ICE7 for subsea networks

Boost submarine cable capacity while minimizing cost, space, and power

Application note

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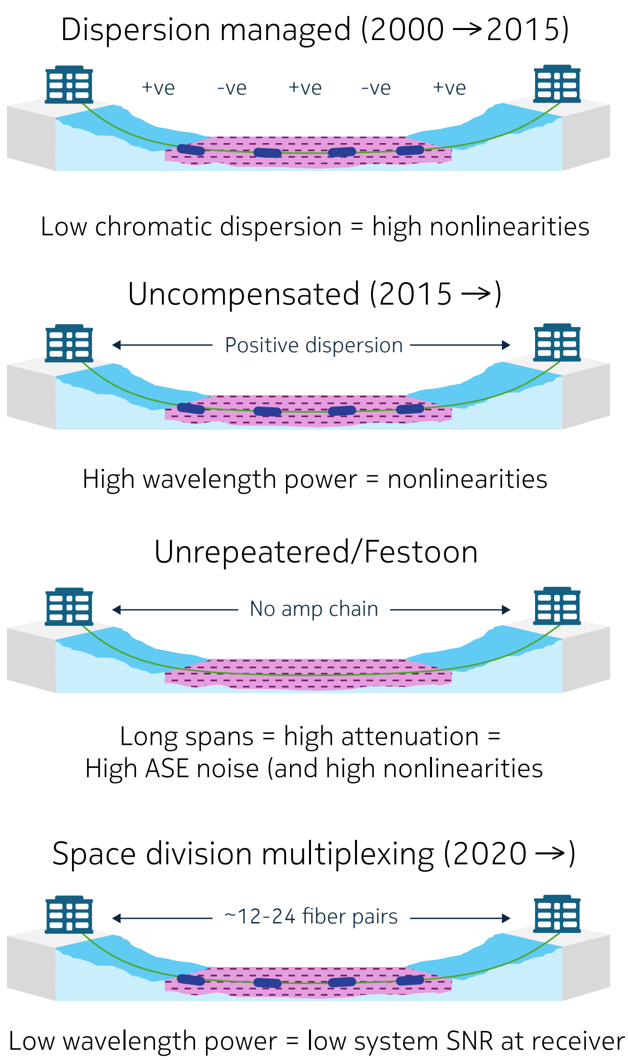
According to TeleGeography's 2024 The State of The Network Report, demand for international bandwidth continues to nearly double every two years. To meet this demand, submarine network operators are deploying new cable systems, with 77 new systems currently planned. At the same time, submarine network operators need to maximize capacity on the more than 500 submarine cable systems and 1.4 million kilometers currently in service. Moreover, these existing and planned cable systems fall into four categories: dispersion managed (deployed ~2000-2015), uncompensated (from ~2015), space-division multiplexed (from ~2020), and unrepeatered/festoon, as shown in Figure 1.

Figure 1. Submarine cable types and key challenges



Benefits of ICE7 for subsea networks

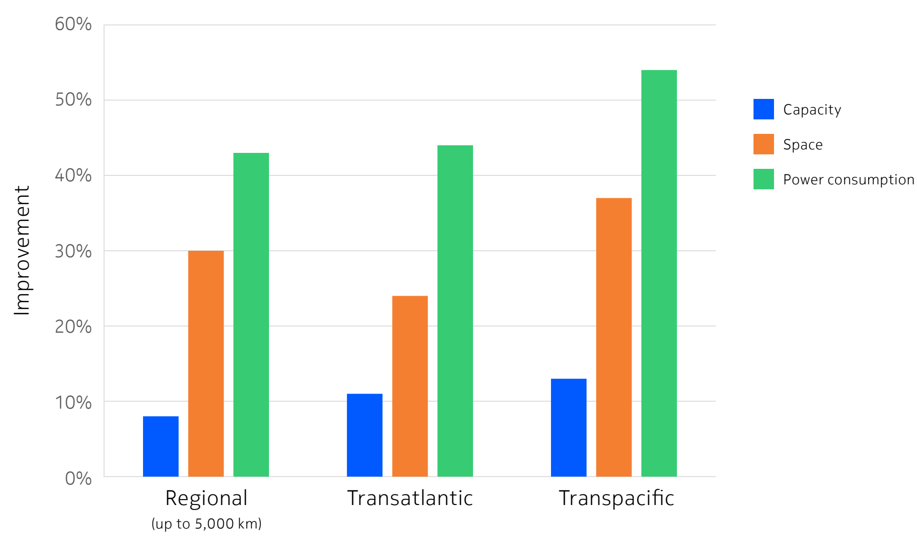
- Boost cable capacity by more than 10% with a continuously tunable baud rate, flexible modulation, and a configurable roll-off
- Reduce transponder power consumption by over 50%, transponder footprint by over 30%, and transponder CapEx by over 30%, leveraging 5-nm DSP technology and high baud rate operation at 140+ Gbaud
- Maintain the maximum possible baud rate on uncompensated transoceanic cables with support for >300,000 ps/nm (>15,000+ km) of chromatic dispersion at 138 Gbaud
- Leverage Super C and Super L on the terrestrial backhaul network to reduce fiber leasing costs
- Address the most challenging dispersion-managed cables with a hybrid solution that leverages both ICE6 and ICE7 in different parts of the spectrum, with both supported in the GX G42 chassis

As all submarine cable systems, regardless of type, require huge investment and take many years to plan and deploy, submarine network operators naturally want to extend the lives of their cables and maximize their capacities. However, each type has specific challenges. For example, nonlinearities can be a key challenge for dispersion-managed fibers due to low chromatic dispersion, especially toward the center of the spectrum. While the large effective areas of uncompensated fibers significantly offset the nonlinear penalties of higher wavelength power, at the high power levels these fibers typically operate at, nonlinearities are still a key challenge. With more fiber pairs, space-division multiplexing (SDM) cable systems run at lower power levels, making low system signal-to-noise ratio (SNR) at the receiver a key challenge. Each type therefore requires a different combination of ICE7 features to maximize performance.

ICE7 increases capacity while reducing cost, space, and power

The seventh-generation Infinite Capacity Engine (ICE7) includes a state-of-the-art 5-nm CMOS process node digital ASIC/DSP, advanced optical front end, and high-performance packaging. It delivers a single wavelength at up to 1.2 Tb/s with a symbol rate of up to 140+ Gbaud, while also enabling significantly improved reach at lower data rates including 800 Gb/s, 600 Gb/s, and 400 Gb/s. ICE7 is available as a 2.4 Tb/s dual-lambda sled for the GX G42, the CHM7. This sled enables submarine network operators that have already operationalized the GX G42 with ICE6-powered CHM6 sleds to quickly onboard ICE7 technology, including deploying CHM7 sleds in any spare slots and operating wavelengths from CHM6 and CHM7 over the same fiber pair.

Figure 2: ICE7 benefits vs. ICE6 (Nokia modeling results of 16 real cables, CLS to CLS)

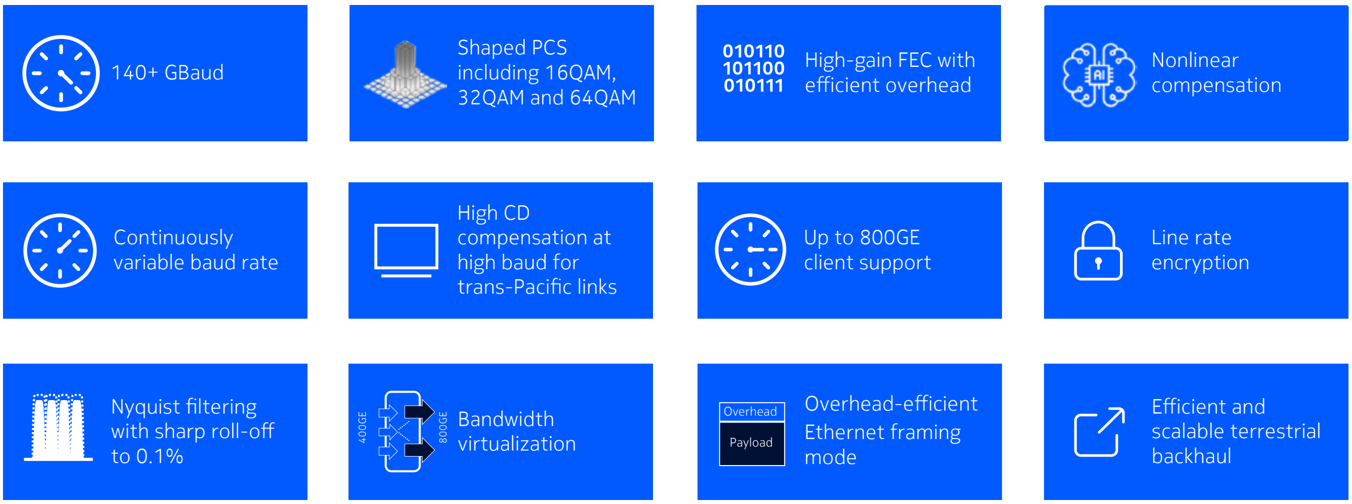


ICE7 delivers multiple benefits relative to the ICE6-enabled CHM6. Nokia conducted cable landing station (CLS) to CLS modeling of 18 real cables – six regional, six trans-Atlantic, and six trans-Pacific. In regional submarine cases (up to 5,000 km), capacity was increased by 8% while space was reduced by 30% and power consumption by 43%. In trans-Atlantic cases, capacity was increased by 11% while space was reduced by 24% and power consumption by 44%. In trans-Pacific cases, capacity was increased by 13% while space was reduced by 37% and power consumption by 54%. The CHM7 also demonstrated cost savings in excess of 30% in all three scenarios.

The ICE7 submarine toolkit

What enables ICE7 to deliver these improvements in capacity, cost, space, and power is a comprehensive submarine toolkit, illustrated in Figure 3, with the key enabling features described in detail below.

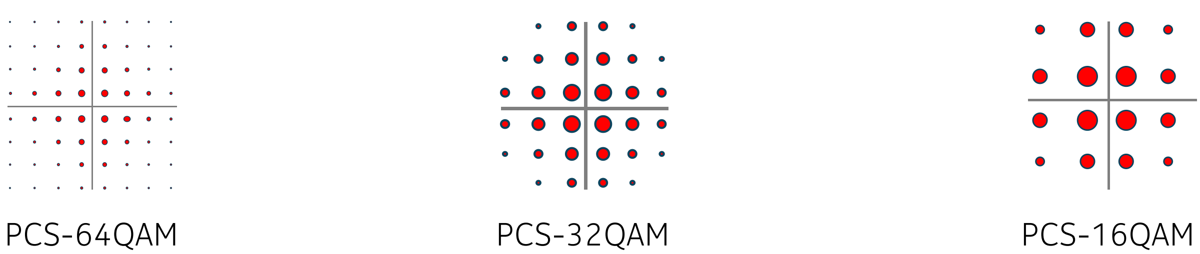
Figure 3: The ICE7/CHM7 submarine toolkit



Flexible modulation including PCS-64QAM, PCS-32QAM, PCS-16QAM, and conventional QAM

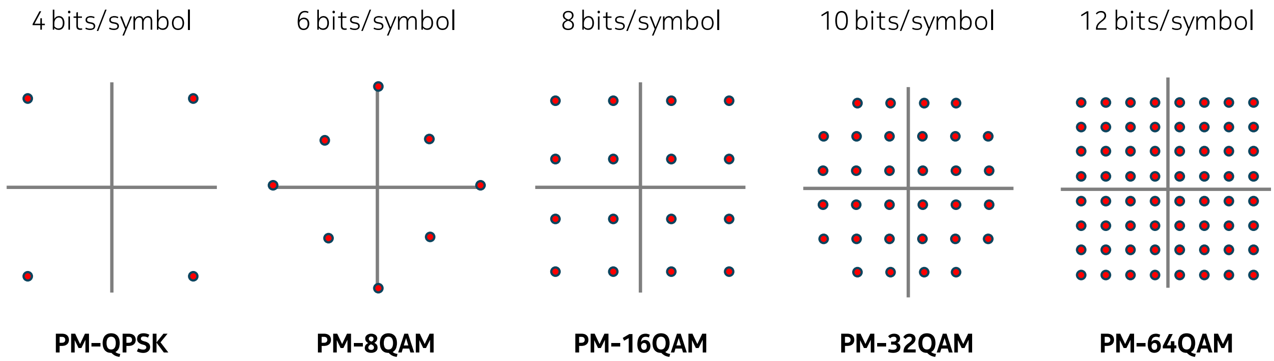
Unlike conventional modulation, where each constellation point has the same probability of being used, probabilistic constellation shaping (PCS) uses the lower-energy/-power inner constellation points more frequently and the higher-energy/-power outer constellation points less frequently. By adjusting the probabilities, PCS provides the option of fine bits-per-symbol granularity, enabling a far smoother capacity-reach curve than conventional QAM modulation. Furthermore, for the same average wavelength power and spectral efficiency, there is greater Euclidean distance between the constellation points relative to conventional QAM, which increases tolerance to linear noise such as the amplified spontaneous emission (ASE) noise from the repeaters. Alternatively, for the same linear noise tolerance as conventional QAM, less wavelength power is required, and therefore nonlinearities are lower.

Figure 4: ICE7 supports PCS-64QAM, PCS-32QAM, and PCS-16QAM



ICE7 supports PCS-64QAM, PCS-32QAM, and PCS-16QAM. The benefit of PCS-32QAM and PCS-16QAM is that at lower bits per symbol, these PCS options provide additional gain relative to PCS-64QAM while also potentially consuming less power. In addition, ICE7 provides the option of convention modulation, including PM-QPSK, PM-8QAM, PM-16QAM, PM-32QAM, and PM-64QAM, as shown in Figure 5.

Figure 5: ICE7 also supports conventional modulation

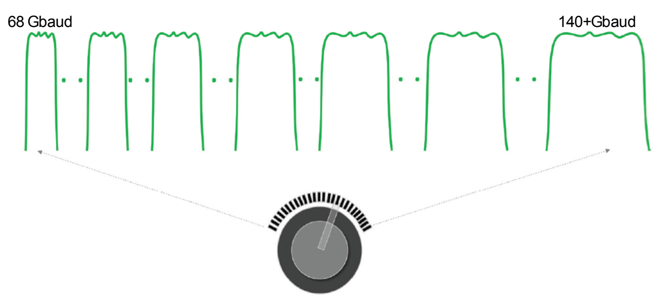


140+ GBAUD

ICE7 supports up to 140+ Gbaud, which is a key enabler for the cost-effective delivery of 400 GbE and 800 GbE services over both regional and transoceanic submarine cable systems. Increasing the baud rate enables a proportional increase in the data rate of a wavelength with only a relatively small reduction in reach and therefore spectral efficiency. Higher baud rates provide a key lever for reducing cost per bit, power consumption, and footprint while also reducing OpEx with fewer individual wavelengths to provision and manage.

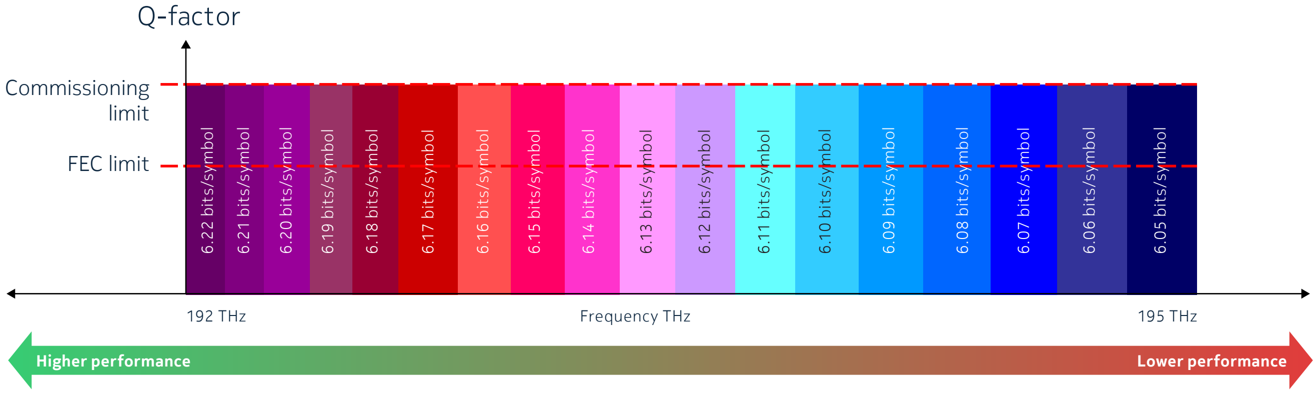
Continuously tunable baud rate

Figure 6: 0.1 Gbaud increments from 68 to 140+ Gbaud



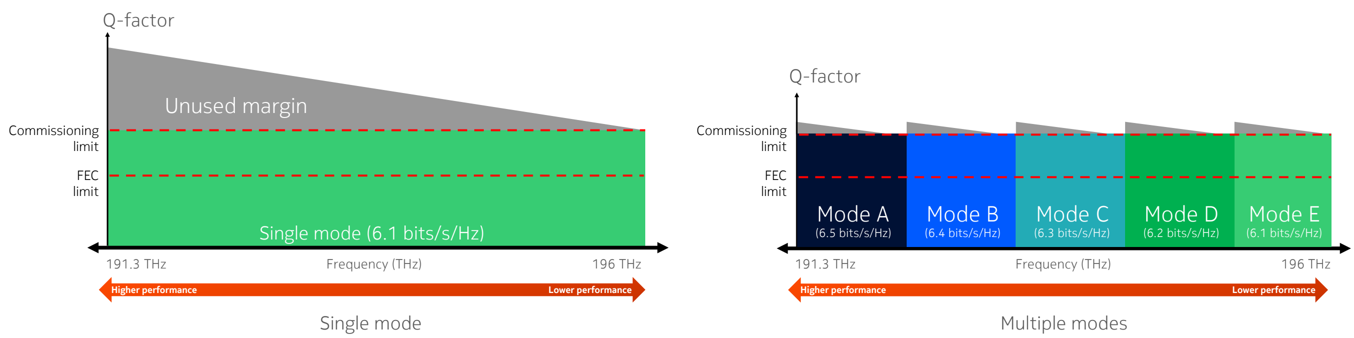
ICE7 supports a continuously tunable baud rate from 68 Gbaud to 140+ Gbaud, as shown in Figure 6, with increments of approximately 0.1 Gbaud. As the performance of a submarine fiber typically varies across the spectrum, with typically higher performance at lower frequencies and worse performance at higher frequencies, this baud rate tunability, combined with the bits-per-symbol granularity of ICE7's PCS modulation, enables submarine network operators to select an optimal mode (combination of baud rate and modulation) for each individual wavelength in order to eliminate unused margin and maximize the total capacity of the fiber, as shown in Figure 7. In total, ICE7 hardware has the ability to support over 14,000 modes. Furthermore, this capability often enables the use of a single line rate across the entire spectrum of the fiber while still maximizing the fiber's capacity.

Figure 7: Maximize capacity with an optimal mode for each individual wavelength



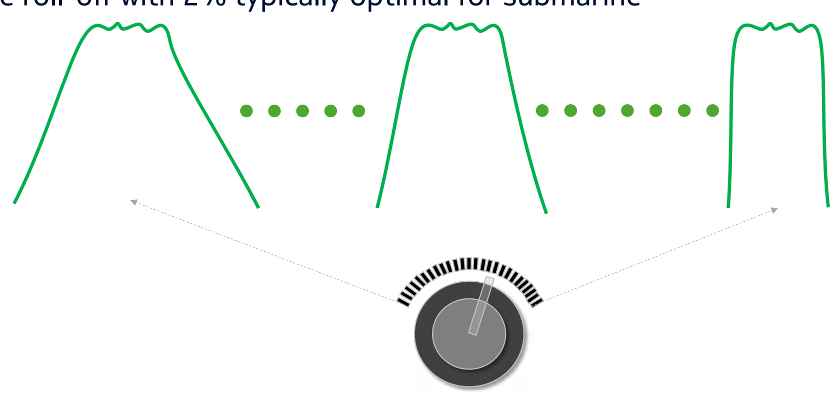
This compares to earlier generations of coherent technology that typically used either a single mode or a more limited range of modes, as shown in Figure 8, leaving unused margin and therefore providing less than optimal cable capacity.

Figure 8: Earlier coherent generations left unused margin



Configurable roll-off

Figure 9: Configurable roll-off with 2% typically optimal for submarine



A wavelength's roll-off is the amount of additional spectrum required to accommodate the slopes and modes at the sides of the wavelength, with a squarer frequency-domain shape reducing the spectrum wasted by the wavelength itself and enabling wavelengths to be packed closer together. ICE7 supports a configurable roll-off from 0.1% to 100% with 0.1% Increments. Given that there are penalties at very low roll-offs, the optimal roll-off for submarine applications is typically 2%. A 2% roll-off is a substantial reduction on the previous 7-nm/90+ Gbaud generation of coherent technology, which typically had a roll-off in the 5% to 10% range.

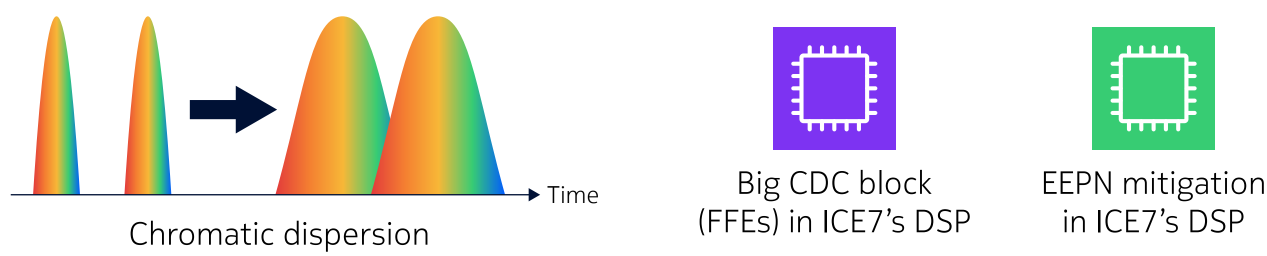
Overhead-efficient ethernet-only framing mode option

ICE7 supports an overhead-efficient Ethernet framing mode that requires less overhead and therefore a lower baud rate and less spectrum for the same data rate compared to traditional OTN framing. While highly dependent on multiple factors, including the available spectrum, this feature can increase capacity by up to 5%, equivalent to up to 1 Tb/s per fiber pair on a typical modern uncompensated or SDM cable system. ICE7 also supports the option of OTN framing for OTU4 clients.

High chromatic dispersion tolerance

Chromatic dispersion occurs because different frequencies travel at different speeds through the fiber – even different frequencies of the same coherent wavelength travel at slightly different speeds and eventually distort the signal. However, in the coherent era, high chromatic dispersion is highly beneficial in terms of reducing nonlinear penalties. High chromatic dispersion decreases the likelihood that symbols on different wavelengths propagate together, changing the refractive index of the fiber at the same time though the Kerr effect, thus causing nonlinear effects such as cross-phase modulation (XPM). Recognizing this benefit of high chromatic dispersion, the submarine industry transitioned from dispersion-managed cables (~2000-2015) to uncompensated cables (~2015) and later SDM cables (~2020) with deliberately high chromatic dispersion (typically around 20 ps/nm/km).

Figure 10: ICE7 chromatic dispersion compensation



These uncompensated and SDM cables can have very high aggregate chromatic dispersion. For example, wavelength distances over trans-Pacific cables can exceed 10,000 km, equating to around 200,000 ps/nm. Compensating for this chromatic dispersion in the DSP becomes increasingly challenging as baud rates increase due to the squared relationship between baud rates and chromatic dispersion. For example, doubling the baud rate reduces the tolerance to chromatic dispersion by a factor of four. To address this challenge, the ICE7 DSP incorporates a large feed-forward equalizer (FFE) block that can compensate for large amounts of chromatic dispersion even at the highest baud rates.

At 138 Gbaud it can support >300,000 ps/nm, enough for wavelengths over even the longest uncompensated and SDM transoceanic cables. In addition to high chromatic dispersion tolerance, ICE7 also includes equalization-enhanced phase noise (EEPN) mitigation circuitry to minimize the phase noise that occurs when compensating for large amounts of chromatic dispersion.

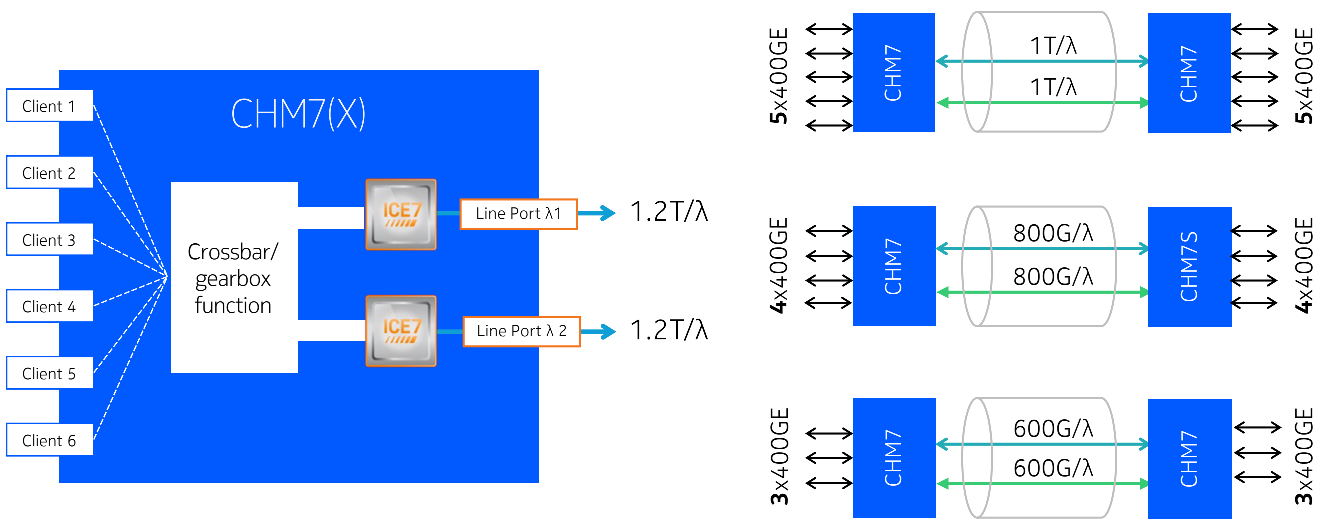
Nonlinear compensation circuitry

In addition to the potential nonlinear benefits of ICE7's PCS modulation discussed previously, ICE7's DSP includes nonlinear compensation (NLC) circuitry. Turning this function on provides approximately 0.5 dB of gain in the 35 Gbaud to 140 Gbaud range of ICE7 on a typical uncompensated trans-Atlantic cable (~7,000 km). This is a significant improvement in NLC performance compared to previous generations of embedded optical engine technology.

Bandwidth virtualization

While the ICE7 optical engine is single wavelength, the crossbar in the CHM7 sled supports bandwidth virtualization. This enables multiple 400 GbE or 800 GbE clients over two paired wavelengths. Examples include one 800 GbE service over two 400 Gb/s wavelengths, three 400 GbE services over two 600 Gb/s wavelengths, and five 400 GbE services over two 1 Tb/s wavelengths, as shown in Figure 11.

Figure 11: CHM7 bandwidth virtualization examples



Service-based encryption

The encryption-capable version of the ICE7-powered CHM7 sled for the GX G42 supports wire-speed AES-256 Layer 1 encryption on a per-client port/service basis. Compliant with IKEv2, secure key exchange is provided by elliptic curve Diffie-Hellman ephemeral (ECDHE), while authentication and authorization are enabled by X.509 certificates or a pre-shared key. In addition, this CHM7 encryption solution benefits from a comprehensive security toolkit on the GX G42 that includes software image signing and secure boot.

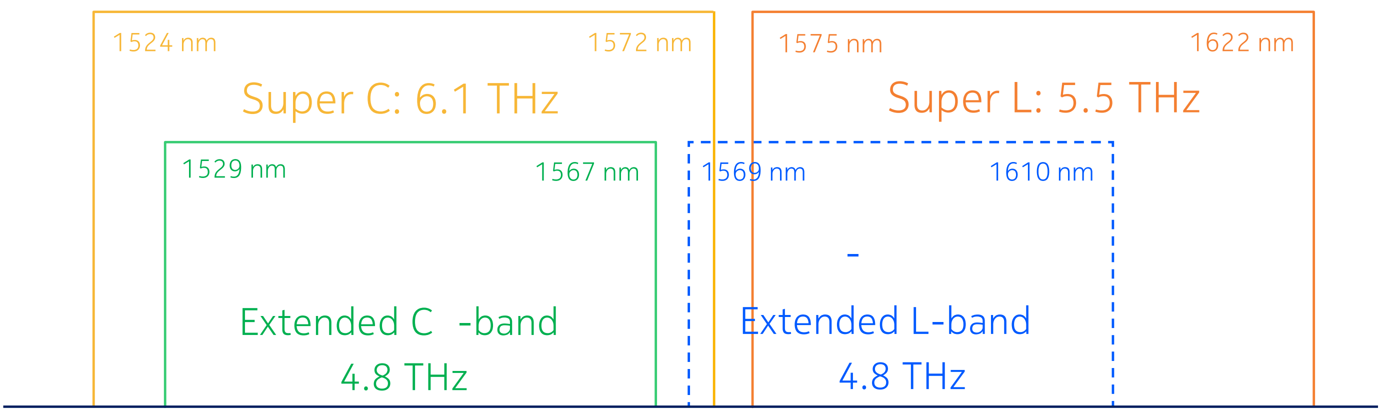
Integrated prbs test and loopback

ICE7 supports integrated PRBS test and loopback facilities that enable the testing phase (i.e., 24-hour or 48-hour soak test) of wavelength commissioning to be conducted remotely without the need for expensive external PRBS test equipment. In addition to reducing test equipment CapEx, this feature can greatly reduce travel time for engineers and test equipment, which together with other aspects of Nokia's submarine line-terminal equipment (SLTE) solution, including Intelligent Power Management (IPM) software and integrated optical channel monitoring (OCM) with optical spectrum analyzer (OSA)-like performance, can significantly reduce service activation time, accelerating time to revenue. It also enables multiple links to be tested in parallel.

Terrestrial backhaul with Super C and Super L

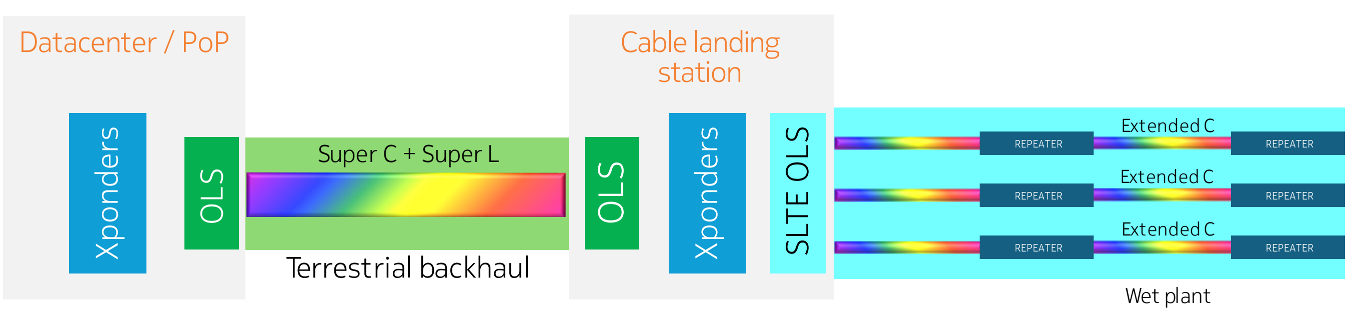
Nokia's Super C increases the amount of C-band spectrum on terrestrial fiber by 1.3 THz (27%), from 4.8 THz to 6.1 THz, while Super L increases the amount of L-band spectrum by 0.7 THz (14.5%), from 4.8 THz to 5.5 THz. Super C and Super L, shown in Figure 12, are supported on the ICE7-enabled CHM7 (extended C/Super C on the CHM7 and extended L/Super L on the CHM7L) and the GX OLS, which supports both terrestrial and submarine optical line system applications.

Figure 12: Super C and Super L



While the spectrum on subsea networks is limited by the spectrum of the wet plant repeaters (currently around 4.5 THz on newer submarine fibers), Super C and Super L have applications in the terrestrial backhaul portion of subsea networks. One application is reducing the number of leased backhaul fibers. For example, three submarine fibers could be backhauled over a single Super C + Super L backhaul fiber, leveraging the available 11.6 THz of spectrum and higher-order modulation, as illustrated in Figure 13.

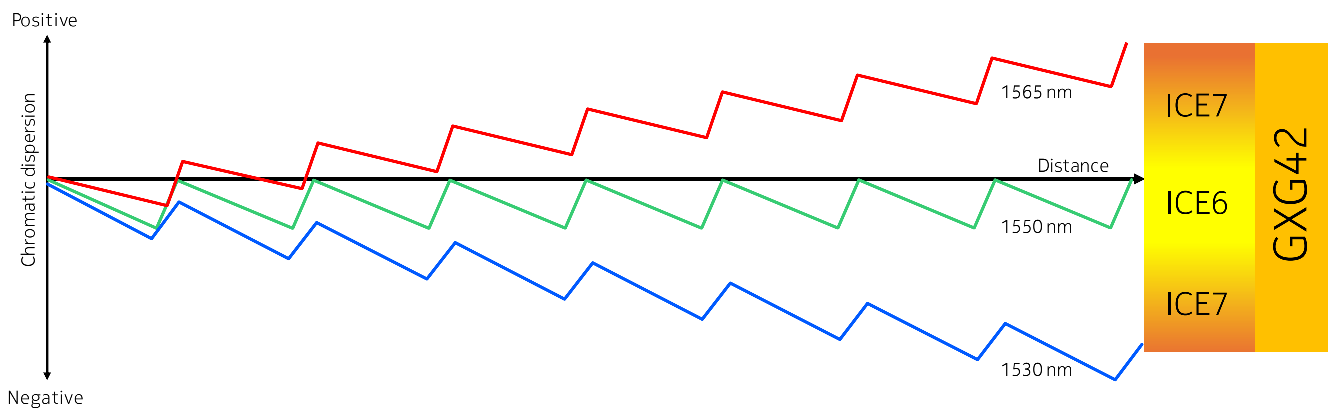
Figure 13: Super C/Super L terrestrial backhaul



Hybrid ICE6/ICE7 solutions for the most challenging dispersion-managed cables

First-generation dispersion-managed cables were designed to optimize the performance of 10 Gb/s non-coherent wavelengths, for which chromatic dispersion was a key challenge. These cables, which were widely deployed between 2000 and 2010, leveraged non-zero dispersion-shifted fiber (NZDSF) with negative and positive chromatic dispersion, resulting in zero dispersion around the center of the C-band. For example, there would be nine lengths of fiber with chromatic dispersion of -2 ps/nm/km for every one length of +18 ps/nm/km. However, due to the frequency-dependent nature of chromatic dispersion, there are large variations in chromatic dispersion across the C-band spectrum. As shown in Figure 15, while at the center wavelengths (~1550 nm) the chromatic dispersion stays close to zero, over longer distances chromatic dispersion becomes highly positive (~1565 nm) or highly negative (~1530 nm) toward the edges of the C-band.

Figure 14: A hybrid ICE6/ICE7 solution can be optimal for the most challenging dispersion-managed cables



For the most challenging dispersion-managed fibers, an optimal solution could leverage ICE6 in the most challenging central part of the spectrum and ICE7 in the less challenging outer parts of the spectrum, as shown in Figure 15. The most challenging part of the spectrum leverages ICE6's ultra-high-gain 33% overhead FEC option and modulation options with fewer than 4 bits per symbol, including hybrid 3/4QAM with 3.5 bits per symbol, FD-3QAM with 3 bits per symbol, FD-2.5QAM with 2.5 bits per symbol, and FD-eBPSK with 2 bits per symbol. The less challenging parts of the spectrum can leverage the ICE7 submarine toolkit to maximize capacity while minimizing cost, space, and power, with both technologies deployed in the GX G42 platform.

Summary

Nokia's ICE7 optical engine includes a comprehensive toolkit for a wide range of submarine applications, including dispersion-managed, uncompensated, SDM, and unrepeatered/festoon cables. These tools include flexible modulation (PCS-64QAM, PCS-32QAM, PCS-16QAM, and conventional QAM modulation), a continuously tunable baud rate to 140+ Gbaud, a minimized roll-off, an overhead-efficient Ethernet framing mode, very high chromatic dispersion tolerance, and bandwidth virtualization. Benefits can include a 10%+ capacity boost, 30%+ CapEx savings, a 30%+ footprint reduction, and 50%+ power consumption savings, relative to even the best-in-class previous generation embedded coherent engine technology, Nokia's ICE6.

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