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The 400GE inflection point

IP-optical networking solutions for 400G and beyond

White paper

Rapid advances in silicon are fueling a new generation of pluggable coherent 400G router optics that open exciting new avenues for rethinking IP-optical network designs. This white paper takes a closer look at these technology advances, and their impact and applications.

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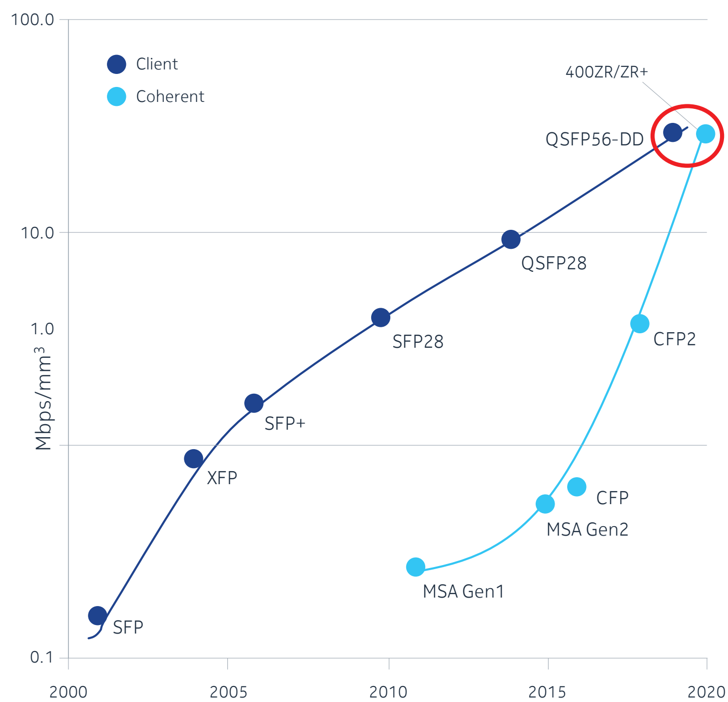
Entering the 400G era

Relentless demand for more capacity at a lower cost per bit is forcing network operators to constantly upgrade and optimize their IP-optical network designs. Metro/regional access, aggregation and the multi-access edge cloud are taking the brunt of this tremendous growth in demand, which is being driven by consumer broadband, ultra-high-definition (UHD) video streaming, cloud-based IT applications and 5G.

Fortunately, rapid advances in silicon are fueling a new generation of pluggable coherent 400G router optics that close the port density gap with conventional gray client optics (Figure 1).

Figure 1 The 400G inflection point in coherent optics evolution



400ZR is an open standard defined by the Optical Internetworking Forum (OIF) that addresses the needs of short-reach, single-span 400GE applications such as data center interconnect (DCI). 400ZR+ is a non-standard implementation that supports a longer reach and multiple line rates.

Both 400ZR and 400ZR+ aim to foster the development of a multi-vendor ecosystem for low-cost coherent DWDM optics in small pluggable formfactors.

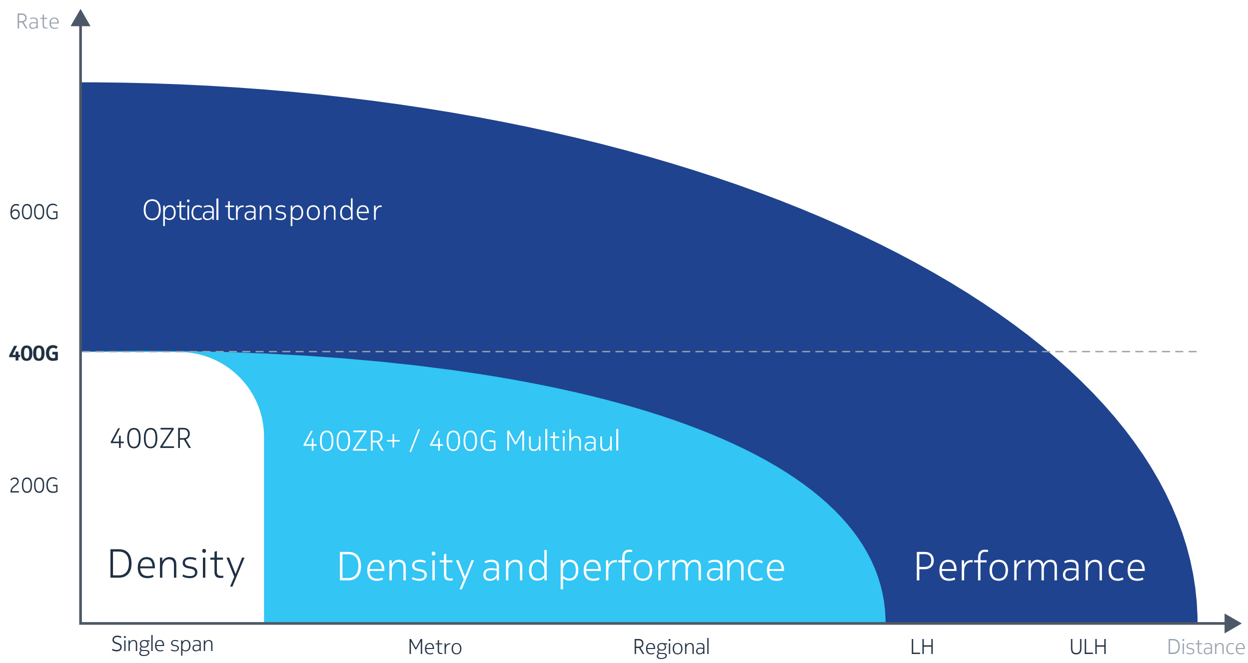
Cost- and space-efficient pluggable coherent transceivers will finally enable the physical integration of the IP and optical worlds. 400 Gigabit Ethernet will trigger a router investment cycle and along with it demand for 400G wavelengths. Commercially available solutions will start shipping mid 2021 and there is a large installed router base that can be readily equipped with coherent 400GE technology. A new IP-optical networking era dawns with this alignment of multiple innovations, standards and technologies that promise to make 400GE the new universal network currency.

This paper examines the impact and applicability of 400GE coherent optical technology for IP access, metro and regional aggregation, core and long-haul transport.

400GE transceiver options

Every network is different and optimally addressing the various link objectives in wide area networks requires a range of connectivity options with different performance (Figure 2).

Figure 2 Coherent transceiver options



DWDM transponders for optical transport systems are designed to optimize transmission performance. They are typically implemented on an integrated line card and apply powerful lasers, sophisticated modulation schemes and high-gain forward error correction (FEC) methods to maximize throughput and reach for regional, long-haul, ultra-long-haul and subsea links. High-performance DWDM optics can cover all rates and reaches, but coherent pluggable router optics such as 400ZR offer a more economical alternative for shorter reaches because they are optimized for low power and high density.

Most metro, regional and even long-haul optical networking applications will require a careful balance of performance and density. Power, space, cost and pluggability are important – but sufficient performance is needed to minimize regeneration. Additional features such as programmability, performance monitoring and failure detection are critical for all applications, regardless of reach. Flexibility and choice in transceiver types are essential for optimizing cost and performance for a given (sub-)network or link because of dependencies on fiber availability, quality, reach, link topology and service requirements. Table 1 lists the 400GE transceiver options and their key characteristics.

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Table 1 400G coherent transceiver overview

Technology	400ZR	400ZR+	400G Multihaul	WDM transponder
Bit rate	400 Gb/s only	100–400 Gb/s	100–400 Gb/s	100–400+ Gb/s
Reach	40–120 km (amp)	400–600 km (amp)	500–750 km (amp)	>1,000 km (amp)
Modulation	16QAM	QPSK, 8/16QAM	QPSK, 8/16QAM	QPSK, 8–64QAM
FEC	CFEC	CFEC+, oFEC	CFEC+, oFEC, NOK FEC	NOK FEC
Tx power	-7 to -10 dBm	-7 to -10 dBm	~0 dBm	>0 dBm
Form factor	QSFP-DD	QSFP-DD	CFP2	Integrated line card
Interfaces	100GE, 400GE	100GE, 400GE	100GE/OTU4, 400GE	100GE/OTU4, 400GE
ROADM bypass	No	Limited	Multiple	Many
Application	Access/Metro DCI	Metro/regional	Metro/regional	Metro/regional, long haul/subsea

400ZR is the first interoperable 400G coherent interworking standard. Released in March 2020, 400ZR is profile-optimized for high-density metro access and point-to-point DCI applications. Its specifications ensure that performance and power consumption limits fit within smaller module sizes. 400ZR uses 16QAM modulation and standardized forward error correction. Different module types can be used from a line interface interoperability standpoint, but QSFP-DD is projected to be the most popular choice given its low pricing and small footprint.

With a profile optimized for density, 400ZR can deliver 400 Gb/s for up to 40 km over a single dark fiber span without amplification. It can support up to 64-channel WDM in the C-band and reach up to 120 km with external amplifiers.

400ZR+

400ZR+ targets higher optical performance, with flexible 100G–400G line rates. It supports longer reaches by leveraging multiple modulation types (16QAM, 8QAM and QPSK) and a high-gain forward error correction (i.e., CFEC+, oFEC).

400G Multihaul

400G Multihaul is a category of modular transceivers that package coherent optics in a larger formfactor (CFP2) that can be equipped in routers or WDM transponder systems. Due to their larger power and heat dissipation envelope, Multihaul DCOs achieve better optical performance while incorporating many more features than 400ZR+ modules. 400G Multihaul leverages high-performance forward error correction, higher launch power, and high-performance optical front-end components to achieve longer optical reaches, resulting in the ability to optically bypass multiple ROADMs. They also may incorporate features important to their use in optical transport systems, such as encryption and OTN support.

WDM transponder

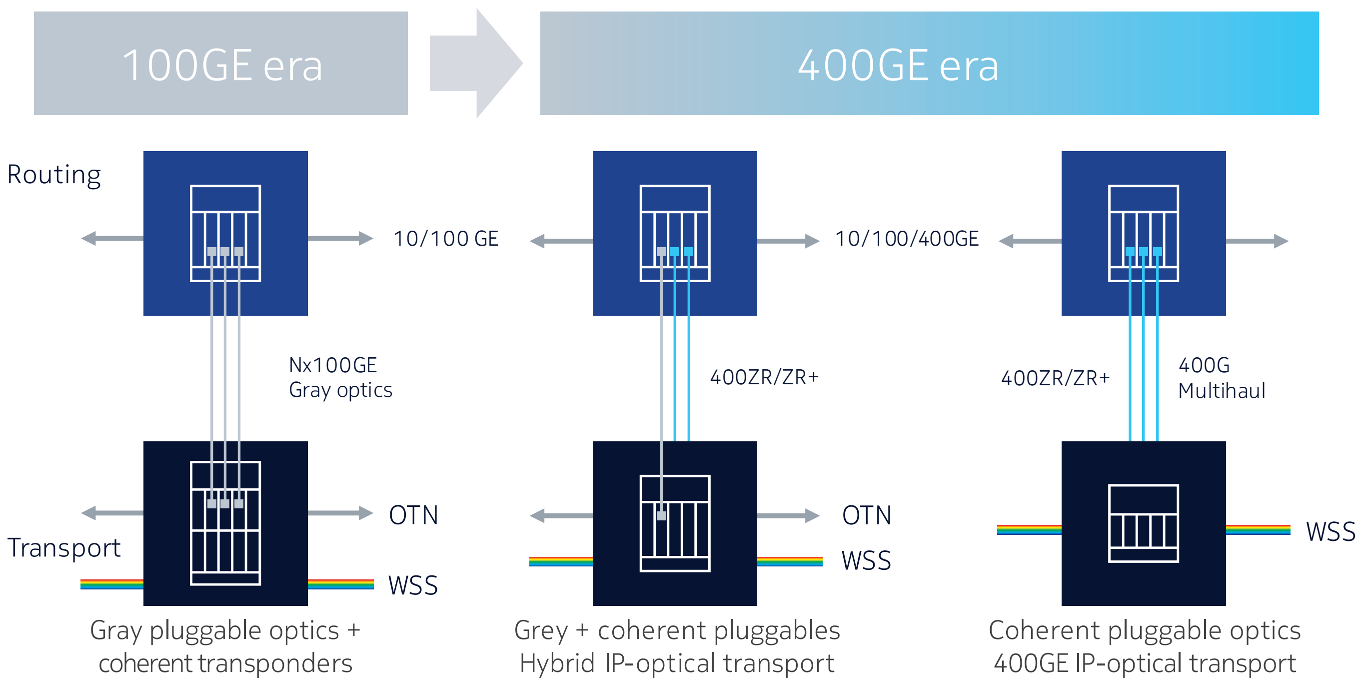
WDM optical transponders are performance-optimized to maximize wavelength capacity and reach. They take the form of integrated line cards that reside within WDM optical transport systems. Operating at high baud rates in excess of 90 gigabaud enables these interfaces to transport 400G over ultra-long-haul and subsea distances, and even higher rates at shorter distances. WDM transponders can also maintain 400G bitrates when deployed in combination with ROADMs for regional and long-haul networks where fiber is scarce, costly and usually monetized as managed wavelengths for multiple services.

Combined, these coherent transceiver options help establish 400G as the new network currency for applications ranging from IP access to metro, regional and long-haul transport.

Transition to 400GE

The 400GE era presents an opportunity to rethink and reoptimize IP-optical networks. The choice of whether to evolve and optimize existing deployments or make a fresh start with next-generation solutions optimized for 400GE will largely depend on the hardware readiness of the installed network base. Figure 3 shows the transition to the 400GE era and the various IP-optical interworking options.

Figure 3 Transition to the 400G era



Present-mode operation

The present mode of 100GE operation for most, if not all, network operators is to use gray router optics in combination with optical transponders, as shown on the left side of Figure 3. The 100GE era started roughly ten years ago with the transition of IP backbone links to 100GE. It triggered a major upgrade cycle of core routing platforms. Today 100GE is a ubiquitous interface in each part of the network with 1, 2 and 4x 100GE interface ports as the popular break-out options for QSFP DD connectors.

The present mode maintains a clear demarcation between IP routing and optical transport. The optical transport layer offers OTN grooming and managed wavelength services. The present-mode optical transport network typically provides OTN and wavelength services for multiple internal customer departments, as well as managed private line services for external customers.

Present-mode evolution to a hybrid IP-optical network

Present-mode evolution is attractive or even necessary to ensure operational continuity and to preserve existing network investments and revenue streams. Any operator evolving its 100GE network to 400GE is likely to operate in a hybrid mode for the foreseeable future. This mode allows operators to leverage investments in the current optical network, while growing incremental cost savings by using lower-cost pluggable coherent 400GE transceivers. Hybrid IP-optical solutions will optimally meet variable capacity and reach objectives in mixed deployment scenarios that combine 100GE and 400GE interfaces or have link requirements that are beyond the reach of pluggable coherent transceivers.

Router-based coherent 400G transceivers eliminate the need to use an optical muxponder or transponder – saving cost, space and power. The router effectively becomes an Ethernet muxponder, but the lower transmit power of smaller-sized pluggable coherent 400GE transceivers do have an impact on line system architectures. Most WDM systems require approximately –2 to +2 dBm input power for proper operation. The lower output powers of coherent QSFP-DD modules will need to be increased, either by using external amplification prior to the WDM node, or by additional amplifiers within the WDM node add/drop stage.

If high-density 400ZR and 400ZR+ QSFP-DD pluggables with external amplification do not provide sufficient reach, the higher-performance 400G Multihaul DCOs that use the larger CFP2 formfactor may offer an alternative. Performance-optimized optical transponders will still be required on long fiber routes and for traversing multiple ROADM hops in mesh and ring networks, and to deliver high-capacity and low-latency private line services.

Future-mode all-coherent 400G IP-optical network

Building an all-coherent 400G IP-optical network requires an operational rethink but presents an opportunity to start over using next-generation network technology that is cost-optimized for the 400G era. Higher upfront investment needs to be factored in and some (initial) restrictions may apply.

Because the power consumption and heat dissipation of 400G coherent router optics are significantly higher than those of conventional gray short-reach optics, power and cooling of line card cages can become an issue for high-density routers that are cost-optimized for delivering speeds and feeds. Routers with an inadequate hardware design may not be able to power and cool the 17-20 watts needed to run 400ZR+ coherent QSFP-DD router optics at full throttle, which could leave port capacity stranded or limit reach. Support for 400G Multihaul DCOs that consume 20–26 watts in the larger CFP2 formfactor is equally important to cost-efficiently meet all performance objectives.

Optical line systems are an essential part of the solution to cost-efficiently manage coherent alien wavelengths and monetize fiber capacity. ROADMs play a vital role in ring and mesh network topologies by adding a flexible photonic layer that decouples the logical (IP/MPLS) and physical (fiber) network topologies and enables dynamic routing, protection and restoration of select wavelengths. ROADMs also allow provisioning of low-latency express routes for internet and data center traffic, thereby offloading IP transit traffic from intermediate router hops. Other uses are to divert packet traffic in preparation for planned maintenance or router upgrades. Currently, most optical transport networks carry predominantly 100 or 200Gb/s wavelengths over 50 GHz-spaced fixed-grid line systems. 400G interfaces utilize higher baud rates that require 75–100 GHz channels, requiring optical line systems or ROADMs with flexible grid spacing (FlexGrid).

The operational convergence on unified 400G IP-optical fabric is a departure from the traditional separation of administrative powers between IP routing and optical transport, but it may help operators in building a nimbler organization. 400G IP-optical metro/regional networks must support a combination of density - and performance optimized transceivers with different pluggable formfactors to optimally address all connectivity requirements. Optical line systems and in-line amplifiers can be deployed in addition to extend reach, efficiently groom wavelengths and enable 1+1 fiber protection.

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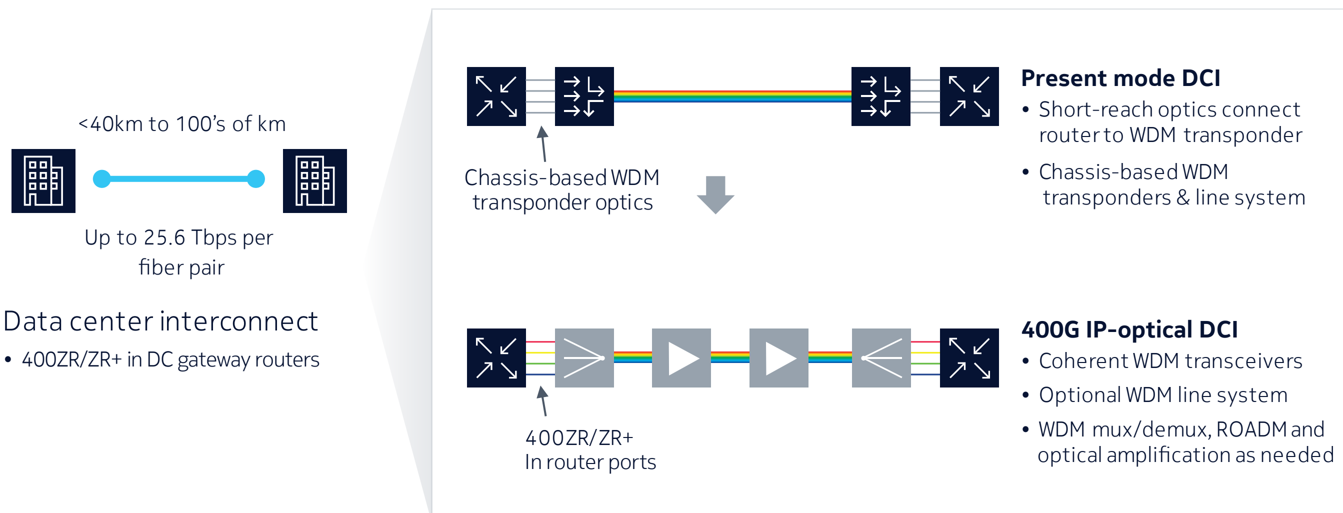
400GE IP-optical applications

There are several 400GE coherent deployment scenarios for operator networks. The following sections offer a closer look at scenarios for single-span DCI, metro/regional aggregation rings and metro/regional edge and core networks.

Data center interconnect (single span)

The 400ZR interworking specification is optimized for low cost, high-density applications with DCI as the primary example. As web scalers and CSPs build the edge cloud, there are many data center locations that need to be interconnected at intermediate distances between 40 and 120 km. Typical applications are backup and synchronization between distributed data centers to facilitate geo-redundancy and load balancing arrangements (Figure 4).

Figure 4 Data center interconnect



Conventional DCI solutions use short-reach gray optics to interconnect data center gateway routers with DWDM transponders in chassis-based optical line systems that multiplex these 400G wavelengths on the available fiber pairs.

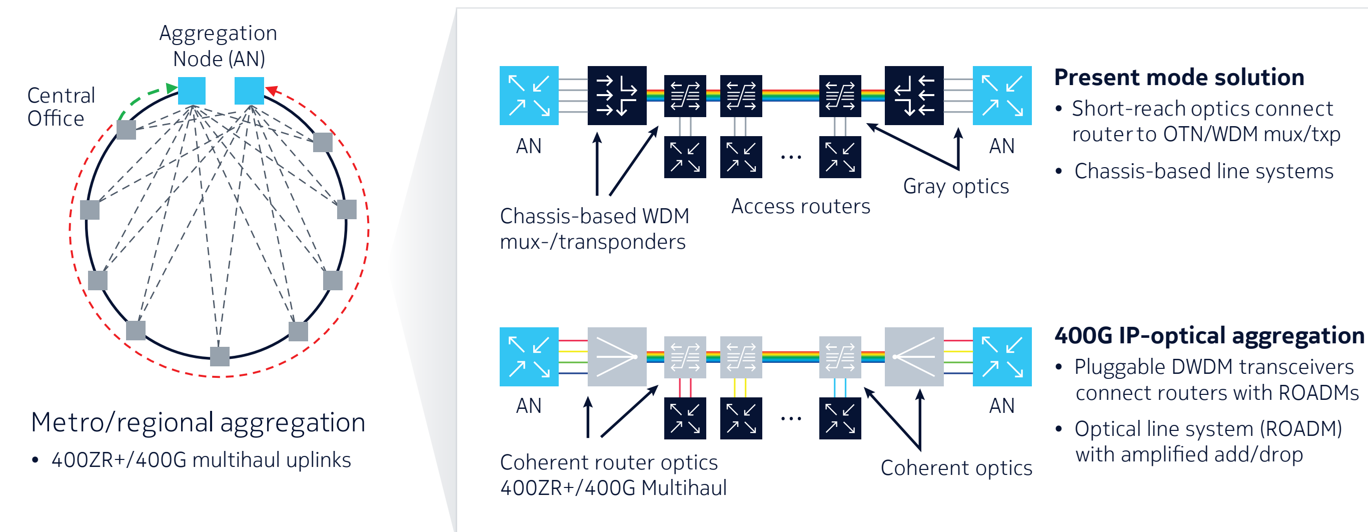
Equipping data center gateway routers with 400ZR pluggable optics allows them to directly connect over dark fiber for distances up to 40 km. An optical line system with external amplification will allow the solution to bridge longer distances up to 120 km and scale to 64 wavelengths, or 25.6 terabits/s on a single fiber.

Metro/regional aggregation rings

Interconnected ring topologies are used in many metro/regional carrier networks to collect IP traffic from geographically dispersed central offices. Capacity and reach requirements may vary per ring depending on subscriber density and services offered. Rural areas and suburbs are served by large, low-capacity rings with a circumference of several hundreds of kilometers and hop distances up to 40 km between sites. Metropolitan and urban aggregation rings will be smaller in size and serve large central offices that are closer together.

Aggregation rings may carry mixed packet traffic from residential broadband, mobile backhaul, enterprise data networking and high-capacity private line services with different service-level agreement (SLA) objectives. Aggregation rings usually deploy a physically diverse fiber pair and short-reach gray optics to connect IP routers with chassis-based optical line systems that groom OTN circuits, multiplex wavelengths and protect traffic against fiber cuts. The OTN/DWDM transport layer also allows for the decoupling of the logical (layer 3) and physical (layer 0) network topologies. This enables each central office aggregation router to be dual-homed to the head-end routers (AN) in a hub-and-spoke topology, and for IP transit traffic to bypass intermediate router hops on the ring (see Figure 5).

Figure 5 Metro/regional aggregation rings



Alternative IP-optical aggregation scenarios based on pluggable coherent router optics will need to balance density and performance because trail lengths are long and coherent wavelengths must pass multiple ROADMs along the ring. 400ZR+ transceivers will optimize port density, but their limited performance may require operators to run 400GE ports at sub-rates. This trade-off may be acceptable for low-capacity aggregation rings, but it will consume more ports and wavelengths to scale up capacity in the future. 400G Multihaul transceivers offer better performance and allow operators to run 400GE router ports at higher rates. They may ultimately deliver the same capacity while consuming fewer ports and wavelengths.

The (alien) wavelengths generated by pluggable coherent router optics can be added to the ring by a ROADM and dropped off at the ring head end for termination on coherent 400GE transceivers in the destination routers. The aggregation routers on the ring may use simple two-degree ROADMs to groom and carry wavelengths around the ring in both east and west directions.

The resulting number of wavelengths on the ring may grow rapidly because each access router on the ring will require a minimum of four uplinks (and wavelengths) to protect against single fiber or port failure. Coordinated management and supervision of optical parameters such as optical channel, modulation type, power level, baud rate, data rate, optical signal-to-noise ratio (ONSR) on routers and optical line systems will help ensure proper interworking as scale and complexity increase.

Metro/regional service edge and core

The metro/regional edge and core network provides the packet infrastructure that interconnects distributed service nodes in the edge cloud with regional data centers and peering points.

Figure 6 Metro/regional edge and core

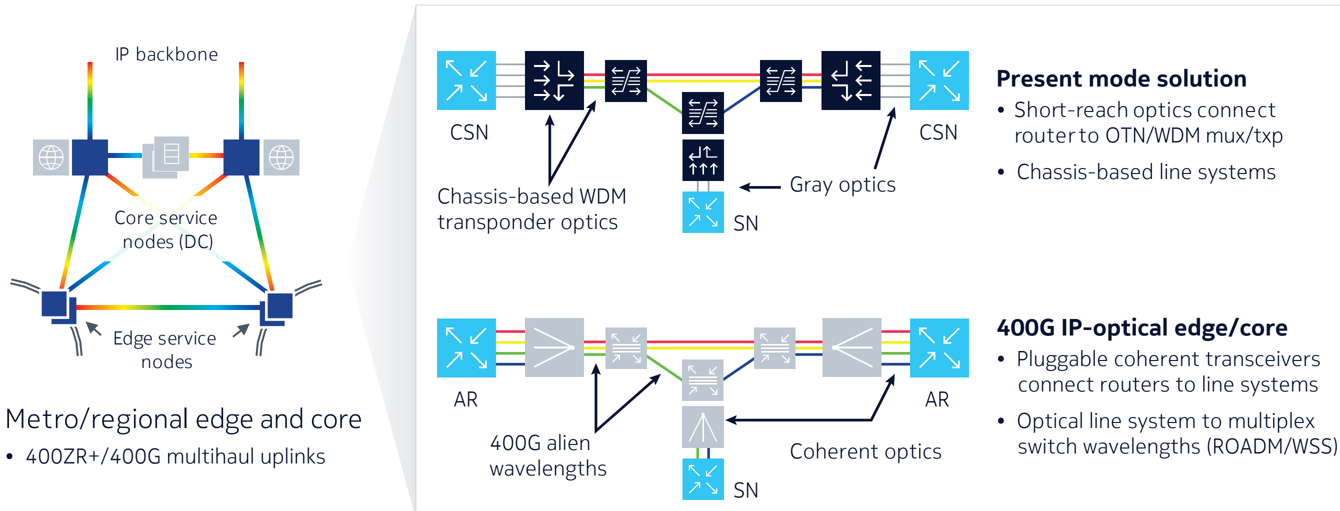
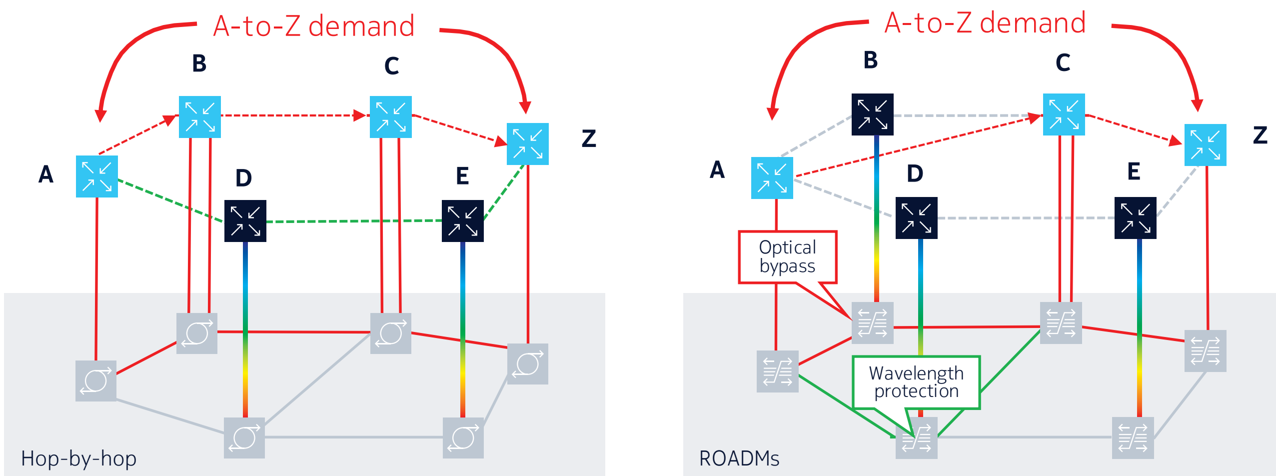


Figure 6 shows a simplified metro/regional edge and core topology. These can be large, diverse and highly meshed networks. Fiber-optical connections between routers can span several hundreds of kilometers and contain multiple fiber patches. They typically deploy CDC-F ROADMs to enable efficient sharing of fiber by multiple applications. Physical topologies vary from simple linear links to interconnected rings and mesh topologies with variable hop distances. To efficiently cover all capacity and reach requirements, network operators will require a mix of density and performance-optimized 400GE transceiver options in different formfactors.

The use of 400GE coherent router optics and simple point-to-point line systems may be an attractive option for interconnecting routers in simple linear link topologies and small, packet-centric service areas. This deployment model collapses the logical (IP) and physical network topology and results in a hop-by-hop forwarding of A-to-Z traffic. The performance requirements of coherent router optics are reduced because each router becomes a regenerator. But more coherent ports will be required from end to end because of these hop-by-hop OEO transitions, as shown on the left side of Figure 6.

Figure 7 Hop-by-hop versus selective router bypass



Therefore, larger and more complex metro/regional packet networks will scale more cost-efficiently by maintaining a flexible photonic service layer based on ROADMs, as shown on the right side of Figure 7. This approach allows network operators to decouple and optimize the IP topology independently of the physical network topology and to minimize OEO transitions of aggregated transit traffic by selectively bypassing intermediate routers at the photonic layer. A flexible photonic service layer based on ROADMs also makes it easier to manage coherent alien wavelengths and private wavelength services.

Leading in the 400GE era

The advent of pluggable coherent 400G router optics is a game changer for optimizing IP-optical network designs for the 400G era. Promising multi-vendor interworking and powered by state-of-the-art silicon photonics, these compact and modular 400GE transceivers offer a low-cost/high-density alternative to conventional solutions by using gray router optics in combination with integrated WDM transponders in optical line systems.

Nokia is a leader in 400G routing and optical technology, and has achieved several industry firsts, including:

- Launching FP3, the first 400 Gb/s-capable routing silicon, in July 2011
- Demonstrating the first 400Gb/s IP routing interfaces in February 2015
- Shipping the industry's first commercially available 400GE line cards in July 2018
- Supplying the first commercial deployment of 400GE router interfaces in March 2019

The Nokia IP routing and optical systems portfolio offers the scope, depth, platforms and tools that operators need to enter the 400G era. The innovative power and cooling designs of Nokia 400GE line cards anticipated the introduction of high-powered router optics. This design advantage allows network operators to readily equip 400GE coherent pluggable transceivers in existing Nokia routers and line cards.

Nokia is also a frontrunner in coherent optical components and line systems. Combining the state-of-the-art silicon photonics from the acquisition of Elenion Technologies with Nokia's fifth-generation PSE-V digital signal processor will expand the 400G ecosystem with new components and subsystems to meet surging demands from 5G and the cloud.

As the 400GE era begins, preparations for the Terabit Era are well underway:

- Nokia launched FP4, the world's first terabit-capable routing silicon in July 2017.
- Nokia and Etisalat completed the world's first terabit optical field trial in September 2019, leveraging a single optical carrier operating at 100 gigabaud.
- Elisa completed the first Terabit Ethernet router interconnect field trial on the Nokia 7950 XRS core routing platform in December 2020.
- In September 2021, Nokia launched it's FP5 routing silicon that will be powering new linecards and platforms with high-density QSFP-DD 800GE support.

Resources

[1] Nokia Coherent routing solution page

[2] Coherent routing for 400GE and beyond. Nokia eBook

[3] Nokia IP network solutions

[4] Nokia optical network solutions

[5] Nokia IP-optical coordination solutions

Abbreviations

CDC-F	colorless, directionless, contentionless with flexible grid spacing
CFP2	C form-factor pluggable 2 specification
CSP	communications service provider
DCI	data center interconnect
DCO	digital coherent optics
DWDM	dense wavelength division multiplexing
FEC	forward error correction
GE	Gigabit Ethernet
HG-FEC	high-gain forward error correction
IP	Internet Protocol
MPLS	Multiprotocol Label Switching
OEO	optical–electrical–optical
OSNR	optical signal-to-noise ratio
OTN	optical transport network
QAM	quadrature amplitude modulation
QPSK	quadrature phase-shift keying
QSFP-DD	quad small form-factor pluggable – double density
ROADM	reconfigurable optical add-drop multiplexer
SDN	software defined network
SLA	service-level agreement
UHD	ultra-high definition
WDM	wavelength division multiplexing

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