Infinite Capacity Engine – Extensible (ICE-X) in PON Overlay Applications

Delivering High-capacity Services over Existing PON Access Infrastructure

Access Network Evolution

Residential broadband access has scaled significantly in recent years, with end users taking advantage of ever-increasing bandwidth packages from service providers. Bandwidth annual compound growth rates are generally estimated to be in the 30-45% range, meaning that network bandwidth doubles every two to three years and hits a tenfold increase every seven to nine years. This ever-increasing bandwidth demand has driven a revolution in access networks and a race to fiber up customers.

As the capacity demand of homes outstrips the capabilities of older copper-based digital subscriber line (DSL) and hybrid fiber-coaxial cable (HFC) technology, fiber to the home (FTTH)-based passive optical network (PON) is rapidly becoming the access technology of choice across the globe due to its ability to deliver and scale gigabit services to the home. It is important to note that PON is a point-to-multipoint (P2MP) technology allowing dozens of homes' traffic to traverse a single shared fiber. This greatly simplifies the building of the requisite optical distribution network (ODN) needed to roll out FTTH services.

Industry analysts from Omdia forecast that PON-based FTTH networks will hit 57% and 66% market penetration in Western and Eastern Europe respectively by 2027, and market penetration in North America will grow to 35%, where HFC-based cable access remains strong and is forecast to maintain 49% share in that timeframe.

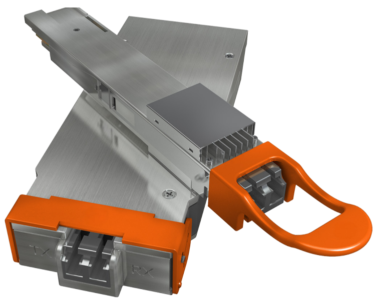
Capitalizing on PON Investments

This expansion of PON deployments is also fueled by the billions of dollars that are being invested globally in fiber broadband infrastructure, from both government-led strategic national investment programs, such as the $42.5 billion Broadband Equity, Access, and Deployment (BEAD) program in the U.S., and substantial private investment. Published analysis by network operators shows that up to 90% of the investment in a PON access network goes into single-fiber working (SFW) ODN infrastructure via civil works, ducts, cables, and passive splitters. Only 10% goes into the active PON hardware. Essentially, the SFW ODN infrastructure at the edge of the optical network driven by this surge in PON deployments is here to stay, and network operators need to be able to capitalize on this access infrastructure for all services, not just residential ones.

Because of the use of SFW within the PON access network, this domain is generally considered by the transport team within an operator as a separate access domain from the rest of the DWDM-based optical transport network. These PON access domains are viewed in a similar way to perhaps a radio access network. The main task for the DWDM network is typically just to provide backhaul capabilities to the PON optical line terminal (OLT).

Benefits of ICE-X Point-to-Multipoint DCOs in PON Overlay Networks

- Greatly simplify and cost-reduce the addition of high-capacity services by leveraging coherent DWDM optics in single-fiber PON access networks
- Deliver demanding N x 25G services for applications such as 5G xHaul, multi-access edge compute, high-capacity enterprise services, and remote PON OLT backhaul
- Support both point-to-point and point-to-multipoint services utilizing digital subcarrier technology
- Prevent costly and time-consuming dual-fiber deployments that are typically needed for coherent optics in fiber-constrained PON access networks with ICE-X's lower installation costs and quicker time to revenue
- Avoid impacting all PON technologies, both existing and near term, by operating within the C-band where only NG-PON2 and RF video overlay deployments reside



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Similarly, the SFW ODN access domain is typically considered by the access team as a separate network supporting PON technology only, with a backhaul handoff to the separate DWDM transport domain.

This creates a real challenge for network operators, who can leverage their substantial investment in SFW infrastructure for residential and small/medium enterprise (SME) customers using the latest PON technology but may struggle to use this same resource for higher-capacity services such as 5G xHaul, high-capacity business services for larger enterprise customers, or even backhaul of remote PON OLTs. These services can exceed the total capacity offered by PON technology, currently 10G or 25G shared across all the users of the network, and they typically require DWDM technology using coherent optics and a dedicated fiber pair per customer. Deploying a dedicated pair of fibers per service can make these higher-capacity services very slow and expensive to deploy, and cost-prohibitive for the end customer. Ideally network operators would like a solution to this problem that would enable them to deploy higher-speed coherent optics over this extensive SFW ODN access network to reduce deployment costs and enable an earlier time to revenue for the service.

The Challenge of Conventional Coherent Optics over PON

The challenge that network operators face is that the higher-speed coherent DWDM optics needed to support high-capacity services typically can't be used over SFW networks. This is because coherent optics need a local oscillator in the receiver, and almost all modern designs use a tap from the transmitter laser to provide this, which locks the transmitter and receiver wavelengths to the same frequency. Lower-speed 10G DWDM networks using direct-detect optics can use a different wavelength in each direction over SFW due to the wideband receiver being able to receive any wavelength in the DWDM range. But higher-speed DWDM optics above 10G rates need to be built using coherent optics and can't do the same two-wavelength technique because the receiver is typically locked to the same wavelength as the transmitter by the shared laser/local oscillator.

It should be noted that there are a small number of coherent optics available in the optics market today that use two lasers to support SFW, one for transmit and one for the receiver reference. These devices are more expensive and power hungry due to doubling up the optics and are limited to a much lower optical launch power and therefore cannot support the required power budget for the PON overlay application. Finally, the additional components mean that these optics are only available in a CFP2 form factor and not the QSFP-DD that is required for direct mounting in routers, switches, and other third-party devices.

10G services using 25G-PON or 10G DWDM may provide a stopgap solution, but many service and backhaul rates already exceed 10G, and with bandwidth demands growing as fast as they are, operators need a solution that can scale to higher rates. However, there are new advances in intelligent coherent optics that can provide a solution to this challenge. New subcarrier-based point-to-multipoint XR optics can provide a solution to this quandary. This new architecture offers support for high-capacity coherent optics over SFW PON infrastructure, enabling network operators to capitalize on their significant PON-based FTTH investments for lucrative higher-capacity services for large enterprise customers, mobile xHaul, and backhaul of remote OLT devices.

The Innovation of New Intelligent Coherent XR Optics

These new point-to-multipoint XR optics use advanced signal processing in the digital signal processor (DSP) chip to modulate a single laser into many individual digital subcarriers. This capability enables a single higher-speed hub optic to communicate with multiple lower-speed leaf optics. For example, in a dual-fiber environment, a 400G hub optic would have a single laser, but the DSP would modulate the signal into 16 individual 25G subcarriers. These subcarriers could then be routed to up to 16 different leaf nodes by the underlying fiber infrastructure, where lower-speed 100G optics can support one to four subcarriers supporting services from 25G to 100G, as shown in Figure 1.

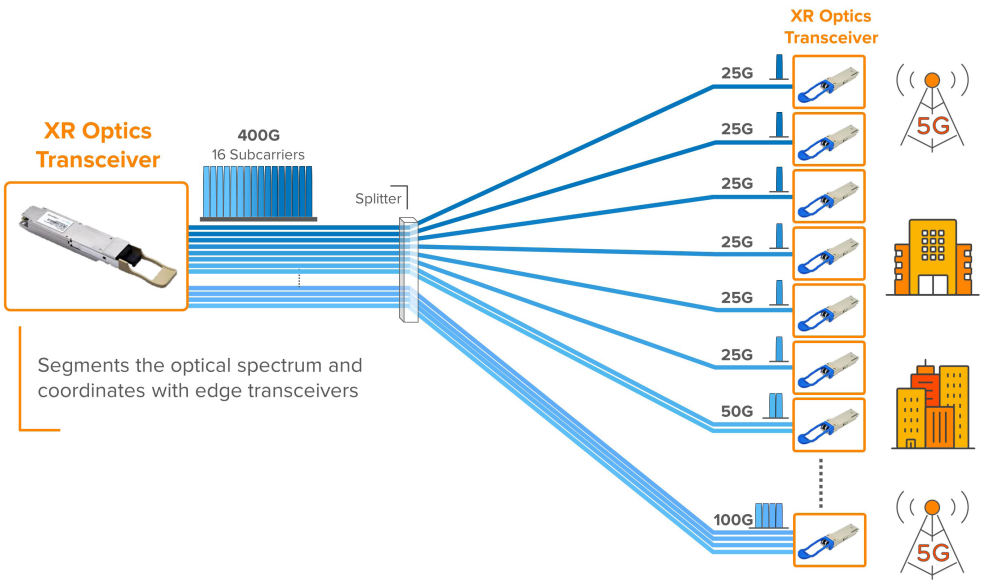

Figure 1: The XR optics point-to-multipoint architecture in action

In an SFW environment, operators can leverage these subcarriers and use them selectively in each direction to enable coherent optics to work over the single fiber, as shown in Figure 2. In a similar way to how 10G DWDM optics use different wavelengths per direction, this approach does the same but at the subcarrier level of granularity. This capability can then be overlaid on top of an existing SFW network to enable those high-capacity services in parallel to the existing PON-based residential and SME customers.

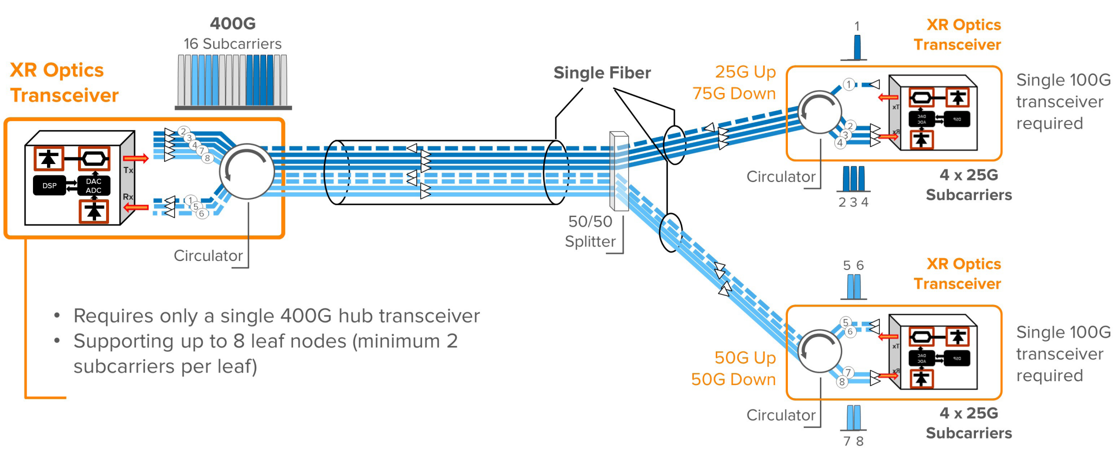

Figure 2: XR optics in single-fiber working environments

Coherent technology comes at a different price point than PON-based services, so this isn't a replacement technology for the PON network. The two technologies coexist on the same SFW infrastructure to broaden the range of services possible over the access network. If high-capacity services that need coherent optics are required, then overlaying these on the existing PON infrastructure by using subcarrier technology is substantially quicker and more cost-effective to deploy than the alternative of pulling a new dedicated fiber pair all the way from the hub to the customer just to support the dual-fiber requirement of standard coherent optics.

High-capacity PON Overlay in Practice

Deploying subcarrier-based XR optics over PON simply requires that the DWDM signals can be combined with the existing and planned PON technology running over the SFW ODN, typically via a coexistence element, as shown in Figure 3. Many ODNs either contain coexistence elements today or are planned to in the future to enable the ODN to support multiple generations of Combo PON technology, such as GPON, XGS-PON, 25G-PON, and, in the future, 50G-PON (G.hsp).

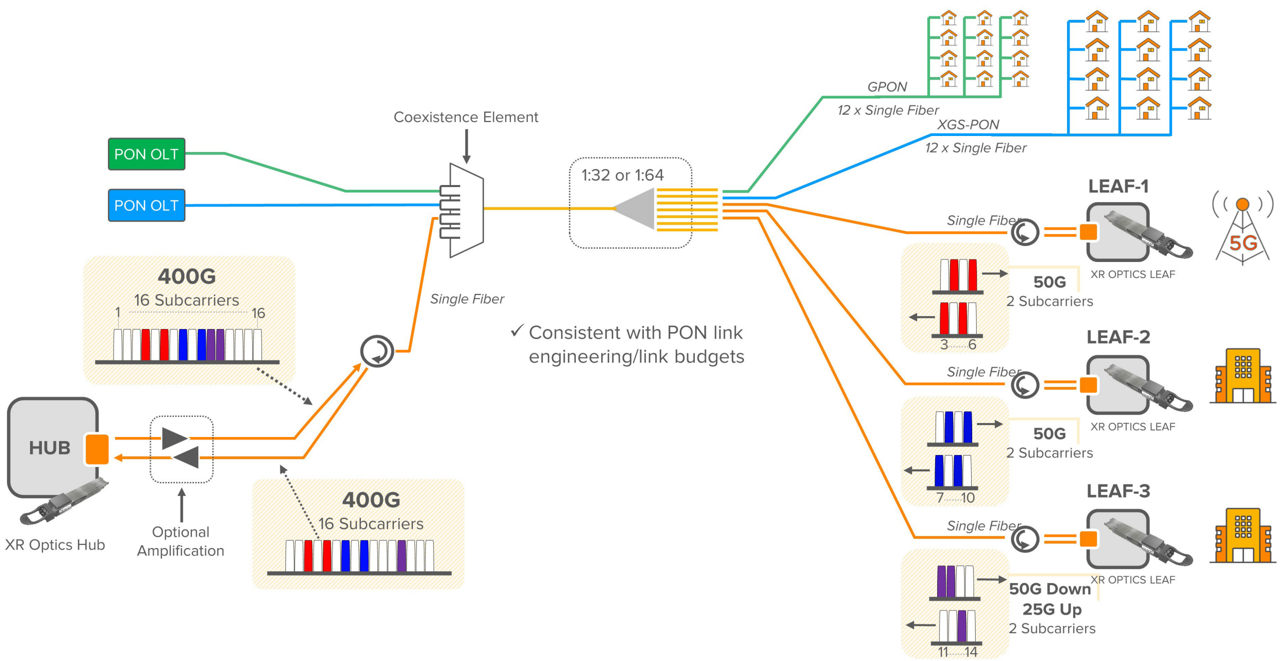

Figure 3: High-capacity services over a combined GPON/XGS-PON using subcarrier-based XR optics

Once the XR optics hub node is connected to the ODN via the coexistence element, high-capacity coherent services can be delivered to leaf nodes over the ODN using the coherent subcarriers. A single 400G hub optic will support up to eight leaf nodes with 25G per node for the maximum number of nodes, or up to two leaf nodes with 100G per node for the highest capacity per node. As capacity to specific leaf nodes grows, additional subcarriers can be simply allocated via software, up to the maximum of 100G per leaf in point-to-multipoint networks or 200G in point-to-point networks. As the solution is based on DWDM technology, if more total capacity or more leaf nodes are required, then we simply need to add additional hub optics using different DWDM wavelengths. Furthermore, in some deployment scenarios, a single hub optic can support leaf nodes spread across multiple PON ODNs if required.

Once this capability has been validated in a test environment to the operator’s satisfaction, the operator’s sales teams can get started promoting and selling the new high-capacity service capability. No initial hardware needs to be deployed until a service is sold, assuming the ODN passes the customer. At that point, drop fiber is installed, the hub and leaf optics and host devices are installed where needed, and the connections are then established to support the new service. All the rest of the underlying SFW infrastructure is already in place from the residential/SME PON services.

Ensuring Smooth Coexistence

DWDM optics operate over what is known as the conventional band, typically shortened to C-band. The C-band overlaps with the 1530-1540 nm NG-PON2 upstream spectrum and the 1550-1560 nm RF video spectrum, as shown in Figure 4. As XR optics are fully tuneable across the whole C-band, this enables many existing coexistence elements to utilize these existing ports for new high-speed services if suitable coexistence elements have been deployed and either of these ports is available. The NG-PON2 spectrum can be particularly useful here as this technology was widely anticipated but not widely deployed. If both the NG-PON2 and RF video spectrum are required for those services, then XR optics modules can utilize the spectrum between these windows for PON overlay applications utilizing additional low-loss coexistence units.

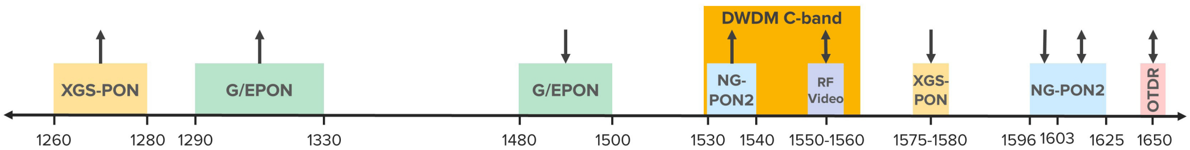

Figure 4: PON and C-band DWDM operating spectra

PON overlay based on XR optics running over DWDM C-band spectrum is also anticipated to be forward compatible with future PON technology such as 50G-PON, which is currently working through standardization. Current plans for 50G-PON include spectrum options that overlap with both current XGS-PON and G/EPON spectrum so that network operators have a roadmap to coexistence between 50G and either XGS-PON or G/EPON. Importantly, this also enables coexistence with XR optics-based PON overlay solutions.

PON Overlay Applications

Numerous PON overlay applications exist; essentially any service requirement that exceeds the capabilities of the existing PON solution can be an opportunity for PON overlay. Possible applications include:

- **High-capacity business services** – Business parks or larger enterprises within the ODN footprint may demand 10G, 25G, or higher services.
- **5G xHaul** – Cell towers close to residential areas that are served by PON technology or existing GPON/XGS-PON 3G/4G backhaul networks that require capacity upgrades to support 5G.
- **Multi-access edge computing (MEC)** – Closely linked to 5G and the cloudification of business services, MEC will drive storage and compute resources ever closer to the edge of the network and potentially into SFW domains.
- **Community anchor institutions** – Schools, libraries, medical centers, and other municipal buildings have much higher bandwidth requirements than single-family homes, small businesses, and branch offices. The community would benefit once anchor institutions were afforded the ability to connect to the internet without bandwidth constraints.
- **Remote OLT backhaul** – This application may be driven by a range of scenarios:
  - **Extending PON ODN reach** – Operators may choose to push OLT nodes deeper into the ODN to extend the reach of the ODN. This then requires OLT backhaul over the existing single-fiber infrastructure.
  - **New builds requiring ODN expansion** – Operators may have an existing ODN where new house building requires infill within the footprint. To gain additional capacity within the ODN, the operator may choose to use an existing ODN fiber intended for a customer ONU and deploy a new OLT at that location. The new extension ODN can then be built from this location and the OLT can be backhauled over the existing ODN using the PON overlay solution.

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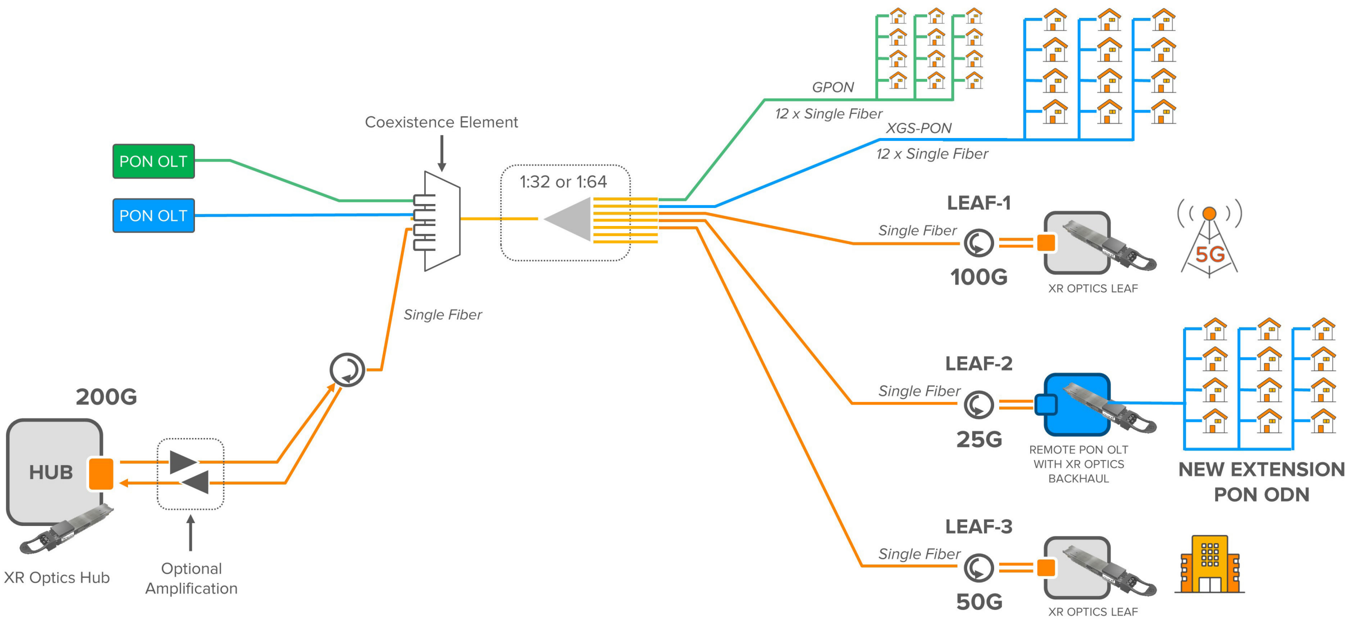

Figure 5: PON overlay to support ODN extension with a remote OLT

Nokia's ICE-X PON Overlay Solution

Nokia is implementing the XR optics architecture via a range of ICE-X pluggable DCOs, demarcation devices, and management software. Nokia's ICE-X portfolio comprises a number of key components that together enable network operators to deploy PON overlay networks:

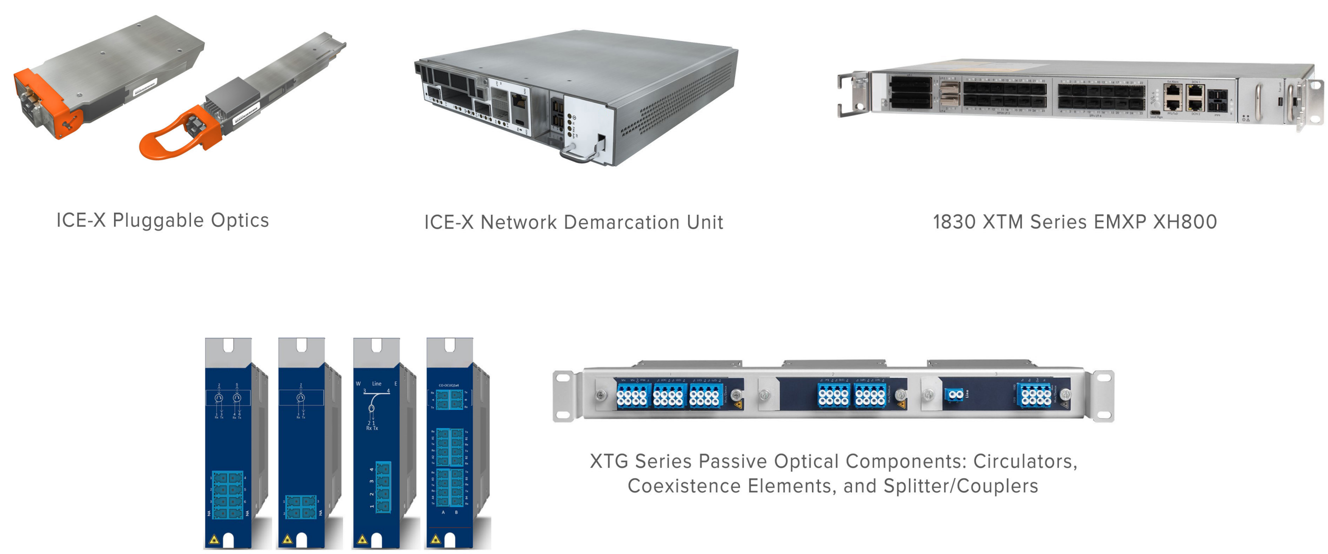

Figure 6: Nokia ICE-X PON Overlay Solution

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ICE-X Pluggable DCOs

Nokia's range of ICE-X pluggable DCOs includes CFP2-DCO and QSFP-DD modules that support operation from 25G to 400G flexibly using between one and 16 digital subcarriers. Over time, the range of ICE-X pluggable DCOs will be extended; for example, to include higher-capacity 800G optics supporting 32 digital subcarriers.

In addition to supporting full tuneability across the DWDM C-band, ICE-X pluggable DCOs also support a subset of 17 PON-optimized wavelengths that support enhanced performance with +2 dBm launch power vs. the 0 dBm figure for general ICE-X support across the whole C-band. This additional 2 dBm enables additional reach in demanding PON overlay applications.

ICE-X Network Demarcation Unit

The ICE-X Network Demarcation Unit (ICE-X NDU) is designed to provide an effortless translation of ICE-X pluggable DCOs into a standardized 100G QSFP28 as well as 25G through a 4:1 breakout configuration. This enables ICE-X deployment in locations requiring 100G/25G grey optics handoff.

The ICE-X NDU enables simple extension of ICE-X pluggable DCOs and creates a demarcation point between 100G/200G ICE-X line optics (supporting from one to eight digital subcarriers) and two QSFP28 100G client optical ports (each supporting from one to four digital subcarriers). Through the embedded virtual transport interface of ICE-X, bandwidth can be sliced in steps of 25G up to the full bandwidth of the client interfaces.

1830 Express Transport Metro (XTM) Series EMXP XH800

The EMXP XH800 is a hardened Layer 2 packet optical transport switch optimized for demanding transport applications such as 5G xHaul. As part of the 1830 XTM Series' range of EMXP packet optical transport switches, the EMXP XH800 has a comprehensive range of Ethernet and MPLS-TP features and capabilities. The series is optimized for transport applications with an output-queued buffer architecture that provides industry-leading low latency and synchronization performance.

The EMXP XH800 supports up to 960G of switching capacity with dual coherent 100G/200G DWDM uplinks that support ICE-X pluggable DCOs, and an extensive range of client ports including QSFP28 100G, SFP28 25G/10G, and SFP+ 10G/1G ports. The device is designed to support both standard telco environments and hardened non-telco environments such as street cabinets.

XTG Series Passive Optical Layer Components

The XTG Series provides a range of passive optical networking devices that can support WDM and PON overlay applications. To support PON overlay networks, the XTG Series includes:

- Single and dual circulators to connect dual-fiber components to single-fiber networks
- Low-loss coexistence elements to connect ICE-X components into existing PON networks
- Splitter/coupler modules

All XTG Series components are totally passive and temperature hardened and can be deployed in a range of mounting options such as standard rack mounts or wall-mounted cabinets.

Benefits of Nokia's ICE-X PON Overlay Solution

Nokia's ICE-X PON Overlay Solution enables network operators to capitalize on the XR optics architecture and bring high-capacity services to SFW PON networks. The solution is highly flexible, supports a broad range of PON deployment models, and can coexist with any existing PON network.

The solution solves the challenge of delivering high-capacity services over SFW without the need to deploy a dedicated new pair of fibers from the hub to every high-capacity customer. Once this capability is validated by the operator, sales teams can promote and sell the service without any initial capital outlay or pre-deployment of equipment. Not only does the approach avoid the additional cost of deploying new fibers for high-capacity services, but it also accelerates time to revenue on the new services as deploying an overlay solution is significantly quicker than deploying new fibers. This approach can also give these PON-based operators a time-based competitive advantage over enterprise-focused operators that always have to roll out bespoke fiber connectivity to new customers rather than leveraging existing network infrastructure.

Advanced ICE-X Functionality

In addition to supporting the generic subcarrier-based XR optics PON overlay architecture, Nokia's ICE-X DCOs support additional advanced functionality including:

- **High optical launch power for extended ODN reach** – ICE-X DCOs utilize integrated semiconductor optical amplifiers in the indium phosphide (InP) photonic integrated circuit (PIC) to support a higher launch power than many alternative approaches. This architecture avoids the higher cost and power of integrating a separate small EDFA into the pluggable that some alternative optics designs require. Using the InP PIC enables ICE-X DCOs to support a higher 0 dBm launch power across the whole of the DWDM C-band. ICE-X DCOs also support an optimized window of 17 wavelengths with an even higher +2 dBm launch power, which enables support for even larger ODNs.

- **Dynamic power allocation** – ICE-X DCOs support per-subcarrier power management within the individual wavelengths, which brings numerous benefits such as the ability to shape wavelengths to support legacy DWDM line systems with older ROADM nodes. This capability can also be used in PON overlay networks to move some optical power from the subcarriers supporting closer leaf nodes that don't need the full available power to subcarriers supporting leaf nodes that are further away that might need additional power budget to close the link. This capability is particularly useful in PON networks as the network endpoints can vary considerably in optical reach and power budget.

Conclusions

Due to the substantial global investment in single-fiber PON access networks, access networks are becoming increasingly focused on single-fiber infrastructure. As enterprise customer bandwidth increases, community anchor institution broadband needs are funded, and new network technologies such as 5G and MEC drive an increasing number of high-capacity services into access networks, these services will require higher-capacity transport over this SFW infrastructure. An alternative approach is required for those services that outstrip the sub-10G capabilities of the underlying PON technology.

The new XR optics subcarrier-based PON overlay approach enables network operators to capitalize on their significant investment in SFW access infrastructure and seamlessly offer the full range of services over this fiber network – from residential/SME services using PON technology to the highest-capacity services leveraging the Nokia ICE-X PON Overlay Solution. This approach utilizes the underlying PON infrastructure and avoids pulling a new dedicated fiber pair to the new end customer, which significantly reduces the cost of the new deployment. It also increases the operator's time to revenue for new high-capacity services by avoiding the time taken to deploy new fibers, especially if obtaining new wayleaves is required for any additional digging.

Network operators can easily capitalize on this approach with minimal upfront investment as no new network infrastructure is required until the first services are sold and deployed.

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