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INDUSTRY INITIATIVE

Independent market research and competitive analysis of next-generation business and technology solutions for service providers and vendors

Making IPoDWDM a Reality

A Heavy Reading Industry Initiative produced for OIF, Ciena, Infinera, and Juniper

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INTRODUCTION

The commercialization of 400G coherent pluggable optics in QSFP-DD and OSFP form factors has sparked a resurgence of interest in integrated colored optics in routers, known as IP over DWDM, or IPoDWDM. To date, IPoDWDM is dominated by hyperscalers, but some leading-edge communications service providers (CSPs) have followed the hyperscalers' lead. Longer term, the real opportunity among CSPs is with high performance coherent pluggable variants generally referred to as ZR+. The ZR+ pluggable optics provide greater reach and the ability to run over telecom operators' reconfigurable optical add-drop multiplexer (ROADM)-based line systems.

The Optical Internetworking Forum (OIF) is taking a lead role in IPoDWDM standardization and interop testing for multiple coherent pluggable options, including 400ZR, 400G OpenZR+, OpenROADM, and 800ZR. Such work is important for all types of service providers and crucial for CSPs that have particularly complex networks that mix multiple distances and data rates and greenfield and brownfield environments.

Anchored in the pioneering standards work of the OIF and its member companies (which include Ciena, Infinera, and Juniper), this white paper makes the case for IPoDWDM adoption, specifically for CSPs. It describes the work that OIF has completed and is producing to make IPoDWDM a reality and discusses key roles for other organizations, particularly in open network-level management. Topics addressed include the following:

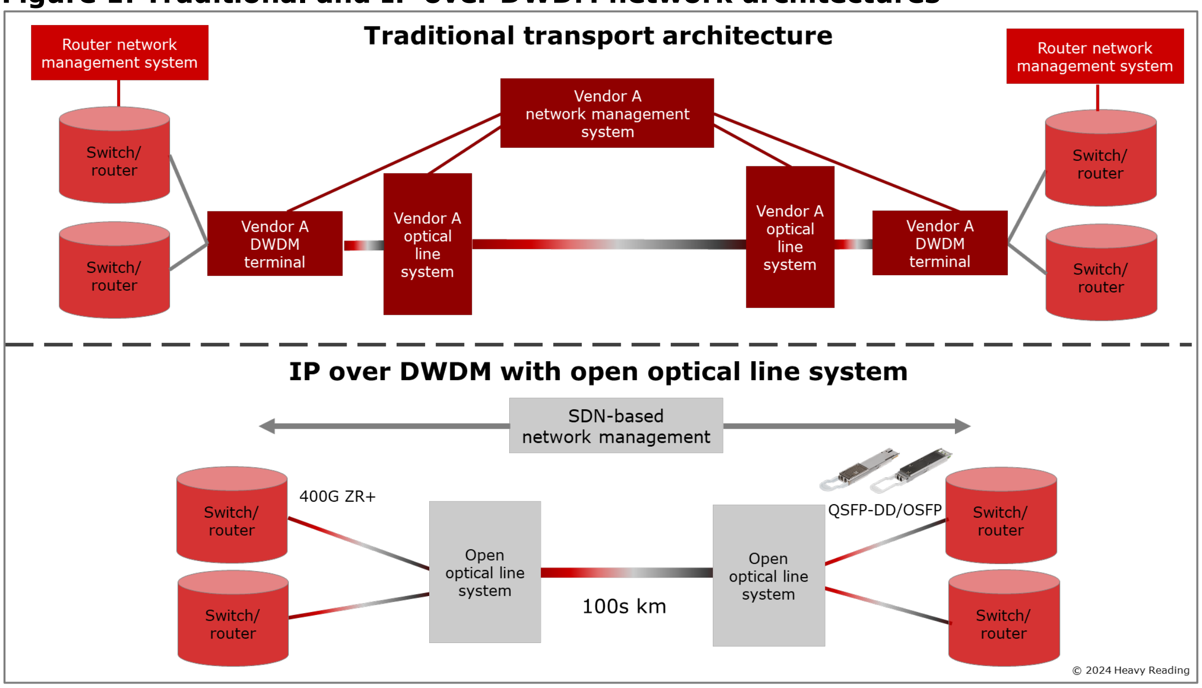
- Past barriers to IPoDWDM adoption
- The 400G turning point
- Drivers and benefits for CSPs
- CSP requirements for IPoDWDM adoption
- Scaling up to 800G, scaling down to 100G IPoDWDM
- Plug-to-host management with the Common Management Interface Specification (CMIS)
- Approaches for network management
- Interoperability ecosystems
- What is next for the industry

PAST CHALLENGES/BARRIERS TO IPoDWDM ADOPTION

IP and optical integration has a long history, going back to the late 1990s. It has had various names over the decades—including IP over DWDM, IP + optical, IP-optical convergence, and IP over glass. Today, some vendors are using newer terms, such as routed optical networks, coherent optical routing architecture (CORA), and coherent routing. Heavy Reading uses the generic term IP over DWDM (or IPoDWDM) to reference the concept, which involves the physical integration of long-reach, coherent, colored optics directly in a router (or other packet hosts) in place of short-reach client optics.

The architecture eliminates the short-reach optics otherwise needed to connect optics on the router to a DWDM system. The resulting simplified architecture saves on both capex and opex and, on paper, has always appealed to network operators. **Figure 1** illustrates simplified examples of traditional and IPoDWDM network architectures.

Figure 1: Traditional and IP over DWDM network architectures



Source: Heavy Reading, 2024

Despite its promise, however, aside from niche deployments over the years, IPoDWDM never took off at either 10Gbps or 100Gbps data rates. One of the biggest historical barriers is the "faceplate trade-off." At 10Gbps and 100Gbps, line-side optics were generally twice the physical size of client optics. Due to space constraints, outfitting a router with IPoDWDM effectively stranded up to half the router's capacity at a time when routing capacity was struggling to keep up with internet traffic growth. Additionally, line-side optics consumed much more power (~7x higher) compared with client optics at the time, further restricting available capacity.

The lack of interoperability and standardization presented another major problem for operators. More specifically, the lack of IPoDWDM standardization required single-vendor implementation for both the routing layer and the optical transport layer. For Tier 1 network operators, in particular, multi-layer vendor lock-in was and continues to be a non-starter.

Lastly, even if the above challenges could be overlooked, early IPoDWDM deployments lacked the right functionality for broad deployment in CSPs. A point-to-point routed connection over less than 100km is suitable for use by enterprise or hyperscaler data centers but is not compatible with large, diverse telecommunications networks largely based on ring and mesh connectivity.

For the above reasons, IPoDWDM failed to take off before the 2020s.

THE 400G TURNING POINT

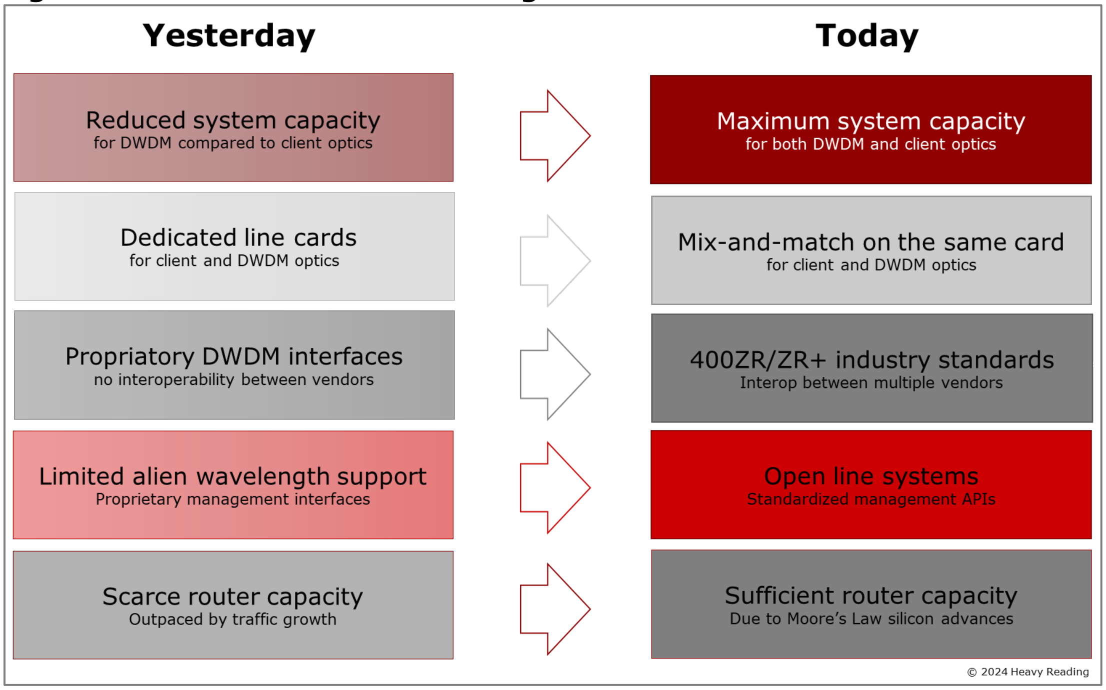
What has changed to make IPoDWDM viable? The first big change was the elimination of the "faceplate trade-off" challenge that stranded valuable router capacity. Inphi's 2016 introduction of the ColorZ 100Gbps module in a QSFP form factor, built for Microsoft, marked the first time that line-side optics were housed in a "client" form factor (and with comparable power consumption). This was the start.

But the real industry turning point was the 2020 standardization of the OIF 400ZR coherent pluggable optics designed to fit in QSFP-DD or OSFP form factors with unamplified reach up to 40km and amplified reach up to 120km. 400Gbps was the right data rate for the time, and OIF standardization met the essential requirement of multi-vendor interoperable coherent optics.

In addition to QSFP-DD/OSFP form factors and line-side interoperability due to standardization, other key factors converged to propel IPoDWDM to wide adoption, particularly among hyperscalers. Years of ASIC evolution along the path of Moore's Law have made router capacity far less scarce than in the early years of the internet. For years, router capacity growth has exceeded global internet traffic growth and the growth of optical capacity. It is no longer the network bottleneck. As a result, "router bypass" no longer needs to be a default rule in network planning.

Lastly, open optical line systems have decoupled the optical line system from the terminals such that network operators can choose transponder suppliers independently from the line system. Today, operators can buy 400ZR pluggables from multiple suppliers while maintaining line systems supplied by yet others. This gives operators another important degree of flexibility.

Figure 2: IPoDWDM factors converge at 400G



Source: Heavy Reading, Juniper, 2023

OIF 400ZR overview

First published in March 2020, the OIF 400ZR Implementation Agreement (IA) defines an interoperable, cost-effective, 400Gbps interface based on single-carrier coherent dual polarization (DP)-16QAM modulation, low power DSP, and a standardized concatenated forward error correction (CFEC). As noted, line-side optics interoperability with a standardized FEC marked an optical industry first.

Although the standard does not define form factors, the goal from the outset was coherent pluggable optics with port densities equivalent to client-side (or grey) optics. In commercial deployments, QSFP-DD and OSFP are the dominant 400ZR form factors.

Significantly, 400ZR development was spurred by the same metro data center interconnect (DCI) applications that drove the 100Gbps ColorZ collaboration between Inphi and Microsoft, and Microsoft was a major contributor to the 400ZR standard. In addition to Microsoft, Google was another hyperscaler to launch the 400ZR project.

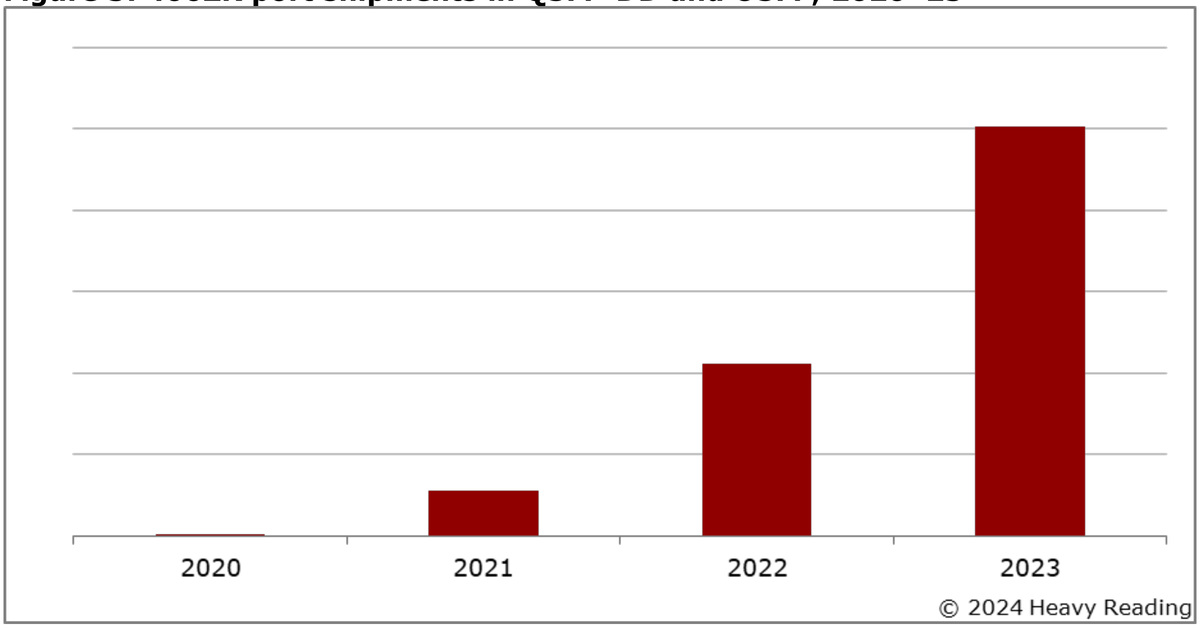
Ideally suited for the metro DCI requirements of large cloud providers, the IA specifies a coherent 400Gbps interface for three applications:

- 120km or less, amplified, point-to-point, 100GHz DWDM noise-limited links
- Unamplified, single wavelength, loss-limited links
- 120km or less, amplified, point-to-point, 75GHz DWDM noise-limited links

The current OIF 400ZR IA, published in November 2022, is OIF-400ZR-02.0 – Implementation Agreement 400ZR (see link for this and other IAs in the ***Appendix***).

Following a slow start, 400ZR took off in 2022 and quickly became the most successful coherent interface in history by units shipped. Omdia estimates that more than 385,000 400ZR ports were shipped cumulatively from 2020 through 2023, with 250,000 of those ports shipped in 2023 alone (**Figure 3**). Rapid 400ZR growth is expected to continue over the next several years, as well as migration to even higher data rates, such as 800ZR.

Figure 3: 400ZR port shipments in QSFP-DD and OSFP, 2020–23



Source: Heavy Reading, Omdia's Total OC Components Forecasts, 2021, 2022, 2023

400ZR volumes are driven almost entirely by the large hyperscalers. Notably, 400ZR itself was not developed for CSP applications (other than their own limited DCI deployments). IPoDWDM for this large—though slower moving—segment of the industry is met with different requirements than those of hyperscalers.

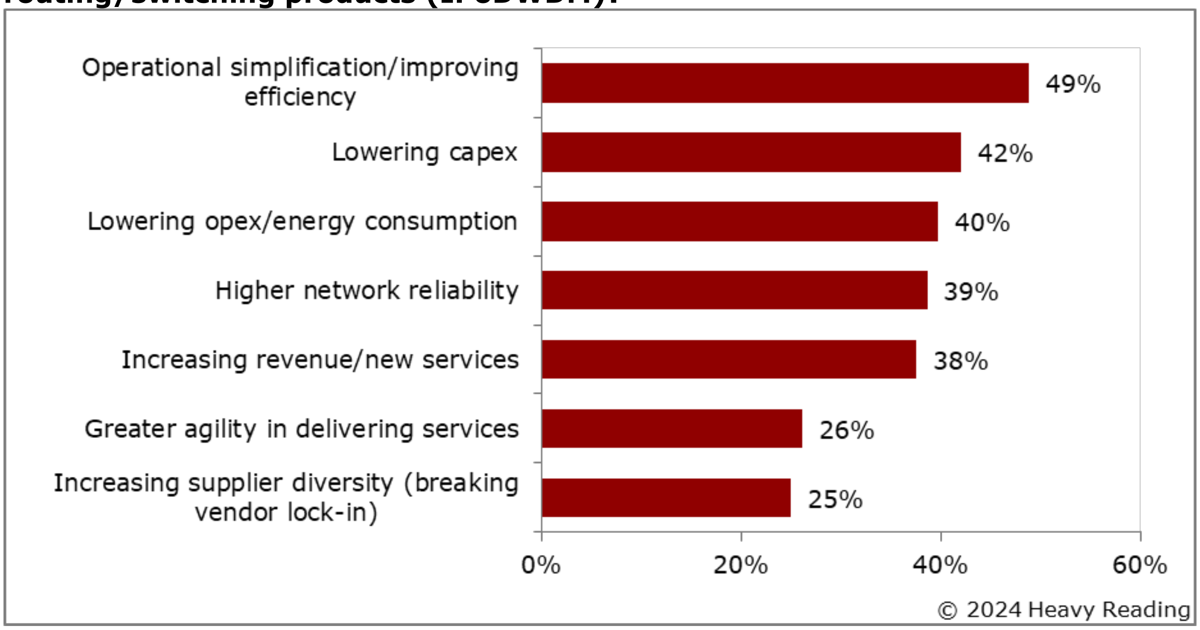
The remainder of this paper addresses the evolution of IPoDWDM with coherent optics, primarily with the needs of global CSPs in mind.

DRIVERS AND BENEFITS FOR CSPS

Heavy Reading has been tracking CSP interest in coherent pluggable optics and IPoDWDM for several years. Their interest in coherent pluggables generally and in IPoDWDM using coherent pluggables is clear. As the performance of coherent pluggables improves, an increasing percentage of operators intend to standardize on pluggable optics, particularly for metro applications, and to weigh the pros and cons of embedded versus pluggable optics for long-haul applications. Many of these CSPs intend to use pluggables in traditional DWDM architectures and for IPoDWDM.

Factors driving IPoDWDM adoption interest among CSPs include operational simplification, lowering capex, lowering opex, improving reliability, and even fostering new services, according to survey data from a 2024 Heavy Reading report (see **Figure 4**).

Figure 4: What are the main drivers for coherent pluggables adoption in routing/switching products (IPoDWDM)?



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Source: Heavy Reading, Coherent Pluggable Optics: A 2023 Heavy Reading Survey, February 2024

During a time of global cost reductions and increased focus on sustainability among operators, the capex and opex savings potential of IPoDWDM is significant. For example, global fixed and mobile telecom capex declined 6.9% in 2023, according to Omdia, which expects an additional drop of 2.2% in 2024. Nearly half of operator respondents in Heavy Reading's *Coherent Pluggable Optics: A 2023 Heavy Reading Survey* expect 20−39% total cost of ownership (TCO) savings (including capex and opex) using IPoDWDM compared with transponder architecture, with an additional 20% expecting TCO savings of 40% or more.

Significantly, the capex and opex savings figures that CSP early adopters publicly report are surpassing the expectations expressed in the Heavy Reading survey. For example, Arelion has reported capex savings of 64% and opex savings of 76% with IPoDWDM, as well as a reduction of potential points of failure throughout the network. Colt has reported a 70% improvement in backbone transport circuit costs with its adoption of 400G coherent optics.

REQUIREMENTS FOR CSP IPoDWDM ADOPTION

Higher performance

As noted, OIF's 400ZR standard was designed for a specific application: point-to-point data center interconnection at reaches below 120km. CSPs' networks are characterized by significantly longer reaches, often through multiple central offices along a route. Metro/regional routes require up to 1,000km, while long-haul routes will exceed 1,000km. Typically, CSPs have multiple ROADM nodes at network intersections that allow traffic to be added or dropped, with perhaps a dozen (or more) nodes along a route. To be a viable alternative to transponders, coherent pluggable optics must be compatible with these ROADM-based architectures.

Open ZR+

The CSP-specific requirements described above gave rise to high performance variants of coherent pluggables that are also housed in QSFP-DD or OSFP form factors and known as ZR+. To drive interoperability similar to 400ZR, the OpenZR+ Multi-Source Agreement (MSA) was formed in 2019. It has since defined a standardized version of ZR+, officially called ZR400. Key characteristics of OpenZR+ include the following:

- Standardized FEC using open FEC (OFEC).
- Support for 16QAM, 8QAM, and QPSK modulation formats for flexibility in maximizing reach for data rates from 100G up to 400G.
- Multi-rate Ethernet-only client interfaces from 100Gbps to 400Gbps.
- 100Gbps to 400Gbps line-side data rates, based on the modulation format selected.
- Target reach at 400Gbps of ~500km with OIF demonstration of 1,000km (Optical Fiber Communications Conference and Exhibition [OFC] 2024).
- Generally accepted power consumption of less than 20 watts.

Proprietary ZR+

Most industry interest in ZR+ is centered on the Open ZR+ MSA, which drives interoperability. However, many vendors also offer ZR+ capabilities that do not comply with OpenZR+. These proprietary modes will offer higher performance compared with OpenZR+, such as by implementing a proprietary FEC or by boosting the baud rate slightly. The trade-off of performance gains is that operators must sacrifice interoperability.

Suppliers will typically build coherent modules to support multiple modes of operation, including both OpenZR+ and proprietary options. It is then up to the operators to select which mode(s) to use in their networks.

OpenROADM

The OpenROADM MSA specifies higher performance 400G modules with a focus on CSP open networks that incorporate ROADMs and optical transport network (OTN) interfaces. There is some commonality between OpenROADM work and Open ZR+ work, including OpenZR+ MSA's use of the open FEC defined in OpenROADM. But there are also differences, as the scope of OpenROADM is much broader than that of Ethernet interfaces and IPoDWDM.

Key characteristics of OpenROADM include the following:

- Standardized FEC using OFEC.
- Multi-rate Ethernet and OTN client interfaces from 100Gbps to 400Gbps.
- 100Gbps to 400Gbps Ethernet and OTN line-side data rates, based on the modulation format selected.
- Target reach at 400Gbps of about 500km with OIF demonstration of 1,000km (OFC 2024).
- Form factor options including QSFP-DD and OSFP, as well as C form factor pluggable 2 (CFP2).
- Module power consumption of less than 25 watts.

The expansion of use cases to include OTN requires higher module power compared with Ethernet-only alternatives. Because of the power requirements, CFP2 form factors may be needed for OTN applications. OTN applications are important to many operators, but CFP2-based modules—and OTN client traffic, for that matter—are not suitable for IPoDWDM. Thus, Open ROADM QSFP-DD and OSFP modules are suitable for IPoDWDM, but CFP2 modules will serve transponder shelves only.

Scale

Scaling up

The OIF 800ZR IA is based on single-carrier coherent DP-16QAM modulation, OFEC, 150GHz channel spacing, and a 120 Gbaud rate. Like 400ZR, 800ZR is designed for point-to-point reaches of 80−120km with Ethernet client and line-side interfaces. OIF hosted the first 800ZR module interoperability demo at OFC 2024 and a follow-up demo at the European Conference on Optical Communication (ECOC) 2024. The IA was published in October 2024.

Compared to 400ZR, 800ZR is on a faster track from standardization to commercialization. After the OIF 400ZR IA was published, it took two years for module shipments to take off in volume. An ecosystem around coherent optics needed to develop and mature to ensure the success of coherent 400G pluggable optics. With a large coherent module ecosystem in place, 800ZR promises to be different. Multiple components vendors have 800ZR modules timed closely to the standard and ready to ship. The maturity is evidenced by the participation of seven 800ZR module suppliers (Cisco, Coherent, Eoptolink, HGGenuine, Juniper, Lumentum, and Marvell) across the OIF OFC and ECOC 2024 demos, covering QSFP-DD and OSFP form factors, including an industry-first 800ZR system demonstration. There will be no adoption lag.

Another key difference is that most 800G modules will support both 800ZR and higher performance ZR+ modes on day one. This is particularly good news for CSPs, as route lengths and ROADM infrastructure do not change when moving from 400G to 800G. Although non-standard ZR+ modes will be options on many 800ZR modules, the timeline for open 800G ZR+ modules is further out.

Probabilistic constellation shaping (PCS) FEC is a function of high performance 800G ZR+ modules, and open PCS is needed for 800G ZR+ module interoperability. The OpenROADM MSA has published a specification for PCS interoperability (OpenROADM 6.0), and several suppliers will support it in coherent 800G ZR+ modules, including Cisco, Infinera, and Nokia.

Scaling down

In addition to scaling up to 800G, coherent pluggables are scaling down to 100Gbps data rates. For their aggregation and edge network migrations, 100G coherent pluggable optics are of particular interest to CSPs, according to Heavy Reading research. CSPs have a large installed base of 10G aggregation networks that need greater capacity as bandwidth requirements in fixed and mobile access continue to grow. Direct detect modulation is not suitable at 100Gbps data rates for these types of distances.

Although larger CFP-based modules have been sold for years (especially to cable operators), industry interest is directed toward QSFP28-based modules that can occupy 100G client ports in switches and routers. "100ZR" is the industry label for this new generation of 100G coherent optics that are based on the IEEE 100GBASE-ZR standard published in 2021. 100ZR uses single-carrier coherent DP-DQPSK modulation, with a low power DSP supporting staircase FEC, and reaches up to 80km unamplified and 300k amplified. Line-side specifications align with IEEE 802.3-2022 and ITU-T G.698.2. There are no specific module requirements for 100ZR, but operators have made their needs known: QSFP28 modules that consume about 5 watts and are outdoor hardened for non-central office environments.

Unlike 400ZR and 800ZR, 100ZR (based on IEEE 802.3 100GBASE-ZR) is not an OIF project. However, as showcased in OIF's ECOC 2024 demo, OIF has taken on interoperability testing for 100ZR.

Openness and interoperability

On equal footing with the performance and scale advances discussed above are open networking and multi-vendor and multi-layer interoperability, which showcase one of the key distinctions between IPoDWDM of the 2000s and the new era of IPoDWDM. Some of these value propositions, such as the OIF 400ZR standard itself, have already been described. But, there are multiple aspects of openness. Below, Heavy Reading summarizes the four essential components of openness in IPoDWDM architectures:

- **Partial disaggregation:** This refers to the separation of a line system vendor from the optical terminal vendors(s). As it allows operators to source their optics and line systems from separate vendors and on separate timelines, it is often seen as a precursor to IPoDWDM.
- **Line-side interoperability:** This enables a module from vendor A to interoperate with a module from vendor B and is fundamental to the definition and success of the 400ZR standard. Open ZR+ and OpenROADM MSA's bring similar interoperability to higher performance modules.
- **Plug-to-host interoperability:** This permits routers or other host devices to source optics from multiple suppliers using standardized management that allows for rapid deployment.
- **Network management interoperability:** Multi-vendor networks must be controlled and managed. Open APIs and common data models allow for multi-vendor and multi-layer operation with extensive automation. SDN, which stands for software-defined network, is the general moniker for the automated control and management of transport networks.

This paper has already addressed the first two openness requirements. The next two sections focus on the remaining two requirements: plug-to-host interoperability and open network management and control.

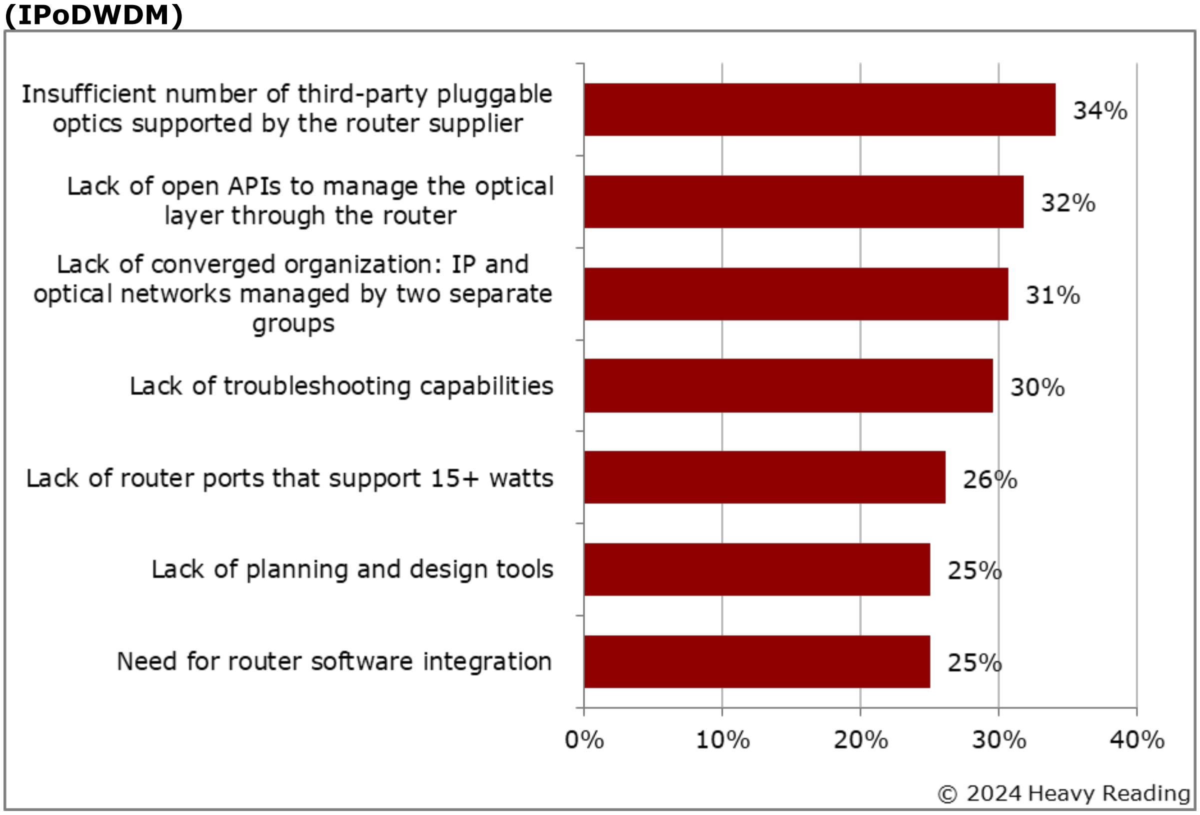
PLUG-TO-HOST MANAGEMENT

Module-to-module interoperability has long been a key topic in coherent pluggable optics, but the industry has increasingly focused on compatibility between coherent modules and the host router.

Over the past decade, Heavy Reading has seen great progress in defining open, multi-vendor transport network architectures. Selecting different optical and IP vendors with separate optical and IP layers is the industry norm today. Operators do not want to go backward and be locked into their router vendors when moving to IPoDWDM. They expect to have control over their choices of router and optical vendors.

For this reason, plug-to-host compatibility has quickly become a more pressing issue than plug-to-plug interoperability. As such, insufficient support for third-party pluggables is now the number one barrier to IPoDWDM adoption, followed closely by a lack of open APIs to manage the optical layer and a lack of converged organization (see **Figure 5**).

Figure 5: Top barriers to DWDM pluggables adoption in routing/switching (IPoDWDM)



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Source: Heavy Reading, Coherent Pluggable Optics: A 2023 Heavy Reading Survey, February 2024

OIF Common Management Interface Specification (CMIS)

The importance of plug-to-host interoperability can best be illustrated by its absence. Without a standard, a pluggable optic can advertise its functions and capabilities to its host router in detail, but the router will not understand the information conveyed. Further, a router can be manually configured to work with the proprietary management of a specific pluggable optic through vendor-specific drivers, but if a second optic is to be added to the network, the configuration process must be repeated.

Alternatively, the plug-to-host management problem can be averted by adopting a single-vendor network for routers and pluggables, but this closes the door to the diverse pluggable optics ecosystem that has emerged. What is more, many operators (particularly Tier 1 CSPs) have policies against such vendor concentration.

Thus, defining (and adopting) a common management interface across pluggable optics modules and their host elements is required for mass adoption of multi-vendor IPoDWDM architectures. Only then can network operators choose from a range of viable coherent pluggable options for their routers. When modules can fully describe their capabilities to host elements in a standardized way, the hosts can write generic software functions to initialize, configure, and monitor the modules without creating vendor-specific drivers. This is the mission of OIF's CMIS.

A 400Gbit CMIS was originally developed within the QSFP-DD MSA in 2018, but OIF took over the administration of the CMIS project in January 2022. OIF continues to maintain and update all CMIS specifications.

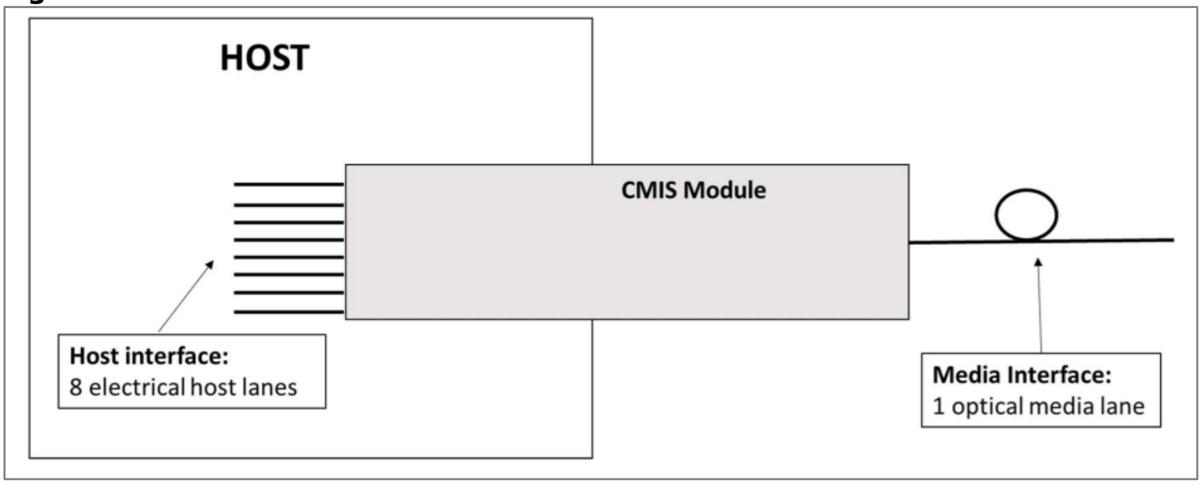
How CMIS works

CMIS specifications do not dictate module form factors and instead broadly apply to pluggable and onboard modules, including OSFP-XD, QSFP-DD, OSFP, COBO, QSFP, SFP-DD, and SFP, as well as existing or future module developments. The key common requirement is that host-to-module management communication is based on a two-wire interface known as the inter-integrated circuit (I2C) interface. CMIS management includes four main functions: advertising, configuration, monitoring, and upgrades.

In addition to the I2C management interface, a CMIS-compliant pluggable module has two other key standardized interfaces. The host interface connects the module to the host packet element, whether it be a router, switch, optical line terminal (OLT), or other network element type. At 400Gbps data rates, host electrical interfaces include 400GAUI-8 and 4 x 100GAUI-2. The media interface connects the pluggable module to the physical media for communications within data centers, across data centers, or in the WAN. Broadly, in CMIS, physical media can include copper wires for short-reach data centers or fiber optics for longer-reach connectivity. In a coherent CMIS (C-CMIS), optical module-standardized optical media interfaces include OIF 400ZR and OpenZR+ ZR400-OFEC-16QAM, among others.

Figure 6 illustrates the host and media interfaces on a coherent module in a host device.

Figure 6: Interface on a coherent CMIS module



Source: OIF, 2024

At the heart of CMIS are a set of application select codes, called appsels, that specify the host interface of the module (for example, 400GAUI-8 or 4x100GAUI-2, etc.), the media interface of that module (for example, 400ZR or 400G ZR+, etc.), host/media lane counts, host lane assignments, and media lane assignments. There are many possible modes for a module, and a single module typically supports multiple combinations.

The host and media codes themselves are cataloged in lookup tables by the Storage Networking Industry Association (SNIA) through its SFF Technology Affiliate Technical Work Group. The group's SFF-8024 Module Reference Codes are updated and published regularly. On the media side, these include codes covering 400ZR, OpenZR+ ZR400, OpenROADM FLEXO, 800ZR/ZR+, and others. The addition of new modes does not require changes to CMIS, just the addition of media codes to SFF-8024.

During configuration, a module uses unique and standardized appsels to advertise all its supported modes to the host device. A CMIS-supporting host can understand the advertised modes and their capabilities and then configure the desired mode for the application. Core CMIS functionality is required, though many of the features are optional and can be implemented at the discretion of the host or module. Functionality that is added to new versions of CMIS is always introduced in a backward-compatible manner that allows higher version modules or hosts to work with lower version hosts or modules. However, the introduction of a new feature requires support from both the host and the module, and a network may have multiple host types.

CMIS 5.2 (published April 2022) supported 15 unique modes of operation, but the newest version, CMIS 5.3, published in September 2024, expands the number of mode possibilities to 240. This expansion is significant because the newest coherent pluggable optics at 800Gbps (and higher) are highly complex and will typically support more than 15 possible modes. Again, for these newest functionalities to be used through CMIS, both the host and the pluggable need to support CMIS 5.3.

Among the IEEE media interfaces supported in CMIS, those based on coherent modulation are most relevant for IPoDWDM because coherent modulation is essential for DCI, metro, and long-haul network applications that range from 80km at the low end to thousands of kilometers using the latest DSP technologies. Coherent modules are far more complex than their direct detect counterparts, with many more capabilities and mode possibilities.

OIF created an additional C-CMIS IA document within CMIS that addresses the coherent functionality required for standardized management of coherent optical modules in packet hosts, including additions for coherent diagnostics monitoring, FEC management, and coherent-specific provisioning. OIF-compliant coherent modules must adhere to both the CMIS IA specifications and the additional specifications defined in C-CMIS.

As of the publication of this white paper, the most current OIF IA covering CMIS and C-CMIS are:

- OIF-C-CMIS-01.3 – Implementation Agreement for Coherent CMIS (October 2023)
- OIF-CMIS-05.3 – Common Management Interface Specification (CMIS) Revision 5.3 (September 2024)

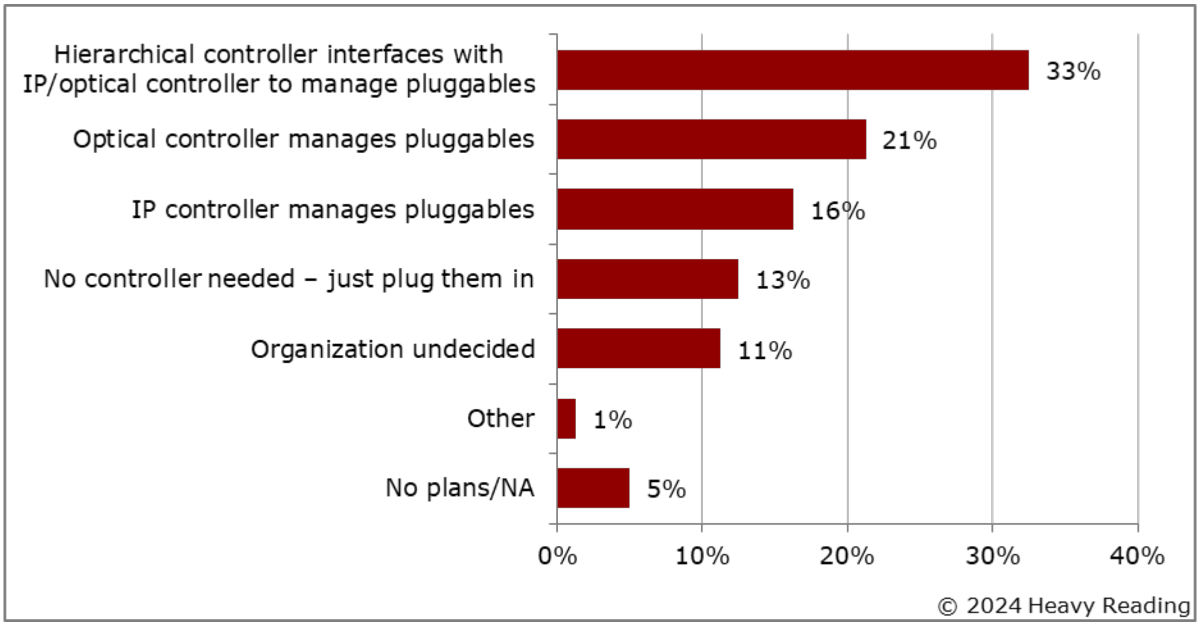
NETWORK MANAGEMENT

OIF CMIS IAs address crucial aspects of node management in IPoDWDM networks, but each node is part of a larger network of nodes that all must be managed and orchestrated—ideally, with extensive automation. Because of its converged nature, IPoDWDM requires different approaches to network management compared with the siloed IP and optical network management of the past. Although network-level management is beyond the direct scope of OIF, CMIS plays an important role.

Organizations active in defining multi-layer and multi-vendor IPoDWDM management include the Internet Engineering Task Force (IETF), OpenConfig, ITU-T, ONF (through T-API, which originated in OIF), Telecom Infra Project (TIP), and Open XR Optics Forum. OIF has liaisons with the IETF, ITU-T, and ONF, among others. These organizations must closely coordinate their efforts to avoid duplication while they close the standards gaps.

Heavy Reading survey data shows diverse operator views on managing coherent pluggables in IPoDWDM networks at this early stage. Based on survey research, all options are in play—including hierarchical controllers, IP controllers, optical controllers, or even no controllers (see **Figure 7**).

Figure 7: What strategy are you adopting for managing coherent pluggables in routers?



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Source: Heavy Reading, Coherent Pluggable Optics: A 2023 Heavy Reading Survey, February 2024

Internet Engineering Task Force (IETF) modelling work

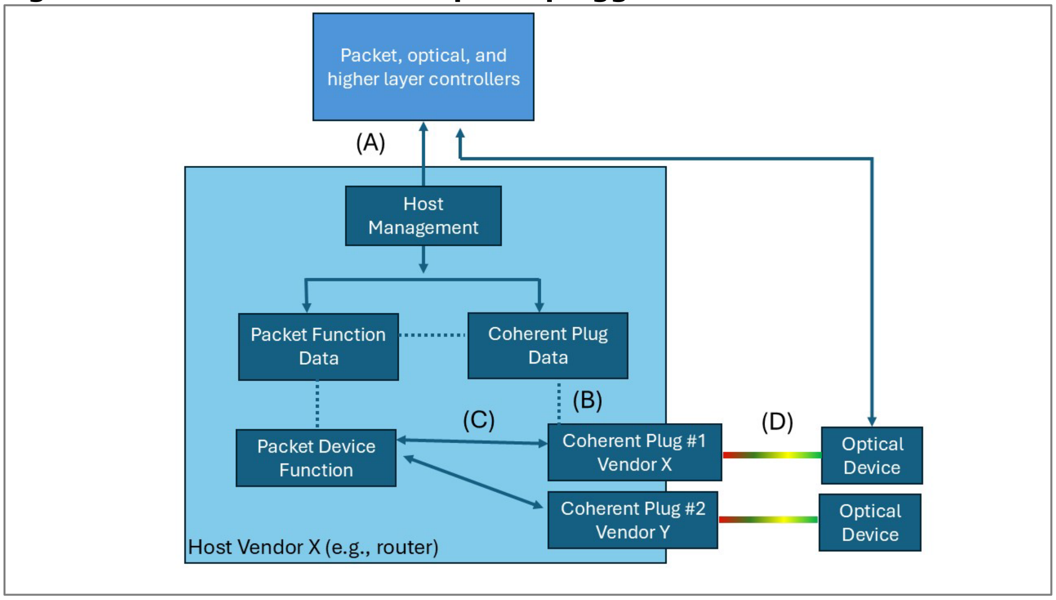
As part of the IETF's Abstraction and Control of Transport Networks (ACTN) framework for dynamically managing transport networks, the IETF is defining network management of IPoDWDM using CMIS-advertised module attributes. Work has not yet reached the request for comments (RFC) stage (i.e., IETF standards), but relevant published documents include *Data Modelling and Gap Analysis of Optical Pluggables in Packet Over Optical Network* (October 2024) and *Use cases, Network Scenarios and Gap Analysis for Packet Optical Integration (POI) with Coherent Pluggables under ACTN Framework* (July 2024). Operator representatives from Telefónica, Vodafone, Orange, and Verizon contributed to the latter document. (See the ***Appendix*** for links to these and other papers referenced in this report.)

Figure 8 presents a schematic view of a router with coherent pluggables being managed by packet, optical, and/or hierarchical controllers. Here, communications between the coherent pluggables and the router host occur through OIF CMIS, including module advertising of all attributes and module provisioning (interface B in the diagram). Packet, optical, and hierarchical controllers access coherent pluggable data through the router via a northbound interface (NBI; interface A in the diagram). Optical controllers have direct access to devices in the optical network, but coherent pluggables are accessible only through the router's management interface, regardless of controller type.

Other interfaces labeled in the diagram include the following:

- (C) electrical interface between the coherent pluggable and the packet data function
- (D) the optical fiber network connection

Figure 8: Packet device with optical pluggables



Source: IETF, Data Modelling and Gap Analysis of Optical Pluggables in Packet Over Optical Network, October 2024

Consistent with the Heavy Reading survey data on management preferences shown above (in **Figure 7**), the IETF believes that there are multiple valid options for managing coherent pluggables, depending on operators' use cases and preferences (which are also influenced by the operators' organizational structures). The goal of current IETF work is to standardize a pluggable data model and, eventually, a YANG model that can be used by any type of northbound controller, whether multi-layer, IP, optical, or even something else. Pluggable accessibility through the router management interface, however, is a key requirement for the IETF.

The general view proposed within the IETF is shared by TIP. The IETF, TIP, and OIF share many individual members and organizations, including people serving in official liaison roles.

Other approaches to management

The network management approach favored by the IETF and TIP has strong merits but is not without its challenges and limitations. On the plus side, relying on the CMIS connection between the pluggable and router as the "single source of truth" avoids synchronization mismatches by which different controllers are working with different configuration databases.

On the minus side, both the optics and the router must support all features and functions being accessed—which is not always the case, particularly for leading-edge functions that have not been widely standardized. There are two scenarios for host-dependent management:

- The coherent modules have features or modes that have not yet been incorporated into the latest CMIS version and, thus, are not yet standardized.
- The coherent module features/modes are included in CMIS, but the host router does not support the relevant version of CMIS. Because the router does not understand the features, they cannot be accessed by controllers.

To address these challenges, the Open XR Optics Forum MSA is developing a dual management scheme that includes both host-dependent (i.e., through the router NBI) and host-independent management of coherent pluggables functions. Host-independent management maintains the packet and optical abstraction layers, decoupling the coherent pluggable from the host development cycle; it provides management uniformity regardless of the type of host device. It also enables fast access to advanced optical features without disrupting the network by having to upgrade the router, host, or operating system.

Of particular interest to the Open XR Optics Forum is the management of modules with the digital subcarrier technology fundamental to its mission. Digital subcarriers are used for point-to-multipoint operation of coherent optics as well as single fiber working (SFW) through which a single fiber operates in both transmit and receive directions, up to 200Gbps in each direction. Heavy Reading research shows that operators are highly interested in both point-to-multipoint functions and SFW, particularly in edge and access applications. CMIS has not yet standardized these functions.

In May 2024, OIF published a white paper entitled *Management of Smart Optical Modules*, which identifies the challenges of managing advanced functions and outlines the host-independent management option. However, OIF has not committed to standardizing host-independent management, and it is unclear whether existing CMIS could or would be applicable to such an effort.

The Open XR Optics Forum continues to lead the industry charge on dual management of coherent pluggable optics that includes both host-dependent and host-independent management options. In September 2023, the forum published a paper detailing the results of a dual management proof of concept (PoC), entitled *Dual Management of Open XR Pluggable Modules in P2MP Applications Hosted in Various Routers with Transmission Over Multiple Line Systems Proof of Concept Demonstration*. This PoC demonstration included Liberty Global as the operator and Infinera, Juniper, UfiSpace, and DriveNets as suppliers.

INTEROPERABILITY ECOSYSTEMS

OIF and Open ZR+ demos at OFC and ECOC 2024

In 2024, OIF ran two large coherent pluggables interoperability demonstrations of OIF standard 400ZR and 800ZR modules, as well as several non-OIF module types, including OpenZR+, OpenROADM, and 100ZR. The first demonstration was held in March at OFC 2024 in San Diego, and the most recent demonstration was held in September at ECOC 2024 in Frankfurt, Germany.

The OFC 2024 demonstrations included 13 module vendors. The event marked the industry's first public 800ZR multi-vendor interoperability demonstration. The OIF demo at OFC also featured high-launch power (0dBm) 400G Open ZR+ interoperability over a 1,000km distance using an optical line system. Participating 400G Open ZR+ optical module vendors included Accelink, Ciena, Cisco, Coherent, HGGenuine, Juniper, O-Net, and Precision Optical Technologies. To achieve this reach, the optical line system used both erbium-doped fiber amplifiers (EDFAs) and Raman amplification. 400G OpenROADM interoperability was demonstrated over the same 1,000km multi-span network by Ciena and Cisco using QSFP-DD pluggables.

Building on the work of the OFC, the ECOC 2024 pluggables demonstration spotlighted four applications:

- **400ZR and 800ZR** demonstration over a single span 100km link, simulating a DCI application. Host devices were Juniper PTX10002-36DD and Cisco 8212-48FH-M routers and Anritsu, EXFO, and Keysight test equipment. 400ZR modules were supplied by seven vendors, including Cisco, Accelink, Juniper, Lumentum, O-Net, HGGenuine, and Hisense. 800ZR modules were supplied by six suppliers: Cisco, Juniper, HGGenuine, Lumentum, Coherent, and Marvell.
- **OpenZR+ at 400GE** demonstration over multiple spans at 300km and 250km distances. Host devices used were Juniper PTX 10002-36DD and Cisco 8201 routers; a Nokia 1830 PSI-M DWDM system; and Anritsu, EXFO, and Keysight test gear. Open ZR+ modules were supplied by nine vendors: Cisco, Nokia, Juniper, Accelink, Coherent, Hisense, HGGenuine, Lumentum, and O-Net.
- **OpenROADM at 400GE** demonstration over multiple spans at a 300km distance. Host devices were the Infinera G34C DWDM system and Anritsu and Keysight test equipment. OpenROADM modules were supplied by two vendors, Cisco and Coherent.
- **100ZR** demonstration over multiple spans at a 250km distance. Host devices were Juniper ACX7024 routers and an EXFO test system. 100ZR modules were supplied by four vendors: Adtran, Cisco, Juniper, and Coherent. ECOC marked OIF's first interoperability demonstration of 100ZR modules.

OIF CMIS demo at ECOC 2024

OIF conducted a CMIS interoperability demonstration at ECOC 2024, highlighting multi-vendor, plug-to-host interoperability for the "path to plug and play." This is a theme OIF takes up in a related white paper published in September entitled *CMIS: Path to Plug and Play*. Additionally, OIF demonstrated appsel-based provisioning showcasing transceiver power monitoring, MSA validation, and appsel code advertisement and transition. CMIS releases covered included 5.1, 5.0, 4.0, and 3.0.

Module vendors in the CMIS demo were Lumentum, Infinera, Juniper, Amphenol, and TE Connectivity, covering QSFP-DD, QSFP-28, and OSFP form factors. Juniper supplied QFX5130-32CD and QFX5240-64OD switches, and MultiLane test equipment was used.

CONCLUSIONS

OIF's 400ZR standard launched a revolution in coherent pluggable optics and paved the way for mainstream commercial adoption of IPoDWDM. The early adopters of 400ZR and IPoDWDM are hyperscalers, but telecom operators (i.e., CSPs) see the potential and are accelerating IPoDWDM adoption—albeit with their own set of requirements. Key requirements among CSPs include the following:

- High performance, with a focus on high-output power 0dBM optics and standards-based approaches coming from the OpenZR+ and the OpenROADM MSAs.
- Scaling up to 800G with a particular focus on 800G ZR+ options, such as 400G ZR+ modules, that will deliver high performance.
- Scaling down to 100G data rates for emerging access and aggregation applications.
- Openness and interoperability across hardware and management.

In addition to defining hardware specifications, OIF plays a central role in defining a common management interface across pluggable optics modules and their host elements, called CMIS. CSPs, in particular, cite management as the primary barrier to IPoDWDM adoption. Beyond the node management addressed by CMIS, open network management is also essential. Here, other industry groups are defining specifications, but they must all work together closely with OIF and one another to move IPoDWDM forward.

Lastly, OIF is advancing IPoDWDM adoption through large-scale interoperability demonstrations. Although it initially focused on OIF specifications, the organization has expanded its interoperability role to test outside contributions, including OpenZR+, OpenROADM, and 100ZR, as showcased at OFC and ECOC this year.

IPoDWDM has been traveling a long road. Although there is still work to be done, deployments are accelerating, and the blueprint and path forward have never been clearer, thanks in large part to organizations such as OIF and the vendor and service provider members that have made pioneering contributions.

APPENDIX

The following are links to the IAs and white papers referenced in this report:

- OIF-400ZR-02.0 – Implementation Agreement 400ZR (November 2022)
- OIF-C-CMIS-01.3 – Implementation Agreement for Coherent CMIS (October 2023)
- OIF-CMIS-05.3 – Common Management Interface Specification (CMIS) *Revision 5.3* (September 2024)
- Reza Rokui, et al. *Data Modelling and Gap Analysis of Optical Pluggables in Packet Over Optical Network*, IETF (October 2024)
- O.G. de Dios, et al. *Use cases, Network Scenarios and Gap Analysis for Packet Optical Integration (POI) with Coherent Pluggables under ACTN Framework*, IETF, Telefónica, Vodafone, Orange, Verizon (July 2024)
- *Management of Smart Optical Modules*, OIF (May 2024)
- *Dual Management of Open XR pluggable modules in P2MP Applications Hosted in Various Routers with Transmission over Multiple Line Systems Proof of Concept Demonstration*, Open XR Optics Forum (September 2023)
- *CMIS: Path to Plug and Play*, OIF (September 2024)