Toward Transport Ecosystem Interoperability Enabled by Vendor-Diverse Coherent Optical Sources Over an Open Line System

Mark Filer, Hacene Chaouch, and Xiaoxia Wu

***Abstract*—Optical line-side interoperability is a critical component for enabling cloud service providers to deploy capacity at scale with a diverse supply chain. Historically, vendor-locked line systems and proprietary coherent digital signal processing (DSP) technologies have been barriers to this goal. Advances in open line platforms and coherent interfaces embedded directly in layer-2/3 switches and routers have begun paving the way toward full end-to-end interoperation. In this paper, we take a partial step toward demonstrating end-to-end interop by interoperating vendor-diverse packet switching platforms from Arista, Cisco, and Juniper, which utilize the same coherent DSP chip set, over an open line system (OLS). All three vendors' switches feature integrated coherent optics and are shown to interoperate over 2000 km at 150G 8QAM and 1000 km at 200G 16QAM on Microsoft's OLS.**

***Index Terms*—Data center networking; Interoperation; Open line systems; Optical coherent transceiver; Optical fiber communication; Software defined networking.**

I. Introduction

Long-haul and metro bandwidth demand continue to increase for large-scale cloud providers, driven by phenomenal growth of cloud services and the globally distributed nature of data centers. To efficiently meet demand, cloud providers have driven the OLS concept [1–3]. OLS disaggregates line system components, such as amplifiers, gain equalizers, reconfigurable add/drop multiplexers (ROADMs), and optical channel monitors, from coherent optical transceivers associated with the line system. Motivation for this disaggregation is multifold but fundamentally rests on the premise that OLS components are relatively long-lived, technologically stable, and largely undifferentiated parts of an optical transmission system compared with transceivers, which are still rapidly evolving.

Manuscript received July 3, 2017; revised November 7, 2017; accepted November 10, 2017; published January 25, 2018 (Doc. ID 301520).

M. Filer (e-mail: mark.filer@microsoft.com) is with Azure Networking, Microsoft Corporation, Redmond, Washington 98052, USA.

H. Chaouch is with Arista Networks, Santa Clara, California 95054, USA.

X. Wu is with Juniper Networks, Sunnyvale, California 94089, USA.

https://doi.org/10.1364/JOCN.10.00A216

Because of this rapid evolution, coherent transceivers have made little progress toward line-side signal interoperability [3–5]. Each coherent digital signal processor (DSP) supplier has improved performance and feature sets with independent efforts and no interoperability standards. Recently, spectral efficiency of the various DSPs has begun to asymptotically approach channel capacities predicted by Shannon, and the various DSPs are now realizing ever smaller relative performance gains while simultaneously chasing ever more esoteric features to claim differentiation (multidimensional modulation [6,7], probabilistic constellation shaping [8], digital subcarrier multiplexing [9], and digital nonlinear compensation [10,11] are in view).

However, cloud providers generally do not require esoteric features. Specifically, long-haul and metro transmissions systems are largely viewed as a means to connect the highest possible bandwidths between clusters of routers or switches in a point-to-point fashion at maximal interface speeds. It is already common for cloud providers to maximally light multiple, entire optical systems in metro areas to interconnect data centers. Accelerating bandwidth demands in the long-haul are driving a need to view long-haul systems in a similar manner. To realize this, simplicity, efficiency, and supply-chain diversity are major focus areas. Emphasis on squeezing out the final 10% or 20% to approach the Shannon limit or adding a plethora of obscure features hinders acceleration of mass deployment. Ultimately, the industry must agree on line-side interoperability to create a robust supply chain and accelerate the deployment of capacity.

This paper is an expansion of the work presented in [12] and is divided as follows. Section II provides context for historical barriers to interoperation as they relate to optical line system technology. Section III discusses the architectural considerations, which go into the design of coherent sources, including choices around electro-optic and DSP integration, optical process technologies, and switch silicon—all of which must interoperate without trade-offs in performance. Finally, Section IV illustrates a partial step toward end-to-end transport ecosystem interoperability by demonstrating interoperability over an OLS between packet switch systems provided by three different suppliers—Arista, Cisco, and Juniper—each with their own version of integrated coherent optics (ICO) line cards, where the coherent

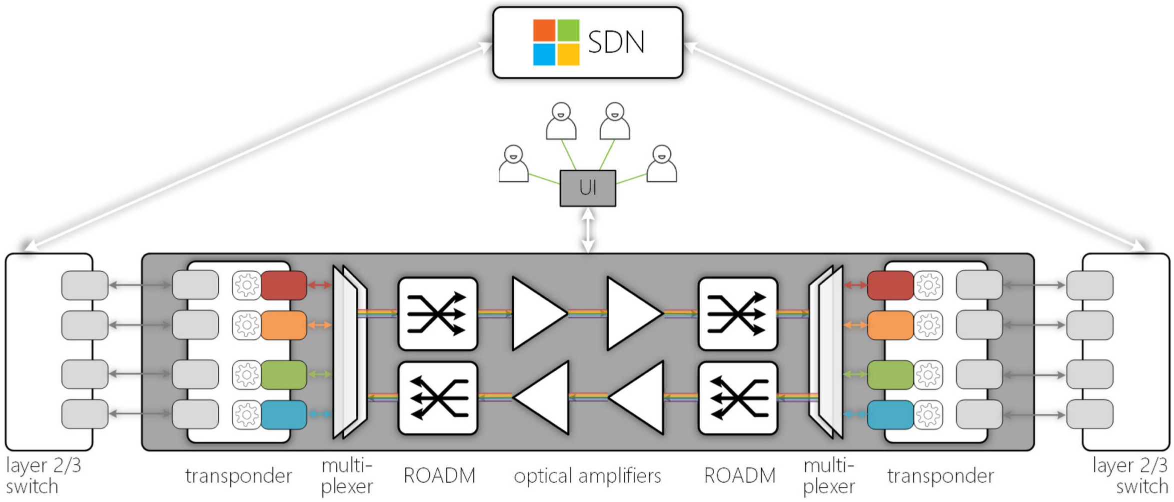

Fig. 1. Traditional "closed" line system, with propriety coherent transponder sources of the same manufacturer (dark gray rectangle).

transponders are integrated directly into the switch platform. The three suppliers interoperate while utilizing two fundamentally different packet chipsets and two different electro-optic technologies; however, all three rely upon the same coherent DSP, which is the only component in the end-to-end ecosystem that is not vendor-interoperable.

II. Prerequisite for Interop

A barrier to line-side interoperation has been the traditional "closed" approach to optical line systems. Historically, line systems have been necessarily paired with optical sources of the same manufacturer. Figure 1 depicts this approach to line system technology, which is what is deployed in Microsoft's legacy backbone today. The transponders and line elements must be from the same supplier because the system network- and element-management software (NMS, EMS) and layer-0 controllers are designed to only handle those sources. Also, such line systems tend to be architected from the ground up around proprietary transponder technologies. Some of these architectural design features make the notion of carrying alien wavelengths from a third-party transponder source cumbersome and difficult to manage from development and operational perspectives.

As shown in Fig. 1, the router and switch ports must have gray optical transceivers and patch cables connecting them to the gray optics in client ports of the proprietary optical transponders. The signals are then electrical-optical-electrical regenerated, typically with the addition of optical transport network (OTN) framing and forward error correction (FEC), before being transmitted out of line ports and multiplexed in a DWDM fashion over the fiber infrastructure. The layer-0 controller, which is also vendor-proprietary, manages the optical channel routing and power leveling, and relies on inputs from the vendor-proprietary transponders. And, unlike the layer-2/3 devices which are under software-defined network (SDN) control and management, the closed-line system must be managed manually via vendor-proprietary NMS, EMS, TL1, or command line interface (CLI). Because of this, the pipe through which the Internet protocol (IP) traffic is flowing is effectively a black box, providing no visibility of root cause to the cloud network SDN controller in the event of a broken link.

In contrast, the backbone optical network requirements of cloud service providers (CSPs) are met by line systems with streamlined feature sets optimized for coherent transmission. The long-haul network is made up largely of point-to-point segments connecting geographical regions, so directionless and contentionless ROADM capabilities are generally not in scope. Traditional telco-grade features such as electrical OTN switching, sub-line-rate aggregation/grooming, optical layer restoration, mesh connectivity (optical bandwidth on demand), are not needed. Additionally, technological advances such as colorless, flexible-grid ROADMs "futureproof" the infrastructure, granting a longer shelf life to the common line system hardware. The line system can now remain in use through several technology refreshes of the coherent sources that connect to it. And because all traffic in such networks are packet-based, there is no need for demarcation between layer-1 and layer-0, and gray optical interfaces can be completely eliminated.

These factors, and a desire for line-side interoperability, have led several CSPs to employ open line system technology [1]—a disaggregation of the photonic layer in which the DWDM optical sources are decoupled from the DWDM line system (Fig. 2). Contrasted with closed line systems, several key advantages are immediately evident for the OLS. The OLS is optical source agnostic—it allows the provider to select and procure optical sources independently from the line system itself and from a variety of suppliers and platforms (e.g., ICO versus transponder) to best suit the needs of each region's requirements. Specifically for Microsoft, the OLS allows the SDN-enabled transport of wavelengths from multiple suppliers' ICO line cards. The OLS also extends SDN control—configuration, monitoring, data collection, alerting, and ticketing—to the individual optical network elements (NEs), from just the layer-2/3 devices shown in Fig. 1, giving end-to-end SDN visibility from layer-0 up through layer-3.

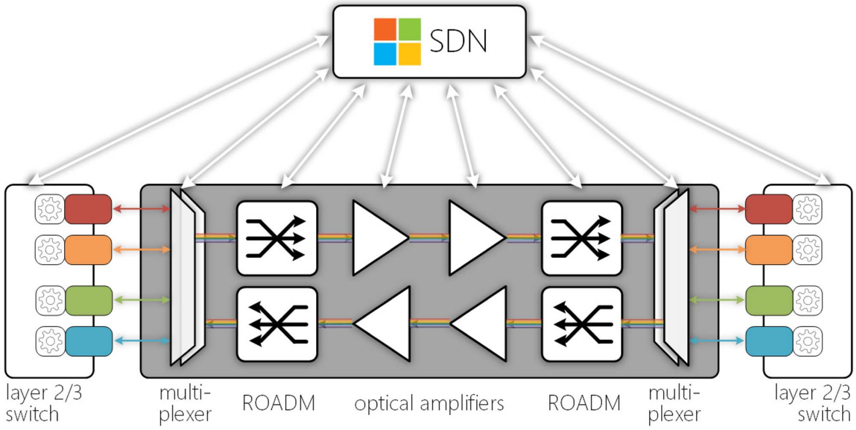

Fig. 2. Open line system (OLS) concept showing the disaggregated photonic layer and layer-2/3 switch with embedded coherent optical sources. All layers of the ecosystem tie into a single overarching SDN controller.

This frees CSPs from having to rely on vendor-supplied, proprietary, manually driven NMS/EMS and is a necessary functionality to move toward developing and operating a zero-touch network with supplier-diverse optical sources.

III. Line Card Implementation Considerations

Armed with an OLS, which can properly handle a diversity of optical sources, one may focus on the various sources available, which are well-suited for CSP's applications. As outlined in Section II and in [1], many of the features required in traditional long-haul solutions may be omitted in CSP applications, and accordingly, the most simple and efficient optical source is optics integrated directly into the Ethernet switching platforms.

Several suppliers are providing such a solution, each with slightly different implementations of an ICO line card. One of the most critical design choices is the coherent DSP, as this drives many of the other decisions around performance, density, and total capacity of the line card. While today proprietary DSP implementations are the primary barrier for end-to-end interop, for the line cards chosen in this demonstration, all three suppliers converged on design choice for the coherent DSP chipset (described further in Section IV), making line-side interoperation possible without incurring performance trade-offs.

In addition to DSP choice, each supplier must make implementation decisions about whether to disaggregate the coherent DSP from the optics, what type of optical process technology to use for the electro-optics, and switch silicon design. The following subsections discuss the architectural and design trade-offs each supplier must negotiate in the development of an ICO offering.

A. Disaggregated Versus Integrated Coherent Optics

Subsections III.A.1–III.A.3 explore trade-offs of disaggregating optical modules from DSP versus an integrated approach. Advantages and drawbacks of each are discussed in detail and summarized in Table I when considering technologies available at the time of publication (and not necessarily what is possible). "Plug-and-play" refers to the idea that a module behaves as a gray optic would—no analog interfaces to consider, modules with digital interfaces and

TABLE I
Optical Integration Comparison

Attribute	DCO	ACO	On-Board Coherent
Density	High density possible for metro with lower process node, low power DSPs	Highest for high-performance long-haul applications	Depends on the mounted optics footprint
Plug-and-play	Yes	Possible	No
Interface management complexity	Relatively simple, low-speed digital interface	Relatively complex, high-speed analog interface	Relatively simple, low-speed digital interface
System integration/ maintenance complexity	Simple deployment and easy replacement	Relatively simple deployment and easy replacement	Simple deployment but complex replacement
Multivendor interoperability	Possible only if vendors are using the same FEC, framing, and tones in the coherent DSP	Yes, photonics level interoperation	Possible only if vendors are using the same FEC, framing, and tones in the coherent DSP

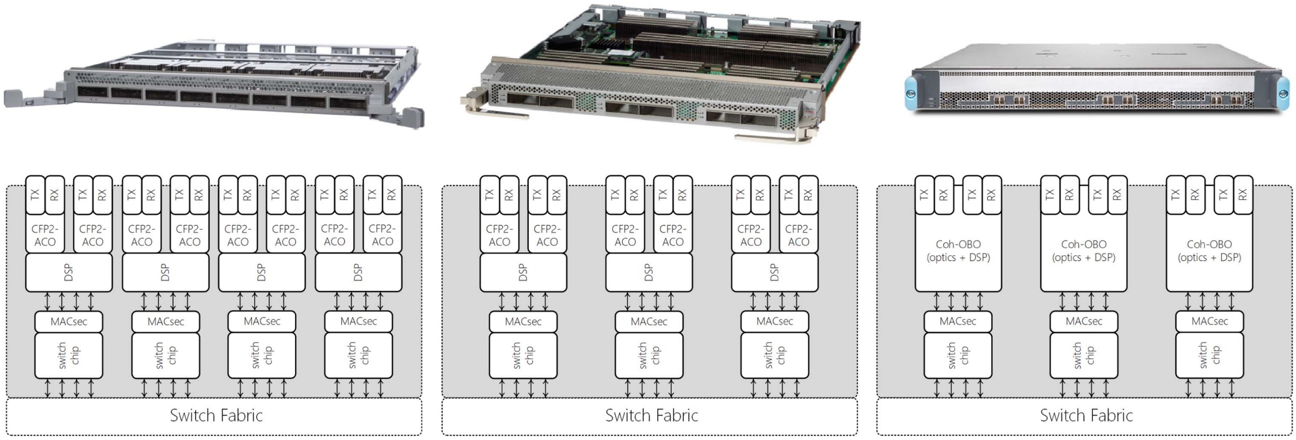

Fig. 3. ICO line card lineup, from left to right: Arista 7500R-series 8-port, Cisco NCS5500 series 6-port, and Juniper QFX10000 series 6-port layer 2/3 coherent line cards.

identical pinouts, fully interchangeable. "Multi-vendor interoperability" should be understood relative to sourcing of modules because, with analog coherent modules, the DSP and optics are disaggregated; thus, a larger number of potential suppliers can provide such solutions than digital modules, which are inherently tied to DSP availability.

1) Analog Coherent Optics: Today's analog coherent optics (ACO) incorporate a wide variety of electro-optic technologies and employ a broad array of modern photonics offerings. Whether it is indium phosphide (InP), silicon photonics (SiP), or lithium niobate ($LiNbO_3$) based modulators, monolithic or discrete laser sources, semiconductor optical amplifier or erbium-doped fiber amplifier power-boosted, a multitude of module architectures are represented in the ACO market with a high degree of product maturity.

Unbundling the DSP chipset from the photonic engine has enabled traditional optics vendors to build transceivers with higher density (e.g., CFP2-ACO), lower cost, and much faster times to market, while giving system vendors the freedom of choosing the DSP and optical solutions that best fit their specific transmission requirements.

This separation did not come for free, however; it required a total redefinition of the overall system ownership and liability from an optical performance standpoint. Within this new analog model, and, despite optics vendors striving to build subassemblies with best-in-class components, many have fallen short in providing binding system-level specifications. Further complicating matters, today system vendors are shipping "empty" coherent ports with the hopeful premise that, once customers plug in their optics, the DSP+ACO pair behaves as one cohesive entity that delivers the intended performance. To address the boundary between optics and DSPs, the OIF has produced a CFP2-ACO implementation framework that aims at specifying all key parameters of the analog E/O and O/E interfaces, including IQ skews in H and V polarizations and S21 responses of the transmit and receive paths [13,14].

The ACO approach was implemented in the Arista 7500R and Cisco NCS5500 platforms (Fig. 3, left and center).

2) Digital Coherent Optics: In contrast with the analog model, digital coherent optics (DCO) integrate the coherent DSP chipset and the photonic engine into the same module. DCOs can utilize all of the same optical technologies that ACOs can, and at the same time minimize the work required to manage the high-speed interface between the coherent DSP and the electro-optics. Consequently, DCOs can substantially reduce integration efforts for system vendors who employ them.

The main drawback to this approach is that the additional power and space required by the coherent DSP chip inside the transceiver potentially reduces the density level of DCO solutions. This is particularly true with high-performance, power-hungry, long-haul optimized ASICs. However, for short-reach metro and data center interconnect (DCI), where systems are not OSNR-limited, DCO modules based on lower power, metro-optimized DSPs are clear winners. DCI reaches of up to 120 km, currently being addressed in the OIF's 400ZR project [15], should provide an ideal use case for DCO-based solutions.

3) On-Board Coherent Optics: A compromise between ACO and DCO approaches is the on-board optics concept. When the same front panel capacity is ensured, on-board

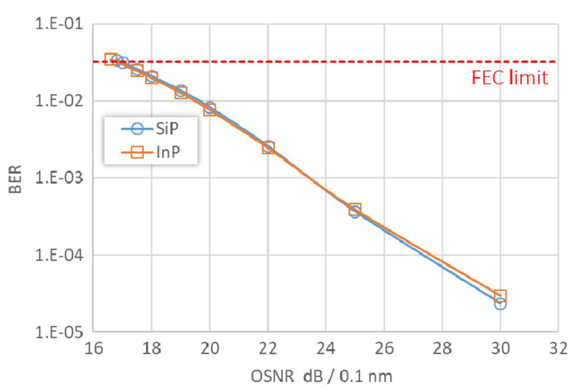

Fig. 4. 16QAM performance, silicon photonics, and indium phosphide.

optics take advantage of the additional footprint and power on the host card to allow higher-performing DSPs (i.e., suitable for long-haul/subsea applications) through a simple digital socketed interface such as a 300-pin MSA package. A fundamental limitation of this integration model, however, is the loss of pluggability. In the case of an individual channel failure, the deficient optics cannot be individually removed and replaced without affecting the operation of the remaining channels. Addressing these limitations, the consortium for on-board optics (COBO) project, established in 2015, aims at promoting the adoption of on-board optics solutions within the industry. A specific workgroup within COBO is targeting a coherent module that can overcome these drawbacks [16].

Juniper opted to implement an on-board coherent MSA solution in the QFX10000 platform (Fig. 3, right).

B. Optical Process Technology

Indium-phosphide (InP) and SiP are the two main technology platforms competing in today's high-density, high-speed intra- and inter-datacenter interconnects. In the CFP2-ACO example, the two materials exhibit both compelling advantages and limiting disadvantages. For instance, InP enables 1) the monolithic integration of lasers and modulators, 2) large E/O modulation bandwidths, 3) low insertion and coupling losses, and 4) moderate drive voltages. However, InP waveguides' lower index contrast and need to be hermetically sealed in principle limit the density level and yields that it can achieve.

On the other hand, SiP, which is denser thanks to a stronger index delta (Δn) due to Si on SiO_2 [17–19], leverages well-established CMOS-like processes to enable wafer production with hundreds of yielded photonic integrated circuits (PICs) per wafer. Recent advances in heterogeneous integration of InP in silicon will further enable the addition of the laser piece within the SiP PIC removing the need for external tunable laser assemblies (TLAs) [20]. Nonetheless, SiP suffers from 1) fundamentally higher switching voltages (V_π), and 2) significantly larger modulation and coupling losses. This often calls for the use of costly micro-EDFAs and tunable filters to guarantee appropriate transmitter powers without compromising out-of-band OSNR levels.

Despite the differences in these two technologies, optical performance between the two is nearly indistinguishable, owing to the DSP's ability to compensate for electro-optic impairments. Figure 4 shows a back-to-back performance comparison between two best-in-class InP and SiP CFP2-ACOs on the Arista 7500R line card [21]. Back-to-back required OSNR at the FEC limit for 16QAM is within 0.1 dB of each other, with no discernable difference in error floor.

C. Switch Silicon

Though the focus of the interoperation is at the optical layer, it is worth noting that the Arista 7500R and Cisco NCS5500 are based on Broadcom's Jericho chipset, while the Juniper QFX 10000 is based on their own internally developed Q5/ExpressPlus chipset. Both chipsets provide deep packet buffers and use virtual output queuing over a cell-based fabric. While there are some differences in capabilities of on-chip forwarding databases and external memory bandwidth, these differences do not hinder interoperation between the switched platforms.

IV. Interop Demonstration

A. Configuration

As mentioned, three packet switching systems participated in the interop demonstration in Microsoft's Redmond labs—the Arista 7500R, Cisco NCS5500, and

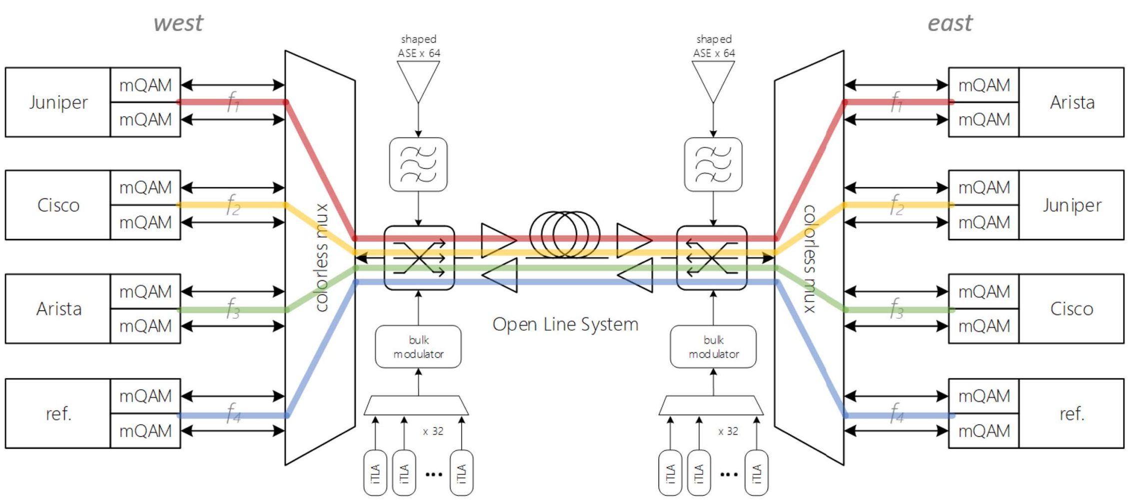

Fig. 5. Interoperation demo configuration–ICO line cards from each of three suppliers along with a reference coherent source utilizing the same DSP. Bulk-modulated lasers (32 channels) and shaped broadband ASE (64 "channels") filled out the rest of the spectrum for worst-case propagation penalties.

TABLE II
CHANNEL SCHEME FOR INTEROP

Freq.	Lane 0 [THz]	Lane 1 [THz]	West	East
f_1	193.5375	193.6875	Juniper	Arista
f_2	193.5750	193.7250	Cisco	Juniper
f_3	193.6125	193.7625	Arista	Cisco
f_4	193.6500	193.8000	Ref.	Ref.

Juniper QFX 10000 (Fig. 3). Each switch chassis was equipped with industry standard 100G QSFP28 gray cards as well as an ICO line card providing coherent DWDM channels. The ICO cards each have distinct implementations, with Juniper electing to integrate a complete and generally available on-board coherent MSA, and the Arista and Cisco using discrete coherent DSP and face-plate-pluggable analog optics (CFP2-ACO). However, because all ICOs opted for the same coherent DSP, line-side interoperation is possible. All ICOs provide selectable QPSK/8QAM/16QAM modulation with a line rate of 100G/150G/200G, respectively, 25% overhead SD-FEC, and Nyquist pulse shaping. The electro-optics used in this demonstration include both SiP and indium phosphide InP processing technologies, and all interfaces support gridless tuning with 6.25 GHz resolution and 37.5 GHz channel spacing at full line rate.

The interop demo system configuration is shown in Fig. 5. An ICO line card from each switch supplier was placed at both ends of the system ("east" and "west") and provided six bidirectional test channels (two per supplier). Interop between the different manufacturer's switch ports was achieved optically via software, utilizing the colorless aspects of the OLS, by simply tuning the lasers of the coherent ports on the east and west ends of the system to achieve the desired combinations of transmit/receive pairs. The laser frequency settings shown in Table II, which correspond to the color-coded lines in Fig. 5, demonstrate how this was done for these measurements. This configuration ensures that each switch supplier is transmitting/receiving to/from each of the other switch suppliers when considering both east and west paths. Figure 6 details the transmitted spectra from each of the line cards in the east to west direction, which correspond to the "east" column of Table II. Each ICO port was configured with identical encoding, and with a root-raised cosine (RRC) pulse-shape at a roll-off of 0.2. A generally available stand-alone integrated transceiver utilizing the same coherent DSP was added as a reference (labeled "Ref." in Fig. 6) [22].

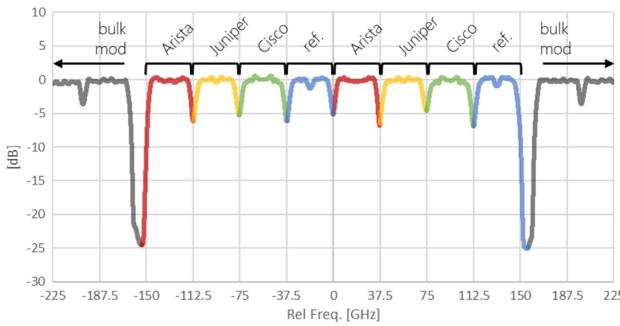

Fig. 6. Optical spectrum of coherent sources.

A total of 32 bulk-modulated sources were evenly distributed on either side of the devices under test (DUT), modulated with the same modulation format, baud rate, and pulse-shape as the DUTs. Another 64 shaped-ASE "channels" were added to load the remainder of the C-band.

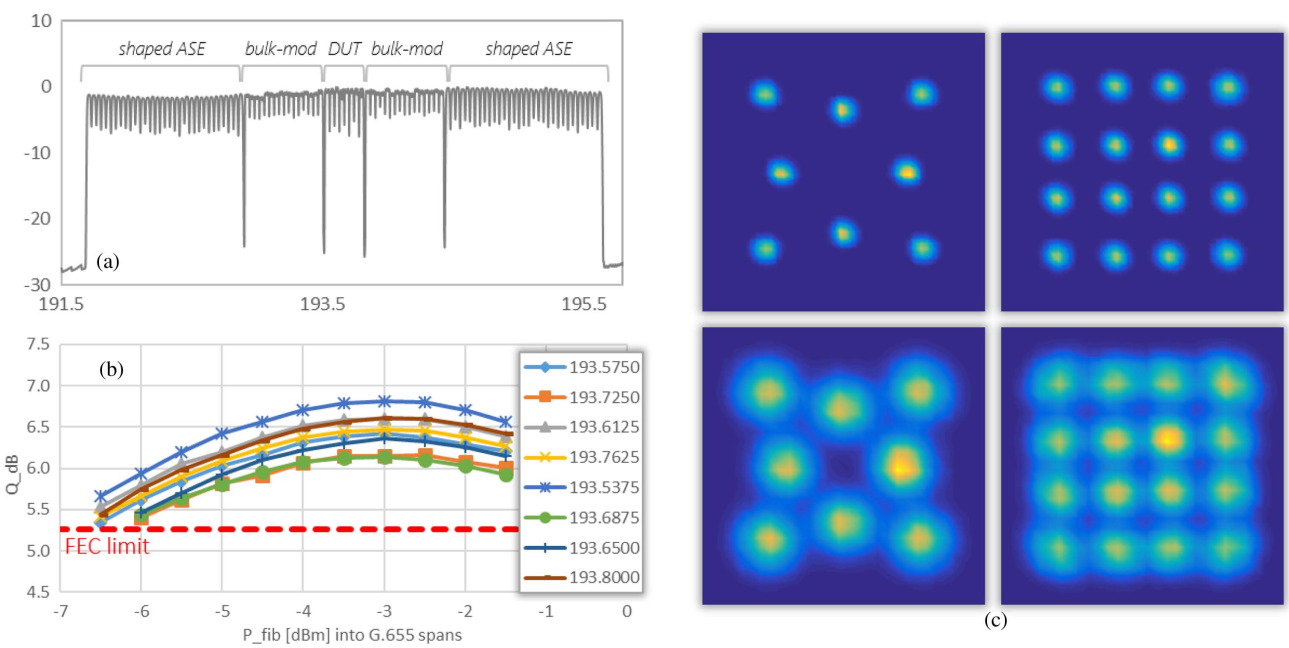

Fig. 7. (a) Optical spectrum launched into fiber with 104 channels spaced 37.5 GHz. (b) Launch power optimization for 8QAM over 2000 km testbed. (c) Constellation for 8QAM and 16QAM reference signal before and after propagation.

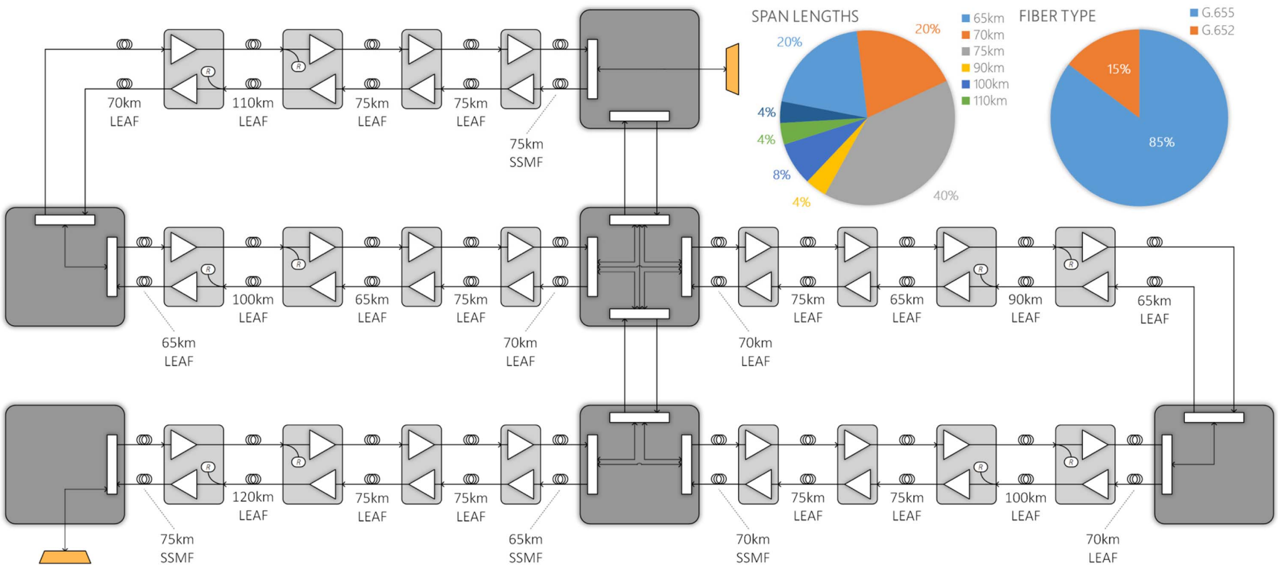

Fig. 8. OLS testbed featuring full bidirectional 2000 km transmission paths. Inset: distributions of fiber span length and fiber type.

The ASE channels were shaped with a programmable WSS to emulate RRC = 0.2 mQAM. Both the bulk mod and ASE channels are shown conceptually in Fig. 5 being added at the ingress/egress ROADM node. In total, 104 channels spaced 37.5 GHz were propagated for all results reported [Fig. 7(a)]. Spectral dips seen between channel groupings are intentionally provisioned 6.25 GHz "dead-bands," which avoid the impact of WSS roll-off as channel groups are muxed or demuxed at terminal ROADMs. Measured performance is expected to be conservative because 1) no specific measures were taken to time-decorrelate the bulk-modulated channels and 2) ASE channels produce more harmful cross-phase modulation than data-modulated carriers.

The transmission testbed consisted of the OLS and fiber plant, as shown in Fig. 8. The OLS features a colorless, directional architecture with full SDN-enabled support for alien wavelengths. The mostly NZ-DSF fiber plant spans 2000 km bidirectionally and is roughly made up of 85% Corning LEAF and 15% Corning SMF-28e LL (Fig. 8, inset). The optical ports of the line cards were patched into the OLS colorless multiplexers on each end, along with the bulk-modulated and ASE channels.

Once the line cards and line system were properly configured, traffic generator test-set ports were connected to 100G QSFP28 gray ports of the switch residing at the beginning and end of the path. The test-set generated traffic at 100% line rate, i.e., 100 Gb/s UDP traffic with a 1000 byte packet size to a fixed IP address. Traffic was weaved through all available 100G client interfaces by setting up virtual routing and forwarding paths (VRFs) and static routes on all three connected switches. A similar traffic flow was set up in the opposite direction, which resulted in bidirectional traffic at maximum link utilization.

B. Results and Discussion

With all ICOs configured for 8QAM transmission at 150 Gb/s line rate, and layer-3 test-set traffic flowing,

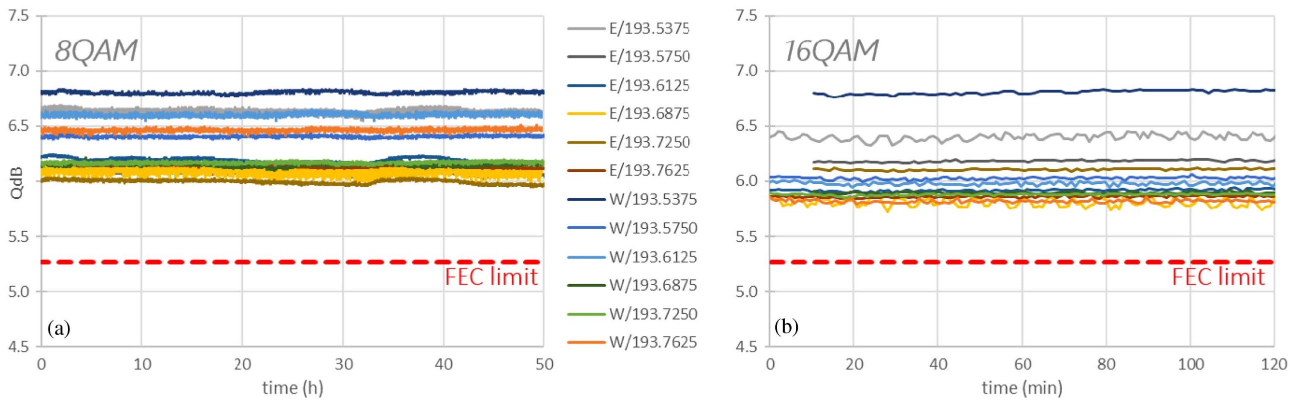

Fig. 9. Long-term BER log of (a) 8QAM over 2000 km and (b) 16QAM over 1000 km. E = east, W = west.

a sweep of fiber launch power was performed for all 104 channels. The result (for the east to west direction) is shown in Fig. 7(b). The *x*-axis references launch power into G.655 LEAF spans; launch powers into G.652 SMF-28e fibers were 3 dB greater than those shown. At the optimum launch power of −3 dBm/channel into LEAF (0 dBm/channel into SMF-28e), the *Q*-factor was more than 1 dB above the FEC limit, and an OSNR margin between 2 and 2.5 dB was measured. The system ran for 48 h with full-rate test-set traffic at optimal launch power, and the pre-FEC BER was logged during the entire period in both the east and west directions [Fig. 9(a)] for stability analysis. The peak-to-peak *Q* factor varied by ∼0.1 dB, and over 2.5e12 packets were transmitted during the logging period, with 0 packets lost. After the logging period expired, a capture of the transmit and received constellations was performed, as shown in Fig. 7(c).

Next, all ICOs were reconfigured for 16QAM at 200 Gb/s line rate. Client traffic VRFs and routes had to be reconfigured to account for the increase from three to four 100G streams on each coherent interface, but optically the interfaces were unchanged. The line system distance was reduced from 2000 km to 1000 km (optimal launch power assumed the same), and once end-to-end traffic was verified, the test set and pre-FEC BER logs were restarted. Between 0.5 and 1.5 dB *Q* margin was measured [Fig. 9(b)], and no packets were lost over a 2 h traffic test. Transmit and received constellations are shown in the right half of Fig. 7(c).

V. Conclusion

Interoperation was demonstrated among three different switch suppliers using ICO and two different electro-optic technologies. Over primarily NZ-DSF, 8QAM at 2000 km and 16QAM at 1000 km was demonstrated without trading performance or spectral efficiency for interoperability. The electro-optics used in this demonstration comprise both SiP and InP processing technologies, and the results presented demonstrate the suitability of both platforms for long-haul 8/16QAM transport and interoperation.

Constructing global network infrastructures at cloud scales already leverages the extensive interoperability that exists in the switching, routing, and gray optical technologies. Additionally, the OLS is essentially a stand-alone system not requiring interop at this time. The only missing interoperable component in the entire network ecosystem is the coherent DSP that drives the electro-optics, interconnecting switches, or routers over OLS.

Acknowledgment

The authors thank J. Gaudette and J. Cox for their contributions to the manuscript upon which this work was based [12] and to the following for the long hours and support of this multivendor interoperability demonstration: A. Bhiday, J. Callaway, U. Panchal, A. Premji, and the rest of the Arista "Cloudrest" team; P. Chou and the rest of the Cisco "Fretta" team; B. Westbrook, A. Gupta, C.-H. Wu, O. Moeller, and the rest of the Juniper "Voodoo" team; and M. Pan of Acacia. This work would not have been possible without the cooperation of all of these individuals and the teams behind them.

References

[1] M. Filer, J. Gaudette, M. Ghobadi, R. Mahajan, T. Issenhuth, B. Klinkers, and J. L. Cox, "Elastic optical networking in the Microsoft cloud," *J. Opt. Commun. Netw.*, vol. 8, no. 7, pp. A45–A54, 2016.

[2] J. L. Cox, "SDN control of a coherent open line system,," in *Optical Fiber Communication Conf. (OFC)*, Los Angeles, California, 2015, paper M3H.4.

[3] M. Gunkel, A. Mattheus, F. Wissel, A. Napoli, J. Pedro, N. Costa, T. Rahman, G. Meloni, F. Fresi, F. Cugini, N. Sambo, and M. Bohn, "Vendor-interoperable elastic optical interfaces: Standards, experiments, and challenges [Invited]," *J. Opt. Commun. Netw.*, vol. 7, no. 12, pp. B184–B193, 2015.

[4] H.-J. Schmidtke and R. Marcoccia, "DWDM optical line-side interoperability," in *Optical Fiber Communication Conf. (OFC)*, 2012, paper OM3G.7.

[5] M. Tomizawa, "100G DWDM transport systems: Driving the technologies and deployment," in *Int. Conf. Optical Internet (COIN)*, 2012, paper TuE.2.

[6] E. Agrell and M. Karlsson, "Power-efficient modulation formats in coherent transmission systems," *J. Lightwave Technol.*, vol. 27, no. 22, pp. 5115–5126, 2009.

[7] D. S. Millar, T. Koike-Akino, S. Ö. Arık, K. Kojima, K. Parsons, T. Yoshida, and T. Sugihara, "High-dimensional modulation for coherent optical communications systems," *Opt. Express*, vol. 22, no. 7, pp. 8798–8812, 2014.

[8] T. Fehenberger, A. Alvarado, G. Böcherer, and N. Hanik, "On probabilistic shaping of quadrature amplitude modulation for the nonlinear fiber channel," *J. Lightwave Technol.*, vol. 34, no. 21, pp. 5063–5073, 2016.

[9] M. Qiu, Q. Zhuge, M. Chagnon, Y. Gao, X. Xu, M. Morsy-Osman, and D. V. Plant, "Digital subcarrier multiplexing for fiber nonlinearity mitigation in coherent optical communication systems," *Opt. Express*, vol. 22, no. 15, pp. 18770–18777, 2014.

[10] E. Ip and J. M. Kahn, "Compensation of dispersion and nonlinear impairments using digital backpropagation," *J. Lightwave Technol.*, vol. 26, no. 20, pp. 3416–3425, 2008.

[11] Z. Tao, L. Dou, W. Yan, L. Li, T. Hoshida, and J. C. Rasmussen, "Multiplier-free intrachannel nonlinearity compensating algorithm operating at symbol rate," *J. Lightwave Technol.*, vol. 29, no. 17, pp. 2570–2576, Sept. 2011.

[12] M. Filer, H. Chaouch, X. Wu, J. Gaudette, and J. L. Cox, "Interoperation of layer-2/3 modular switches with 8QAM/16QAM integrated coherent optics over 2000 km open line system," in *Optical Fiber Communication Conf.*, 2017, paper W4H.1.

[13] "Implementation agreement for CFP2-analog coherent optics module," OIF-CFP2-ACO-01.0, Jan. 22, 2016 [Online]. Available: http://www.oiforum.com/wp-content/uploads/OIF-CFP2-ACO-01.0.pdf.

[14] H. Chaouch, M. Filer, and A. Bechtolsheim, "Lessons learned from CFP2-ACO system integrations, interoperability testing and deployments," in *Optical Fiber Communication Conf.*, 2017, paper Th1D.4.

[15] "The OIF's 400ZR coherent interface starts to take shape," June 22, 2017 [Online]. Available: http://www.gazettabyte.com/home/2017/6/22/the-oifs-400zr-coherent-interface-starts-to-take-shape.html.

[16] http://cobo.azurewebsites.net/.

[17] C. R. Doerr, J. Heanue, L. Chen, R. Aroca, S. Azemati, G. Ali, G. McBrien, L. Chen, B. Guan, H. Zhang, X. Zhang, T. Nielsen, H. Mezghani, M. Mihnev, C. Yung, and M. Xu, "Silicon photonics coherent transceiver in a ball-grid array package," in *Optical Fiber Communication Conf. (OFC)*, 2017, paper Th5D.5.

[18] T. Nielsen, "Engineering silicon photonics solutions for metro WDM," in *Optical Fiber Communication Conf. (OFC)*, 2014, paper Th3J.1.

[19] T. Saida, "Emerging integrated devices for coherent transmission-digitally assisted analog optics," in *Optical Fiber Communication Conf.*, 2017, paper Th3B.4.

[20] H. Chaouch, E. Marchena, J. Spann, H. Cai, H. Potluri, J. Zyskind, S. Krasulick, A. Vigloenzoni, G. Bruno, M. Camera, and A. Tartaglia, "High power narrow linewidth low noise integrated CMOS tunable laser for long haul coherent applications," in *European Conf. on Optical Communication*, 2014.

[21] M. Filer and H. Chaouch, "Transmission performance of layer-2/3 modular switch with mQAM coherent ASIC and CFP2-ACOs over flex-grid OLS with 104 channels spaced 37.5 GHz," in *Optical Fiber Communication Conf. (OFC)*, 2017, paper Th1D.2.

[22] C. Doerr, L. Chen, T. Nielsen, R. Aroca, L. Chen, M. Banaee, S. Azemati, G. McBrien, S. Y. Park, J. Geyer, B. Guan, B. Mikkelsen, C. Rasmussen, M. Givehchi, Z. Wang, B. Potsaid, H. C. Lee, E. Swanson, and J. G. Fujimoto, "O, E, S, C, and L band silicon photonics coherent modulator/receiver," in *Optical Fiber Communication Conf. (OFC)*, 2016, paper Th5C.4.