{-j\alpha_0} \end{bmatrix}$$



# Modeling polarization effects

- Integrated controller comprises:
  - Polarization beam-splitter + polarization rotator.
  - Two couplers + three phase shifters $\varphi_0, \theta, \varphi_1$ in single-polarization waveguides.
  - Can use just two phase shifters if carrier is recovered separately in two polarizations.

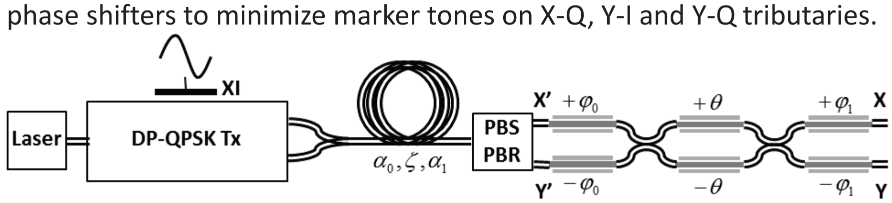


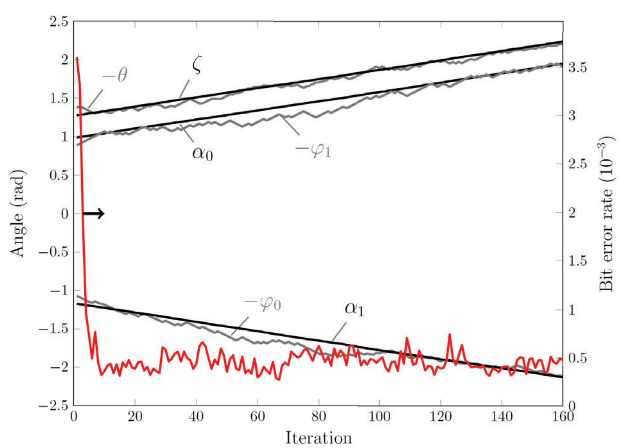

$$\begin{bmatrix} E_{o,x} \\ E_{o,y} \end{bmatrix} = \begin{bmatrix} e^{j\varphi_1} & 0 \\ 0 & e^{-j\varphi_1} \end{bmatrix} \begin{bmatrix} \cos(\theta) & -j\sin(\theta) \\ -j\sin(\theta) & \cos(\theta) \end{bmatrix} \begin{bmatrix} e^{j\varphi_0} & 0 \\ 0 & e^{-j\varphi_0} \end{bmatrix} \begin{bmatrix} e^{j\alpha_1} & 0 \\ 0 & e^{-j\alpha_1} \end{bmatrix} \begin{bmatrix} \cos(\zeta) & -j\sin(\zeta) \\ -j\sin(\zeta) & \cos(\zeta) \end{bmatrix} \begin{bmatrix} e^{j\alpha_0} & 0 \\ 0 & e^{-j\alpha_0} \end{bmatrix} \begin{bmatrix} E_{i,x} \\ E_{i,y} \end{bmatrix}$$



# Marker tone-based polarization control

- Transmitter: intensity-modulate marker tone on X-I tributary.
- Receiver: adjust phase shifters to minimize marker tones on X-Q, Y-I and Y-Q tributaries.

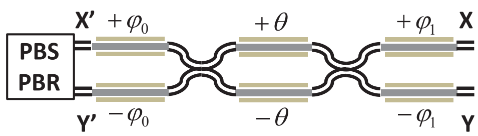



$$\begin{aligned} E_{o,x,i} &= [(\varphi_1+\alpha_0)+\cos(2\theta)(\varphi_0+\alpha_1)]E_{i,x,r} & \varphi_0 &\approx -\alpha_1 \\ E_{o,y,r} &= [-\sin(2\varphi_1)(\theta+\zeta)+\sin(2\theta)\cos(2\varphi_1)(\varphi_0+\alpha_1)]E_{i,x,r} & \varphi_1 &\approx -\alpha_0 \\ E_{o,y,i} &= [-\cos(2\varphi_1)(\theta+\zeta)-\sin(2\theta)\sin(2\varphi_1)(\varphi_0+\alpha_1)]E_{i,x,r} & \theta &\approx -\zeta \end{aligned}$$

# Phase shifter materials and resets

- Phase shifters have finite excursion. Can change any pair by $\pi$ radians to reset.
- Exploit interleaving and FEC decoding to avoid bit errors.




**Thermo-optic**

- Silicon-based photonics.
- May be more compact.
- Subject to speed-power tradeoff:
  ~1 ms at 10s of mW power consumption.
- 1 ms reset requires interleaver depth ~200 kb.

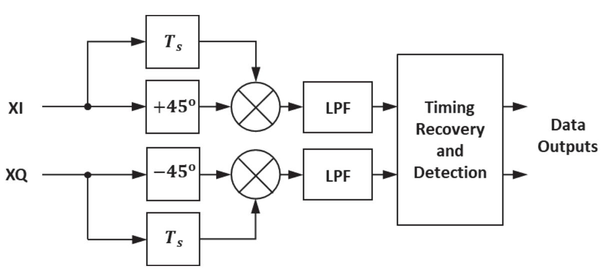
**Electro-optic**

- Bulk or thin-film lithium niobate.
- May be larger.
- No speed-power tradeoff.
  Speed and power may be driver-limited.
- Reset up to 4.5 ns compatible with standard interleaver.

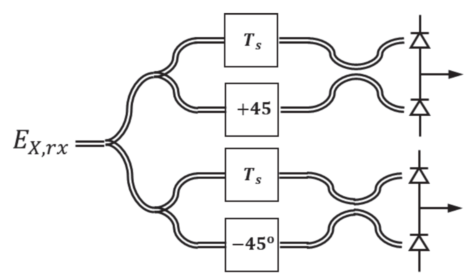


# Analog differentially coherent receivers

**LO-based (may avoid optical amplification)**

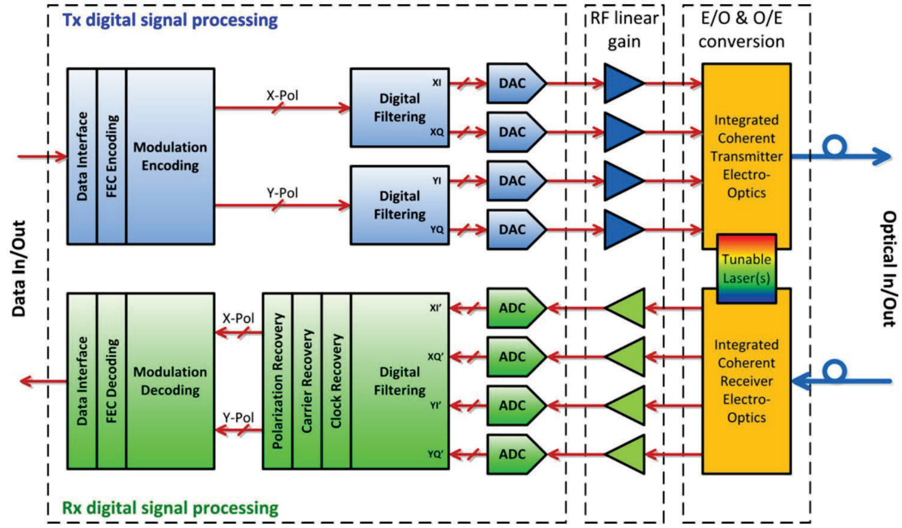



**LO-free (likely requires optical amplification)**




- Differentially encoded QPSK: data encoded in phase transitions.
- Differentially coherent detection:
  - Avoids carrier recovery.
  - Incurs ~2.4 dB penalty relative to coherent detection.
  - Polarization controller requires just two phase shifters.

# DSP-based coherent

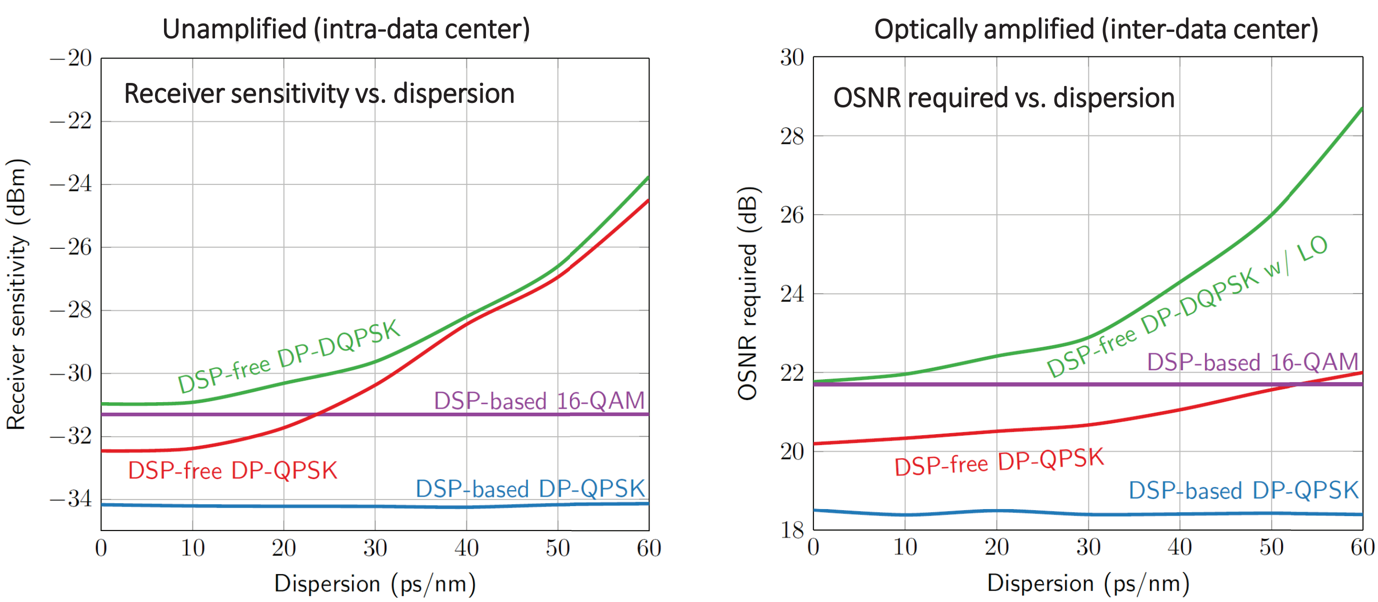



- Significant complexity in optics and electronics.
- For intra-data center links, some DSP functions may be simplified but power consumption may still be too high.

Image:Laperleand O'Sullivan, 2009

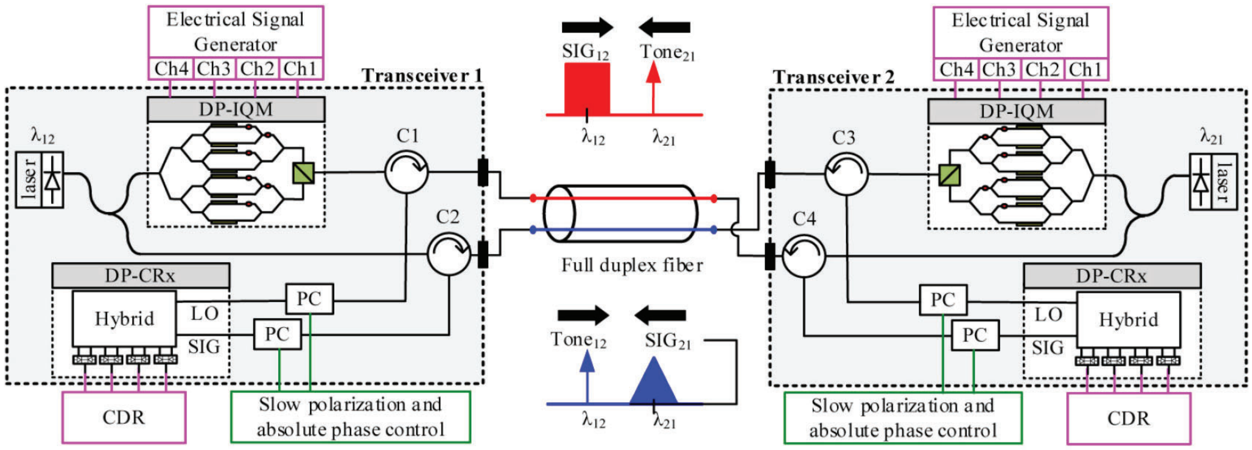


# Performance comparison at 200 Gbit/s




- 18 dB better receiver sensitivity than that of 4-PAM at 100 Gbit/s.
- 8 dB better OSNR than that of 4-PAM at 100 Gbit/s.

# DSP-free "coherent-lite"




- Transmission of the signal allows for self-homodyne, removing need for carrier recovery.
- Polarization demultiplexing performed the same way as proposed for DSP-free analog.
- Expected to consume ~3.75 W for 400 Gbit/s transceiver (56 Gbaud DP-16-QAM ).

M. Morsy-Osman, M. Sowailem, E. El-Fiky, T. Goodwill, T. Hoang, S. Lessard and D. V. Plant, DSP-free 'coherent-lite' transceiver for next generation single wavelength optical intra-datacenter interconnects, Opt. Exp., Vol. 26, No. 7, (2018)



# Summary of coherent detection

- Coherent detection
  - Exploits all four degrees of freedom in electric field.
  - Improves receiver sensitivity or OSNR requirement.
- DP-QPSK is binary per dimension: very tolerant to distortion.
- DSP-based coherent receivers
  - Can compensate CD and PMD, but not needed in many data center links.
  - Can scale to higher-order QAM.
  - May ultimately win for inter-data center links.

## Summary of coherent detection (cont.)

- Analog coherent receivers
  - Can use optical polarization control based on low-speed marker tones.
  - Can use multiplier-free phase detectors.
  - Optical PLL: simpler electronics, more complex integration.
    Electrical PLL: more complex electronics, simpler integration.
  - May be difficult to scale to high-order QAM.
  - May ultimately win for intra-data center links.

J. K. Perin, A. Shastri and J. M. Kahn, "Design of Low-Power DSP-Free Coherent Receivers for Data Center Links", *J. of Lightwave Technol.* 35, 2017.



## Outline

- Optical receiver functions
- Detection methods
- Methods compatible with direct detection
  - M-PAM
  - SSB-OFDM
  - Kramers-Kronig
  - Stokes
- DSP-based vs. DSP-free coherent detection
- Power consumption considerations
- Conclusions

# Power consumption considerations

- Digital architectures will greatly benefit from moving to more power-efficient CMOS nodes such as 7 nm and beyond.
- In digital architectures, the power consumption scales as

$$\propto (\text{Frequency}) \times (\text{Voltage})^2 \times (\text{Capacitance}) \times (\#\text{ bits switching})$$

- As feature size decreases, so typically do voltage and capacitance.

- Analog architectures do not benefit from the same power scaling, since switching is not the dominant operation.
- Moreover, bipolar transistors may be more effective than CMOS to realize high-bandwidth and linear analog circuits.

- For a 400 Gbit/s transceiver (all at 56 Gbaud):

| | Inter-data center (~100 km) | Intra-data center (~10 km) |
|---|---|---|
| Direct detection (4 × 4-PAM, 7 nm) | ~8 W* | ~7 W |
| DSP-based coherent (1 × DP-16-QAM, 7 nm) | ~15 W | ~12 W |
| Coherent-lite (1 × DP-16-QAM) | ~3.75 W* | ~3.75 W |
| Analog coherent (2 × DP-QPSK)† | ~8 W†* | ~8 W† |

†May possibly lower power consumption using 1 × DP-16-QAM    *Requires optical CD compensation



# Outline

- Optical receiver functions
- Detection methods
- Methods compatible with direct detection
  - M-PAM
  - SSB-OFDM
  - Kramers-Kronig
  - Stokes
- DSP-based vs. DSP-free coherent detection
- Power consumption considerations
- Conclusions

## Scaling Beyond 100 Gbit/s per wavelength

- Scaling baud rate while maintaining power consumption will require scaling CMOS:
  - 16 nm → 7 nm: 65% lower power consumption OR 35% higher performance.
  - 7 nm → 3 nm: 50% lower power consumption OR 35% higher performance.
  - 3 nm design costs expected to be 3-5× already expensive 7 nm design costs.
  - Sensitivity improvements from APDs and SOAs can help link budgets.
- Must choose modulation formats that exploit all four electric field dimensions
  - Generally also results in improved sensitivity as compared to direct detection receivers used in current intra-data center links.
- Increasing the number of wavelengths and / or fibers will increase total throughput, but to avoid linear power consumption scaling and to increase density, must leverage:
  - Co-packaging of optics.
  - Sharing of high-power lasers.



## Conclusions

- Direct detection is extremely constrained beyond 100 Gbit/s.
- More degrees of freedom are needed.
- Stokes vector detection and Kramers-Kronig receivers can provide more dimensions, but do not improve receiver sensitivity compared to simpler direct detection methods.
- Coherent detection yields four degrees of freedom while significantly improving receiver sensitivity.
  - DSP-based coherent systems will benefit from more power-efficient CMOS nodes.
  - DSP-free systems offer even lower power consumption at the expense of reduced performance.

- Thank you for your attention!

- To learn more:

  `ee.stanford.edu/~jmk/research/smfcom.html#dcs`