

Multi-Dimensional Detection in Future Hyper-Scale Datacenters

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Abstract— Extraordinary demand of internet services is challenging the growth capacity of datacenters and their networks. In particular, interconnect suppliers will need to explore radical solutions in order to keep up with bandwidth expectations from service providers. In this paper, we discuss key paths towards multi-dimensional detection in interconnect channels that will be relevant for hyper-scale datacenters. The emphasis is on highlighting challenges and opportunities of receiver architectures that have recently been pitched to replace intensity modulation and direct detection in the datacenter interconnect scenario.

Keywords- Fiber optics; Optical communications; Datacenter interconnection.

I. INTRODUCTION

There is a strong demand for delivering interconnect solutions for next-generation hyper-scale datacentre interconnects that support 400 Gb/s and beyond [1]. Technologies that support higher symbol rates per wavelength channel will be critical to connect bigger campuses and regional clusters demanding more efficiency in fibre deployment.

A typical datacentre network is shown in Figure 1. Data Centre Interconnects (DCI), provide connectivity for networking, storage and compute resources inside (intra-DC) or between (inter-DC) datacentres and are based on optical or copper channels. Passive copper cables also known as Direct-Attach-Copper (DAC) are still the most effective solution for links of < 5 m which are used to connect servers to the Top-of-Rack (ToR) switch. Connections from the ToR switch to other layers of the network, as well as all other DCIs are based on optical signalling. Both multimode (MMF) [2] and single mode (SMF) [3] optical fibres are used. Transceivers for use with MMFs have arrays of Vertical-Cavity Surface-Emitting Lasers (VCSELs) and are commonly used for driving channels of lengths within 5 - 100 m linking switches within a room. The vertical design of VCSELs allows them to be produced, tested and packaged at a low cost, while their circular cavity permits low insertion loss when coupling to the core of MMFs. On the other hand, SMF solutions require edge emitting lasers and optical assemblies tailored to couple light to a fibre with a much smaller core. Excitation of a single mode enables communications over longer fibre spans and opens the door to Wavelength Division Multiplexing (WDM) as a technique to parallelize data transmission. Within the datacentre, transceivers for links between a hundred meters and 2 km are increasingly implemented by photonic integrated circuits coupled to arrays of Parallel Single Mode Fibre (PSM4).

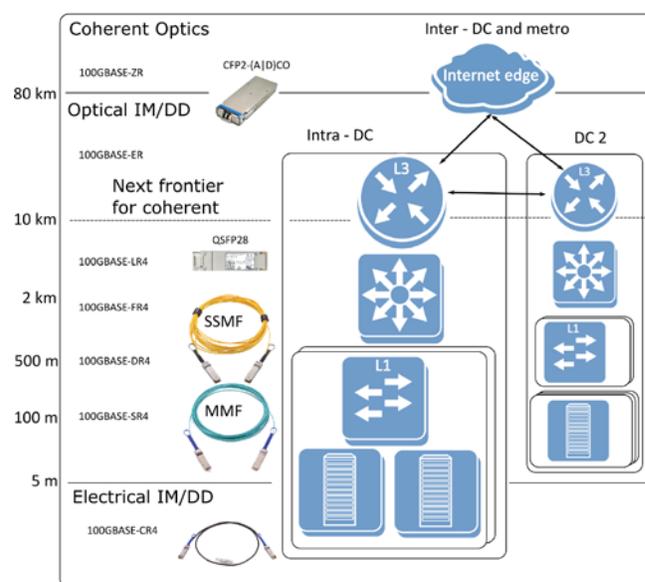


Figure 1. Datacentre architecture and interconnect solutions for inter- and intra-data centre links.

Longer reach solutions connecting campuses (2-80 km) use externally modulated lasers and optical elements for WDM, which are hosted inside hermetically-sealed transmitter and receiver optical sub-assemblies.

Optical interconnects below 80 km use Intensity Modulation and Direct Detection (IM/DD) of optical signals and are so far dominated by the Non-Return to Zero (NRZ) modulation format. Nevertheless, the industry is rapidly migrating from NRZ to Multilevel Pulse-Amplitude Modulation (M-PAM), which has higher Spectral Efficiency (SE) [4][5]. The format with 4 levels, PAM4, is the first to gain broad support and will most likely become and remain dominant in the short term. When looking further ahead in time, overcoming channel impairments on links above 10 km will become difficult without signal processing techniques that are comparable in complexity to more efficient alternatives.

Other advanced modulation formats achieve better sensitivity and SE than PAM4 by taking advantage of higher dimensionality and can become increasingly attractive to increase bitrates in the future, without adding extra channels in the form of wavelengths or fibres. However, these advantages require receiver architectures that are significantly more complex than in DD.

This paper reviews some of the paths towards implementing multi-dimensional receiver solutions in DCI. This

vision is inspired by the current transition between IM/DD and coherent detection in the metro scenario enabled by novel coherent pluggable transceivers, such as the 100 Gb/s (C) Form-Factor Pluggable version 2 (CFP2) [6].

The manuscript is organized in the following manner: In Section 2 the need for architectures that overcome the limitations of IM/DD in our scenario is stated, and a brief overview of the selection of candidate approaches is presented. Section 3 provides a review of each receiver architecture and highlights implementation challenges. Finally, the work is concluded in section 5.

II. TECHNOLOGIES FOR DATACENTER INTERCONNECTS

The relatively low cost of adding fibres, and the advent of WDM has kept IM/DD solutions dominant in the DCI scenario; even though, bitrates per wavelength have remained unchanged at 25 Gb/s per lambda solutions. A possible explanation for the tendency towards multiplexing is the slow progress in the development of production-ready optical building blocks with high bandwidth, low noise and sufficient linearity. It is hinted that the transition to multi-level signalling in the form of PAM4 at high symbol rates (50 GBd) will likely require Digital Signal Processing (DSP) to enable increasingly elaborate equalization techniques [7]. DSP will in turn bring power and heat dissipation issues that need to be resolved to fit the stringent specifications of next generation transceiver modules. In addition, there are limits to: the number of fibres, the fabrication tolerances of WDM, and the power needed to support multiple channels. These limits on symbol rate and spectrum will encourage bitrate increase by means of modulation formats that use other orthogonal dimensions for coding [8].

Well-known dimensions for coding in SMF channels include the phase and linear State of Polarization (SoP) of the optical field. Commercial coherent receivers detect the phase and amplitude of each SoP, and will be regarded here as able to decode in 4 orthogonal dimensions or “4D”. There is also interest in alternative receiver architectures capable to recover signals in 3D and 2D that may be a better fit for the specific conditions of DCIs.

A. Overview of architectures

Figure 2 presents a selection of multi-dimensional receiver architectures that can be pitched to bring multidimensional signalling in the DCI scenario. They are ordered by decreasing level of trade-off between complexity and spectral efficiency. Additionally, selected elements of each architecture have been coloured according to the level of uncertainty or risk needed to develop a mature solution. Red coloured blocks indicate a significant challenge, where either elements are still too complex, or unfit for the DCI requirements. Yellow coloured blocks indicate that there is a mature assessment of the limitations and evidence of strategies to overcome them.

We begin with a light-DSP version of the mainstream polarization division multiplexing intra-dyne coherent approach shown in Figure 2(a). The objective is to further tailor traditionally power-hungry optics and algorithms for the specific conditions of short reach communications.

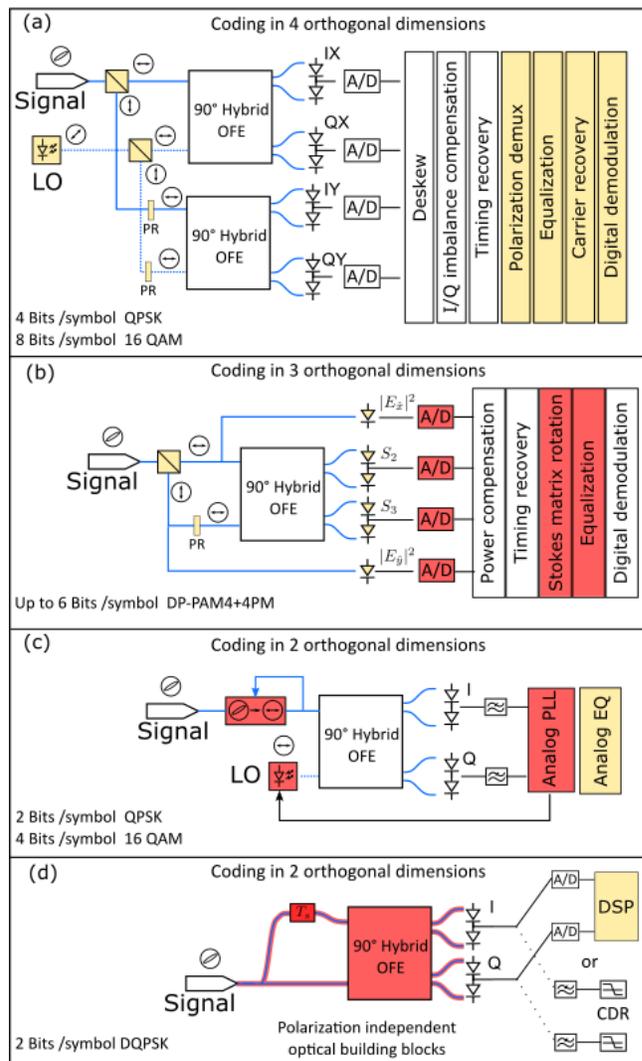


Figure 2. A selection of ordered multi-dimensional receiver architectures for future datacenter interconnects by decreasing complexity: (a) Intra-dyne digital coherent receiver. (b) Stokes vector receiver. (c) Homodyne coherent receiver and (d) self-homodyne differential receiver.

Then, Figure 2(b) illustrates the basic architecture of Stokes Vector Receivers (SVR) [8] which demodulate signals encoded in the power (or Stokes) space. Signals modulated in the Stokes space are independent of the absolute phase of the carrier, but dependent on the relative phase and amplitude ratio between the vertical and horizontal polarization components [9][10].

An SVR as shown here can demodulate signals encoded in up to three orthogonal dimensions, and achieve spectral efficiencies of up to 6 bits per symbol per wavelength.

One can also consider technological developments that revive single-polarization architectures from early coherent demonstrations. Figure 2(c) represents homodyne coherent receivers where analog electronics are used to track variations in the phase of the carrier. Here, we have stressed the importance of including active polarization tracking.

Finally, Figure 2(d) illustrates a concept of single polarization coherent receiver that uses self-homodyne detection

and differential coding to achieve polarization-independent multi-dimensional signalling on the phase and amplitude.

III. IMPLEMENTATION CHALLENGES OF ARCHITECTURES

The objective of this section is to go through the architectures that were briefly mentioned above and highlight some of the specific challenges and advantages of each.

Given that photodiodes can detect only optical power, interferometric techniques are used to obtain the phase of a signal by analysing the effects on the intensity at the outputs of a phase diversity measurement where the modulated signal is mixed with a reference signal [11]. All Optical Front Ends (OFE) in Figure 2 share the building block known as a 90° hybrid used for optical mixing, but differ in the way in which information is extracted from measurements. Additionally, they all use some form of homodyne detection, meaning that signals at the input of 90° hybrids should strive to have the same frequency. Finally, a last critical condition for mixing is the control of the SoP. This is because most integrated optics elements are polarization dependent and received signals have an unknown SoP due to random birefringence in the fibre. Different approaches to deal with polarization control are shown before the 90° hybrids and will be mentioned in what follows.

A. Intra-dyne digital coherent receivers

The OFE in commercial coherent receiver architectures has remained unchanged in the form of the intra-dyne digital coherent receiver in Figure 2(a). It is referred to as intra-dyne because small variations in frequency and phase between the signal carrier and Local Oscillator (LO) are corrected using DSP. Powerful DSP Application Specific Integrated Circuits (ASICs) enabled not only algorithms for Carrier Recovery (CR) and channel impairment compensation, but also techniques for digitally tracking the state of polarization. A trade-off of coherent Polarization Division Multiplexing (PDM) is the doubling in complexity of the OFE. To extract phase information from independent polarizations, polarization beam splitters and rotators project the fields (signal and LO) into the known orthogonal basis of the 90° hybrids. The considerable number of elements, combined with the need of a LO has historically justified scepticism in short reach intra-dyne coherent solutions.

The top-down approach for developing receivers like the one in Figure 2(a) for gradually shorter links is the one most favoured by the industry. Challenges are well known and there is consistent progress in reducing the power consumption and size of optical, thermal and electronic components. The tradition inherited from the long haul encourages multi-level modulation formats like 16 Quadrature Amplitude Modulation (QAM) or even 64-QAM for short reach to better use the channel capacity given a larger Signal-to-Noise Ratio (SNR) [12]. But this approach assumes keeping the DSP complexity and could be challenged by bottom-up implementations that focus on symbol rate and simplicity instead of channel capacity.

Photonic integration of optical components is critical for reducing the costs, size and power consumption of the

optical frontend [13]. Silicon photonics in particular, promises receiver solutions with low loss, no need for hermetic sealing, and can profit from the economics of scale and maturity of established CMOS foundries. In addition, advances in the supporting technologies of components, such as lasers, phase shifters and detectors, could further reduce the complexity of equalization and CR routines in the digital domain.

The complexity of ASICs is dominated by algorithms for compensation of channel impairments, such as Chromatic Dispersion (CD) and Polarization Mode Dispersion (PMD) that decrease in magnitude with shorter fibre lengths typical of the DCI scenario. It is conceivable that big reductions in complexity could be achieved by tailoring ASICs for the next frontier of coherent pluggable, on the condition of sufficient demand of spectral efficiency in the datacentre. Moreover, ASICs have been following Moore's law enabling $\times 0.7$ power savings per process node every two years [12]. A tailored solution for short reach could also loosen vertical resolution requirements on elements for Analog-to-Digital Conversion (ADC) and support implementations with simple constellations at a high symbol rate.

B. Stokes vector receivers

Modern Stokes vector receivers are developments of early attempts to implement PDM of IM/DD signals and are generally categorized as a form of direct detection. Direct detection approaches for PDM, including early versions of SVR, lost the race against coherent detection in the long haul when the opportunity to do linear digital processing on the later demonstrated its superiority for channel impairment compensation. However, there has been a revived interest in SVR [8]–[10] for optical channels that are too long for PAM4 and too short to justify intra-dyne coherent detection. These efforts have now resulted in working implementations of 2D formats like Dual Polarization PAM4 (DP-PAM4), and 3D formats, such as DP-PAM4 with inter-polarization Phase Modulation (DP-PAM4+PM). Thus, one advantage of SVRs is the possibility of detecting formats with SE between 2-6 bits/symbol/wavelength and optimize complexity for a given channel length.

Two of the DSP blocks in Figure 2(b) are highlighted in red because algorithms for de-multiplexing and equalization after the OFE have not converged to a standardized form. They have also not been optimized and synthesized for use in ASICs as is the case for the others. It is not yet clear what is the expected power consumption of a SVR ASIC and how it compares to state-of-the-art coherent DSP. The ASIC could be less complex than an intra-dyne equivalent if implemented for short reach communications where CD and PMD are not significant. Additionally, in demonstrations of multi-dimensional detection using SVR, high performance ADC and DAC blocks have been necessary to showcase high bitrate operation. This suggests that there is a requirement for extra sensitivity given the square root power envelope conditions of direct detection.

Photonic integration is already playing a role in realizing specialized building SVR blocks for next generation multi-dimensional enabled short-reach links [14][15]. It is worth noting that compared to the architecture in Figure 2(a) the SVR has only one 90° hybrid, half the number of polarization beam splitters and rotators, no LO and only 6 PDs of which two are single ended.

C. Homodyne coherent receivers

In homodyne coherent receivers, the LO must track the frequency and SoP of the incoming signal. Analog receivers electronically detect variations in frequency and use electrical feedback signals to lock the LO laser to the carrier frequency. Recent implementations of analog Phase Lock Loops (PLL) [16]–[18] present homodyne receivers working at still modest speeds of 40 Gbit/s. Similarly, integrated polarization controllers are slowly becoming a reality [19]–[21]. Additionally, analog equalization has also been demonstrated recently at low symbol rates [22]. Sufficient innovation in integration and co-packaging could revive single polarization homodyne coherent detection and take full advantage of the cost and power efficiency of analog electronics for the short reach scenario.

Variations on single polarization coherent detection using a LO can also be found in coherent access networks [23], which as the DCI scenario, are also constrained by cost and low power requirements on the LO and DSP. Noteworthy, are heterodyne solutions using 3x3 optical couplers [24]. Other novel ideas based on homodyne detection and inspired in access networks, use carrier delivery for remote modulation in a bi-directional link [25].

D. Delay-line based differential coherent receivers

Delay-line based differential coherent receivers [26], like the one depicted in Figure 2(d), are one important group of receiver architectures known as Self-Coherent (SC). A common trait of self-coherence is the absence of a LO, which allows avoiding carrier recovery schemes. An excellent comparison of SC receivers can be found in [27].

In delay-line receivers, the difference between the phases of consecutive symbols is detected instead of the absolute phase of the field. Detection is achieved by mixing the signal with a delayed copy of itself. Provided that the OFE has a polarization controller or that it can be made of polarization independent optical elements, the SC receiver can recover phase and amplitude modulated signals on a single polarization. Additionally, even though most demonstrations use DSP, analog signal processing, even if not linear, is possible [28] without the loop bandwidth constraints of a PLL or the need of polarization de-multiplexing. The apparent simplicity of this approach hides significant challenges in the design of an OFE that guarantees precise delays in both polarizations at a given wavelength.

Implementations of photonic integrated SC differential receivers have been demonstrated using Mach-Zehnder delay-line interferometers [29][30], and recently ring resonators [31]. Free-space optics based self-homodyne coherent receivers [32] solve the problems of polarization

independence and tuning flexibility, but require bulky and expensive building blocks.

In other manifestations of self-coherent receivers, mixing happens at the transmitter or is done with a reference that travels alongside the signal. When mixed at the transmitter, single polarization DD approaches using only one photodiode can be implemented at the cost of higher DAC/ADC bandwidth, large processing complexity, and a high Carrier-to-Signal Power Ratio (CSPR) [33]. A similar trade-off is present when sending the carrier on an orthogonal polarization [34]–[36].

E. Note on transmitter complexity

In this section, we chose to analyse the technological challenges of receiver architectures, leaving aside the topic of multi-dimensional modulators. This is because a basic IQ modulator in combination with a polarization beam combiner is a sufficiently general system for coding in any combination of the 4 orthogonal dimensions mentioned above. Differences between modulation formats come from the driving signals sent to individual phase shifters placed in the Mach-Zehnder modulators and waveguides that make up a traditional IQ modulator.

F. Common challenges

As hinted above, common challenges are photonic integration and achieving packaging solutions where driving electronics and DSP ASICs are placed closer to the optics.

On the photonic integration aspect, the selection of substrate platform is critical. There are trade-offs to be considered when deciding to implement architectures in the III-V material ecosystem or in silicon photonics. Hence, many commercial solutions tend to favour heterogeneous integration, especially in the transmitter side. Above all, the platform on which multi-dimensional receivers are built should support polarization handling elements, such as polarization beam splitters and polarization rotators. Or alternatively, guarantee polarization independence. Not all foundries have polarization handling building blocks and some designs require extra processing steps, such as wet etching, that can increase the complexity of fabrication and reduce yield.

Regarding packaging, a significant milestone was achieved recently when Ball-Grid-Arrays (BGA) packaged coherent modules were demonstrated [37]. Finally, hybridization of III-V active components on a Silicon substrate is an ambitious objective that could significantly reduce power and footprint constraints [38].

IV. CONCLUSIONS

Multi-dimensional modulation formats are starting to be proposed to achieve better SE in the DCI scenario. We have highlighted four receiver architectures as an attempt to review trends that are relevant for solving requirements of next generation DCI links. The discussion on the specific challenges that are faced on each case will be the foundation of future decisions on a path to follow. Even though it looks like the industry is focusing on gradually reducing the

complexity of traditional coherent transceivers, we have observed and presented examples of architectures such as SVR or variations of SC receivers that have the potential to move the frontier of multi-dimensional modulation formats to shorter reach applications with reduced complexity.

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REFERENCES

- [1] N. Eiselt et al., "Real-time 200 Gb/s (4 X 56.25 Gb/s) PAM-4 transmission over 80 km SSMF using quantum-dot laser and silicon ring-modulator," in 2017 Optical Fiber Communications Conference and Exhibition (OFC), 2017, pp. 1–3.
- [2] K. Kurokawa, "Group delay in multimode optical fibers," *Proc. IEEE*, vol. 65, no. 8, pp. 1217–1218, Aug. 1977.
- [3] D. Marcuse and C. Lin, "Low dispersion single-mode fiber transmission - The question of practical versus theoretical maximum transmission bandwidth," *IEEE J. Quantum Electron.*, vol. 17, no. 6, pp. 869–878, Jun. 1981.
- [4] A. Dochhan et al., "Solutions for 400 Gbit/s Inter Data Center WDM Transmission," in ECOC 2016; 42nd European Conference on Optical Communication; Proceedings of, 2016, pp. 1–3.
- [5] N. Eiselt et al., "First Real-Time 400G PAM-4 Demonstration for Inter-Data Center Transmission over 100 km of SSMF at 1550 nm," 2016, p. W1K.5.
- [6] S. Khatana, "Components for 100G Coherent Pluggable Modules-CFP2," in Optical Fiber Communication Conference, 2016, p. Th3G–5.
- [7] J.-P. Elbers, N. Eiselt, A. Dochhan, D. Rafique, and H. Griesser, "PAM4 vs Coherent for DCI Applications," in *Signal Processing in Photonic Communications*, 2017, p. SpTh2D–1.
- [8] M. Chagnon, M. Morsy-Osman, and D. V. Plant, "Multi-Dimensional Formats and Transceiver Architectures for Direct Detection With Analysis on Inter-Polarization Phase Modulation," *J. Light. Technol.*, vol. 35, no. 4, pp. 885–892, Feb. 2017.
- [9] K. Kikuchi and S. Kawakami, "Multi-level signaling in the Stokes space and its application to large-capacity optical communications," *Opt. Express*, vol. 22, no. 7, p. 7374, Apr. 2014.
- [10] D. Che, A. Li, X. Chen, Q. Hu, Y. Wang, and W. Shieh, "Stokes vector direct detection for short-reach optical communication," *Opt. Lett.*, vol. 39, no. 11, p. 3110, Jun. 2014.
- [11] L. G. Kazovsky, "Phase- and polarization-diversity coherent optical techniques," *J. Light. Technol.*, vol. 7, no. 2, pp. 279–292, Feb. 1989.
- [12] F. Frey, R. Elschner, and J. K. Fischer, "Estimation of Trends for Coherent DSP ASIC Power Dissipation for different bitrates and transmission reaches," in *Photonic Networks*; 18. ITG-Symposium, 2017, pp. 1–8.
- [13] C. R. Doerr, "Silicon photonic integration in telecommunications," *Front. Phys.*, vol. 3, Aug. 2015.
- [14] S. Ghosh, Y. Kawabata, T. Tanemura, and Y. Nakano, "Polarization-analyzing circuit on InP for integrated Stokes vector receiver," *Opt. Express*, vol. 25, no. 11, p. 12303, May 2017.
- [15] P. Dong, X. Chen, K. Kim, S. Chandrasekhar, Y.-K. Chen, and J. H. Sinsky, "128-Gb/s 100-km transmission with direct detection using silicon photonic Stokes vector receiver and IQ modulator," *Opt. Express*, vol. 24, no. 13, p. 14208, Jun. 2016.
- [16] M. Lu, H.-C. Park, E. Bloch, L. A. Johansson, M. J. Rodwell, and L. A. Coldren, "Highly Integrated Homodyne Receiver for Short-reach Coherent Communication," in *Optoelectronic Devices and Integration*, 2015, p. OT2A–4.
- [17] A. Mizutori, T. Abe, T. Kodama, and M. Koga, "Optical 16-QAM Signal Homodyne Detection by Extracting $\pm\pi/4$ and $\pm 3\pi/4$ -Phase Symbols," in *Optical Fiber Communication Conference*, 2017, p. Th4C–6.
- [18] Mingzhi Lu et al., "An Integrated 40 Gbit/s Optical Costas Receiver," *J. Light. Technol.*, vol. 31, no. 13, pp. 2244–2253, Jul. 2013.
- [19] P. Velha et al., "Wide-band polarization controller for Si photonic integrated circuits," *Opt. Lett.*, vol. 41, no. 24, p. 5656, Dec. 2016.
- [20] C. R. Doerr, N. K. Fontaine, and L. L. Buhl, "PDM-DQPSK Silicon Receiver With Integrated Monitor and Minimum Number of Controls," *IEEE Photonics Technol. Lett.*, vol. 24, no. 8, pp. 697–699, Apr. 2012.
- [21] M. Ma et al., "Silicon photonic polarization receiver with automated stabilization for arbitrary input polarizations," in *CLEO: Science and Innovations*, 2016, p. STu4G–8.
- [22] N. Nambath et al., "First demonstration of an all analog adaptive equalizer for coherent DP-QPSK links," in *Optical Fiber Communications Conference and Exhibition (OFC)*, 2017, 2017, pp. 1–3.
- [23] A. Shahpari et al., "Coherent Access: A Review," *J. Light. Technol.*, vol. 35, no. 4, pp. 1050–1058, Feb. 2017.
- [24] J. Tabares, V. Polo, and J. Prat, "Polarization-independent heterodyne DPSK receiver based on 3x3 coupler for cost-effective udWDM-PON," in 2017 Optical Fiber Communications Conference and Exhibition (OFC), 2017.
- [25] S. Echeverri-Chacón et al., "Short range interdatacenter transmission with carrier delivery and remote modulation for 112 Gb/s PM-QPSK signals," in *19th International Conference on Transparent Optical Networks*, 2017.
- [26] X. Liu, S. Chandrasekhar, and A. Leven, "Digital self-coherent detection," *Opt. Express*, vol. 16, no. 2, pp. 792–803, 2008.
- [27] D. Che, Q. Hu, and W. Shieh, "Linearization of Direct Detection Optical Channels Using Self-Coherent Subsystems," *J. Light. Technol.*, vol. 34, no. 2, pp. 516–524, Jan. 2016.
- [28] D. van den Borne, S. Calabro, S. L. Jansen, E. Gottwald, G. D. Khoe, and H. de Waardt, "Differential quadrature phase shift keying with close to homodyne performance based on multi-symbol phase estimation," pp. 12–12, Jan. 2005.
- [29] S. Faralli, K. N. Nguyen, J. D. Peters, D. T. Spencer, D. J. Blumenthal, and J. E. Bowers, "Integrated hybrid Si/InGaAs 50 Gb/s DQPSK receiver," *Opt. Express*, vol. 20, no. 18, pp. 19726–19734, Aug. 2012.
- [30] J. Klamkin et al., "A 100-Gb/s noncoherent silicon receiver for PDM-DBPSK/DQPSK signals," *Opt. Express*, vol. 22, no. 2, p. 2150, Jan. 2014.

- [31] P. Velha, S. Faralli, and G. Contestabile, "A Compact Silicon Photonic DQPSK Receiver Based on Microring Filters," *IEEE J. Sel. Top. Quantum Electron.*, vol. 22, no. 6, pp. 418–424, Nov. 2016.
- [32] J. Li et al., "A self-coherent receiver for detection of PolMUX coherent signals," *Opt. Express*, vol. 20, no. 19, pp. 21413–21433, Sep. 2012.
- [33] X. Chen et al., "218-Gb/s Single-Wavelength, Single-Polarization, Single-Photodiode Transmission Over 125-km of Standard Singlemode Fiber Using Kramers-Kronig Detection," in *Optical Fiber Communication Conference Postdeadline Papers*, 2017, p. Th5B.6.
- [34] R. Kamran, N. B. Thaker, M. Anghan, N. Nambath, and S. Gupta, "Demonstration of a polarization diversity based SH-QPSK system with CMA-DFE equalizer," in *Wireless and Optical Communication Conference (WOCC)*, 2017, pp. 1–4.
- [35] M. Y. S. Sowailem et al., "100G and 200G single carrier transmission over 2880 and 320 km using an InP IQ modulator and Stokes vector receiver," *Opt. Express*, vol. 24, no. 26, p. 30485, Dec. 2016.
- [36] Q. Hu, D. Che, Y. Wang, and W. Shieh, "Advanced modulation formats for high-performance short-reach optical interconnects," *Opt. Express*, vol. 23, no. 3, p. 3245, Feb. 2015.
- [37] C. Doerr et al., "Silicon photonics coherent transceiver in a ball-grid array package," in *Optical Fiber Communications Conference and Exhibition (OFC)*, 2017, 2017, pp. 1–3.
- [38] G. Roelkens et al., "III-V-on-Silicon Photonic Devices for Optical Communication and Sensing," *Photonics*, vol. 2, no. 3, pp. 969–1004, Sep. 2015.