ICE6 for subsea networks

Maximize performance on any submarine cable

Application note

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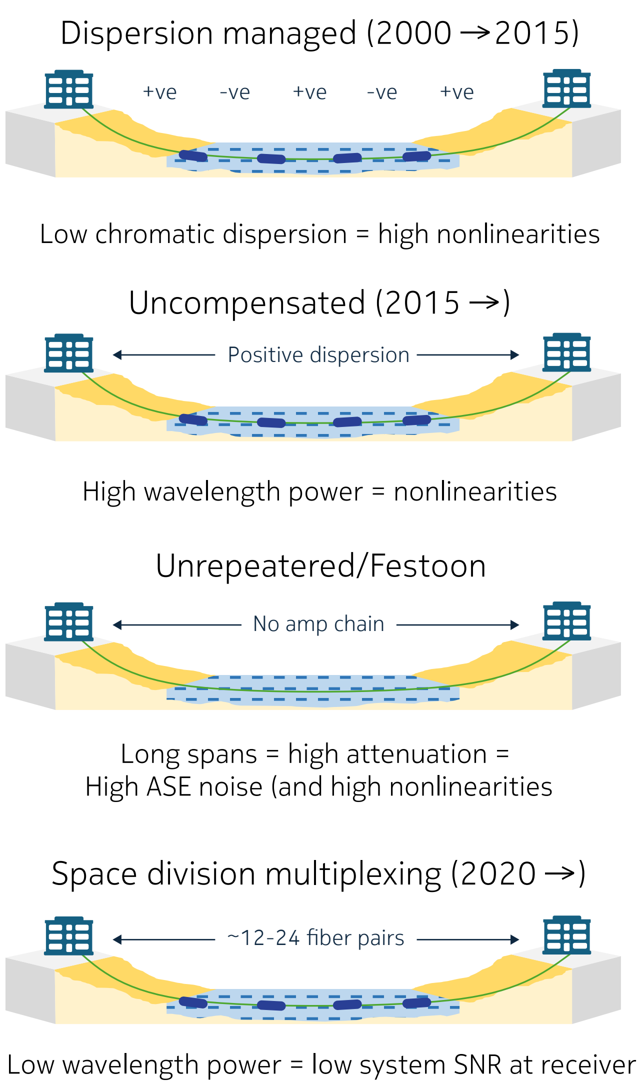
Submarine network operators are currently seeing significant growth in bandwidth demand. According to Telegeography's 2022 The State of The Network Report, international bandwidth more than doubled between 2018 and 2020, while international internet bandwidth grew at a compound annual rate of 45% between 2017 and 2021. Furthermore, Telegeography's 2022 submarine cable map shows 486 cable systems. These cable systems broadly fall into four categories: dispersion managed (deployed c. ~2000-2015), uncompensated (from c. 2015), space-division multiplexing (from c. 2020) and unrepeatered/festoon, as shown in Figure 1.

Figure 1. Submarine cable types and key challenges



Benefits of ICE6 for subsea networks

- Optimize performance for all submarine cable types, including dispersion managed, uncompensated, SDM, and unrepeatered/festoon
- Maximize spectral efficiency with innovative features including LC-PCS and second-generation Nyquist subcarriers
- Squeeze every last Gb/s out of your fiber with tuneable baud rates, granular modulation, SD-FEC gain sharing, and bandwidth virtualization
- Extend the life of dispersion-managed and unrepeatered cable systems with specialized 4D and 8D modulations and a 33% FEC option
- Reduce power consumption and cost per bit with ultra-high baud rates that maximize wavelength capacity-reach

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 their lives and maximize their capacities. However, each type has specific challenges. For example, nonlinearities are a key challenge for dispersion-managed fibers due to their low chromatic dispersion. 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 wavelength power levels, making low system signal-to-noise ratio (SNR) at the receiver a key challenge. Each type therefore requires a different combination of optical engine tools in order to maximize performance.

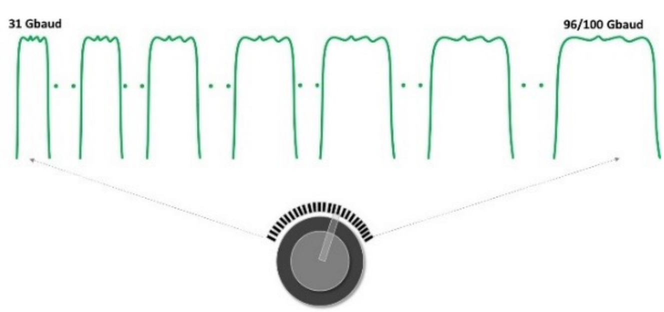
The ICE6 submarine toolkit

Nokia’s 800G generation Infinite Capacity Engine, ICE6, is a single 1.6 Tb/s optical engine that delivers two wavelengths at a maximum data rate of 800Gb/s per wavelength, adjusdable down to 100Gb/s. ICE6 leverages a 7-nm CMOS process node digital ASIC/DSP, combined with a highly integrated indium phosphide (InP) photonic integrated circuit (PIC), high-performance analog electronics, and advanced packaging. Targeted at high-baud-rate applications, the ICE6 Turbo variant extends the maximum baud rate of ICE6 from 96 Gbaud to 100+ Gbaud. ICE6 and ICE6 Turbo both offer a comprehensive toolkit to maximize performance in all submarine scenarios.

Ultra-high, tuneable baud rates

Increasing the baud rate enables a proportional increase in the data rate of a wavelength with minimal impact on its reach. Higher baud rates therefore provide a key lever for reducing cost per bit, power consumption, and footprint over a wide range of distances, while also reducing OpEx with fewer individual wavelengths to provision and manage. With a maximum baud rate of 96 Gbaud, ICE6 already delivered industry-leading reach over a wide range of wavelength speeds. ICE6 Turbo builds on the performance of ICE6, increasing the maximum baud rate from 96 Gbaud to over 100 Gbaud.

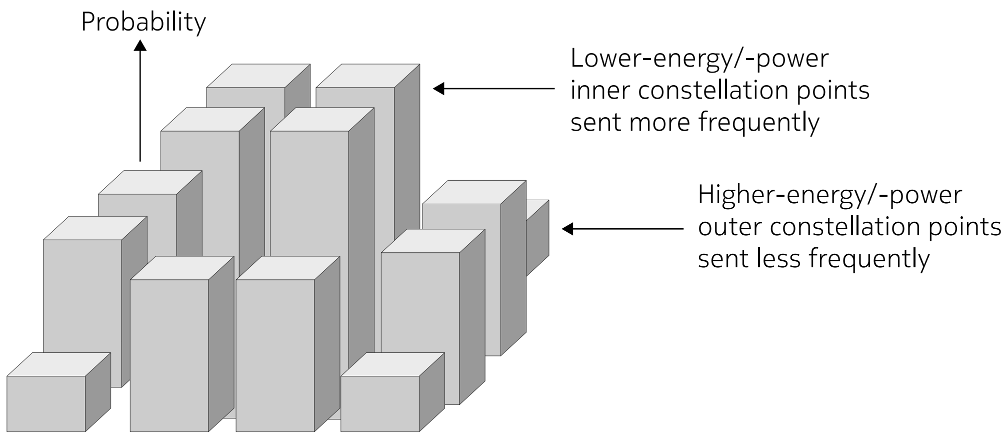
Figure 2. Tuneable baud rate from 31 Gbaud to 100+ Gbaud



As higher baud rates consume more spectrum, this may reduce margin a little for the same spectral efficiency, and are less tolerant of chromatic dispersion, there are multiple submarine scenarios where a lower baud rate can be more optimal. For this reason, ICE6 offers a baud rate that is tuneable down to 31 Gbaud, as shown in Figure 2. A tuneable baud rate also enables the spectrum of the wavelength to be adjusted to match the available spectrum. For example, if only 75 GHz of spectrum is available, a baud rate in the 60 to 70 Gbaud range would typically be required. Finally, a tuneable baud rate contributes to maximizing capacity across the spectrum of the fiber while aligning with useful bandwidth increments, as will be discussed in more detail later in a later section (Extensive Programmability).

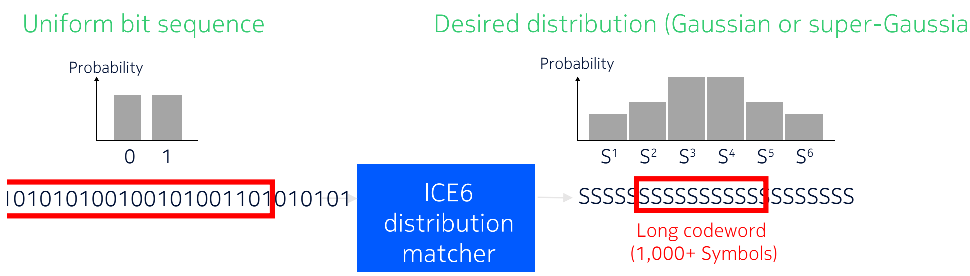
Long-codeword probabilistic constellation shaping

Figure 3: Probabilistic constellation shaping



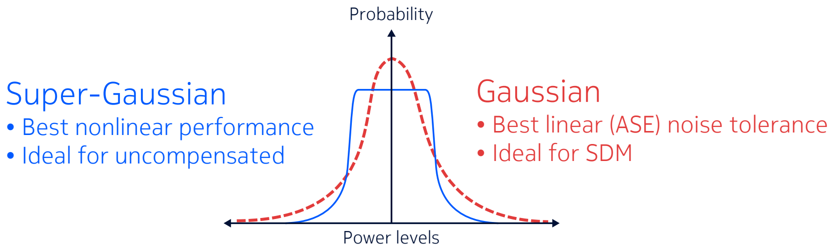
Unlike conventional modulation, where each constellation point has the same probability of being used, probabilistic constellation shaping (PCS) uses the lower-energy/-power inner constellation points more frequently and the higher-energy/-power outer constellation points less frequently, as shown in Figure 3. 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. The PCS distribution matcher converts incoming bits to symbols with the desired distribution



ICE6's 64QAM-based PCS leverages a long codeword (1,000+ symbols vs. ~100 symbols in typical competitor implementations), which makes it easier for the distribution matcher, shown in Figure 4, to find a bits-to-symbol mapping with the desired symbol distribution, and takes ICE6's long-codeword PCS (LC-PCS) gain close to the theoretical maximum. Furthermore, for high-power scenarios, such as uncompensated large-effective-area fibers, ICE6 also supports a super-Gaussian distribution, shown in Figure 5, that results in lower kurtosis, the variation in the power levels of the symbols, and therefore has even lower nonlinear impairments. In addition, ICE6 contains advanced nonlinear compensation circuitry.

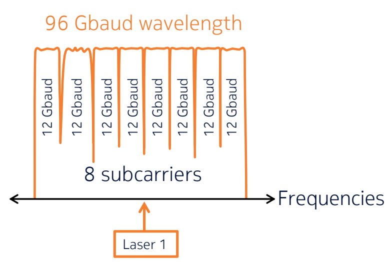
Figure 5. ICE6's super-Gaussian distribution is idea for uncompensated cables



Second-generation Nyquist subcarriers

Nyquist subcarriers take a single high-baud-rate carrier and digitally divide it into multiple lower-baud-rate subcarriers, as shown in Figure 6. In terms of ICE6 performance, the primary benefit of Nyquist subcarriers is reduced chromatic dispersion. Chromatic dispersion occurs because different frequencies travel at different speeds through the fiber – even different frequencies of the same modulated, data-carrying wavelength travel at slightly different speeds and eventually distort the signal. Improving on the four subcarriers of ICE4's first-generation implementation, ICE6's second-generation implementation increases the number of subcarriers to eight.

Figure 6. Second-generation Nyquist subcarriers: 96 Gbaud Example

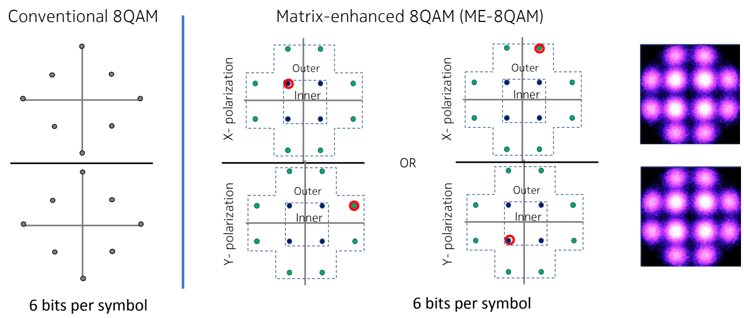


Due to the squared relationship between the baud rate and chromatic dispersion, an eight-subcarrier implementation decreases the effect of chromatic dispersion by a factor of 64 compared to a single-carrier implementation. Even if the single-carrier chromatic dispersion would have been within the capabilities of the digital ASIC/DSP, compensating chromatic dispersion has a cost in terms of additional noise inside the optical engine. Reducing chromatic dispersion has a significant benefit in terms of reducing this noise and therefore improving performance. By combining digital compensation in the DSP, including pre-compensation for uncompensated fibers, and Nyquist subcarriers, ICE6 chromatic dispersion tolerance is sufficient for even the longest transoceanic distances.

Specialized 4D and 8D modulations

In addition to LC-PCS, conventional modulation (i.e., 64QAM, 32QAM, 16QAM, etc.), and frequency-domain hybrid modulation (shown later with the 4/3QAM example in Figure 17), ICE6 also provides the option of specialized 4D and 8D multi-dimensional modulation formats. ICE6's 4D modulation format, matrix-enhanced 8QAM (ME-8QAM), uses phase and amplitude (or in-phase carrier and quadrature carrier/I and Q in a constellation diagram) on one polarization plus phase and amplitude (or I and Q) on the other polarization for a total of four dimensions. With ICE6's 8D formats, we add frequency in the form of a pair of adjacent subcarriers, which doubles the dimensions to eight. The 8D formats, FD-eBPSK with 2 bits per symbol, FD-2.5QAM with 2.5 bits per symbol, and FD-3QAM with 3 bits per symbol, also provide bits-per-symbol options below the 4 bits per symbol minimum of LC-PCS. What makes these formats multi-dimensional is a set of rules for how these dimensions can be combined to maximize performance by minimizing nonlinearities in some specific scenarios.

Figure 7. ME-8QAM balances a higher-power constellation point on one polarization with a lower-power constellation point on the other polarization

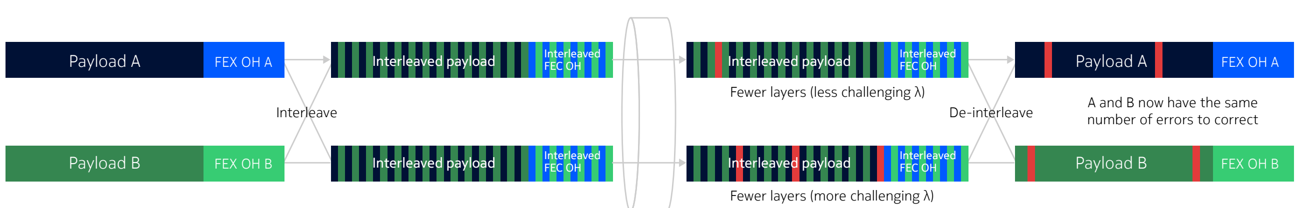


For example, as shown in Figure 7, by using 12 constellation points rather than eight with conventional 8QAM, ME-8QAM always balances a higher-power outer constellation point on one polarization with a lower-power inner constellation point on the other polarization. In this way each dual polarization symbol has the same aggregate power, which minimizes the kurtosis, or variation in power, which is a key cause of nonlinearities. In dispersion-managed submarine fibers, this enables ME-8QAM to have lower nonlinearities compared to conventional 8QAM and compared to LC-PCS with the same number of bits per symbol (i.e., six).

SD-FEC gain sharing

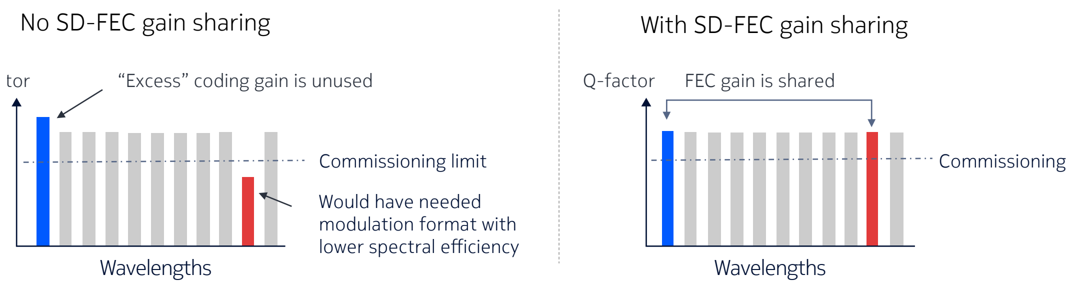
Even along the exact same submarine fiber, different wavelengths are likely to experience different impairments. Repeaters do not amplify each wavelength identically due to tilt and ripple across the transmission band. Polarization-dependent loss (PDL) and polarization mode dispersion (PMD), which occur due to asymmetries in the fiber, can differ for each wavelength. Chromatic dispersion also varies per wavelength, which can be a particular challenge for the first generation of dispersion-managed cables, where chromatic dispersion may be close to zero for wavelengths in the center of the C-band (~1550 nm) and highly negative (~1530 nm) or highly positive (~1565 nm) toward the edges of the C-band, as shown later in Figure 15.

Figure 8. SD-FEC gain sharing: how it works



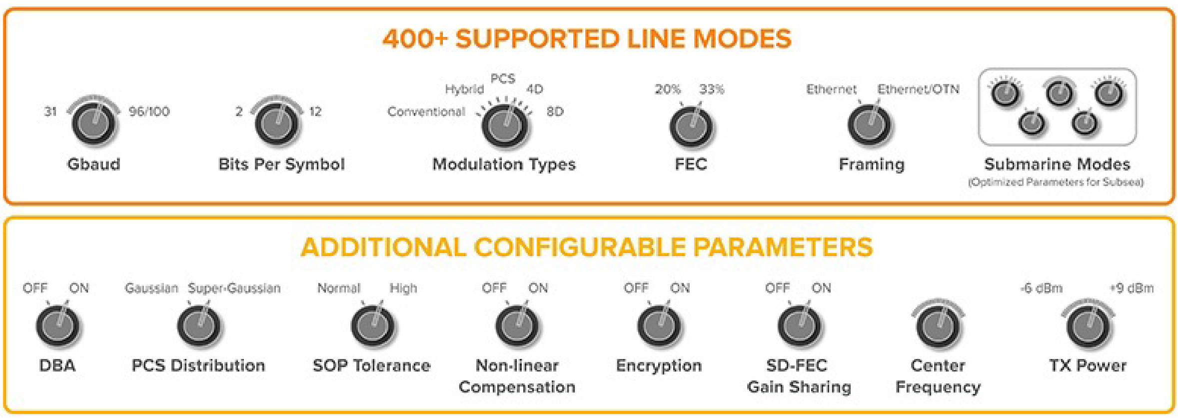
As shown in Figure 8, Nokia's unique soft-decision forward error correction (SD-FEC) gain sharing interleaves two frames, payload and FEC overhead, so that half of each frame goes over each wavelength, and therefore each frame experiences a statistically identical number of pre-FEC errors. Now, when the original frames are reassembled, the FEC decoders have the same amount of work to do, and the FEC gain is the same. The Q-factor for both wavelengths is now above the commissioning limit, as shown on the right of Figure 9.

Figure 9. SD-FEC gain sharing: impact on Q-factor



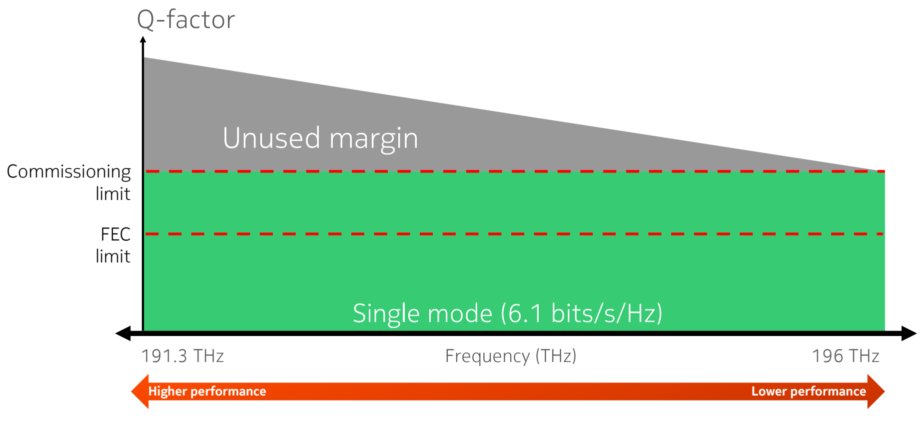
Extensive programmability

Figure 10. ICE6 programmability with 400+ line modes plus additional configurable parameters



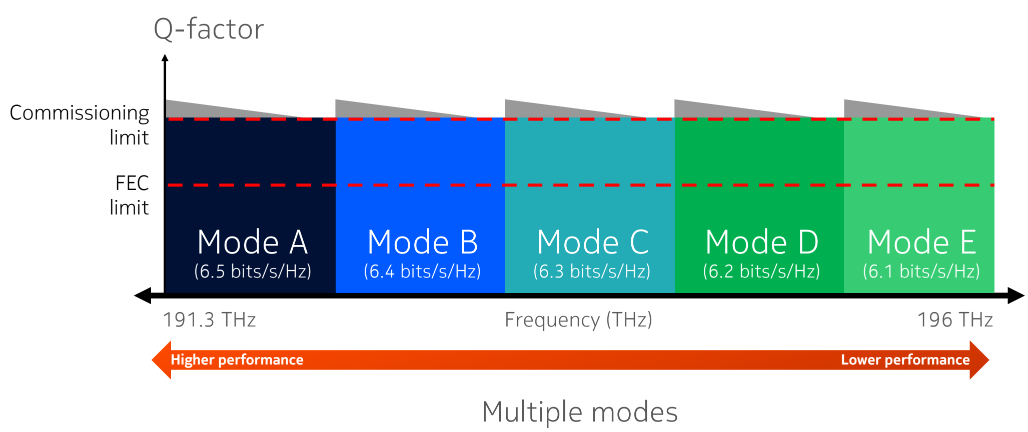
As discussed in the previous section, even on the same submarine fiber, performance in different parts of the spectrum typically varies with tilt, ripple, dispersion, and nonlinearities. The ability to select from a wide range of possible configurations enables network operators to squeeze the maximum performance from their submarine fiber, monetizing any unrequired margin while aligning to useful bandwidth increments (i.e., 50 Gb/s or 100 Gb/s). Aligning to useful bandwidth increments requires both baud rate and modulation programmability, with ICE6 offering over 200 combinations of baud rate and bits per symbol. Submarine modes further tweak various parameters for optimal performance in submarine applications, which together with forward error correction and framing options take the total number of line modes to 400+. On top of these 400+ line modes, additional configurable parameters include PCS distribution, nonlinear compensation, and SD-FEC gain sharing, as shown in the bottom half of Figure 10.

Figure 11. A single mode wastes unused margin



For example, a single mode that works in the lowest-performing part of the spectrum, as shown in Figure 11, leaves excess margin in the better-performing parts of the spectrum that could have been used for additional capacity. ICE6’s 400+ line modes enable the optimal mode to be selected for each part of the spectrum, as shown in Figure 12. This minimizes the unused margin and maximizes the capacity of the fiber.

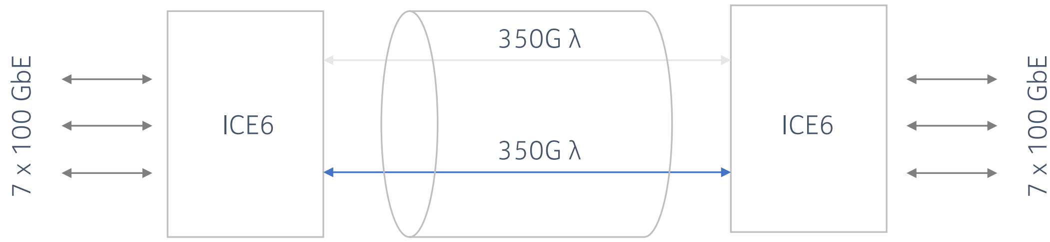
Figure 12. Maximize capacity with optimal modes for each part of the fiber’s spectrum



Bandwidth virtualization

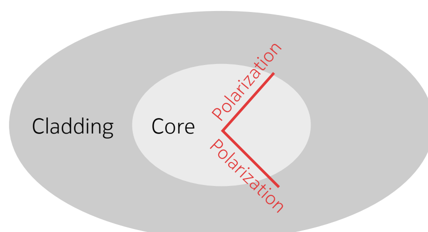
Complementing this extensive programmability is ICE6's bandwidth virtualization feature. Leveraging ICE6's dual-wavelength DSP, bandwidth virtualization enables multiple 100 GbE/OTU4 and 400 GbE clients over two paired wavelengths. This is especially useful with wavelength data rates that are multiples of 50 Gb/s. For example, it enables seven 100 GbE clients over two 350 Gb/s wavelengths, as shown in Figure 13.

Figure 13. Bandwidth virtualization example, 7 x 100 GbE over 2 x 350 Gb/s Waves



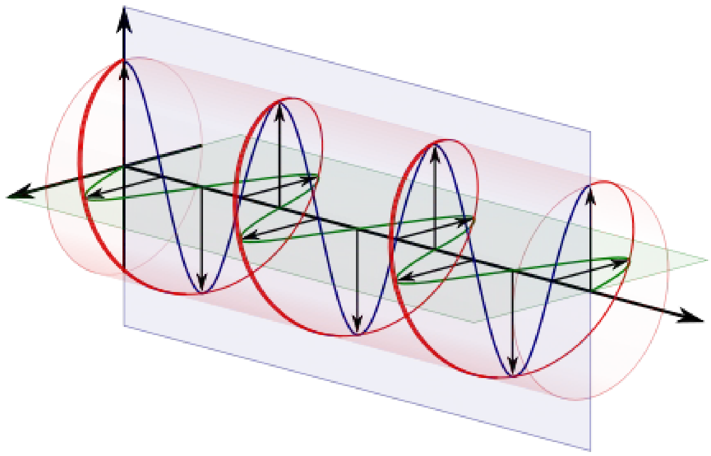
PDL mitigation

Figure 14. PDL can occur due to fiber asymmetries but mostly comes from the repeaters



Polarization-dependent loss occurs due to asymmetries, for example, when one polarization is more impacted by the cladding than the other polarization and incurs higher loss, as shown in Figure 14. However, in submarine cables PDL primarily comes from the repeaters, not the fiber, with the PDL on a transoceanic cable typically around 2 dB. PDL can also come from any wavelength-selective switch (WSS; typically 0.3 to 0.5 dB per WSS) in the submarine line terminal equipment, the terrestrial backhaul network (i.e., cable landing station to POP/data center), or undersea branching units. PDL is challenging for coherent communications because the noise aspect of PDL (different SNR on each polarization) cannot be compensated for in the DSP.

Figure 15. X and Y polarizations combine to create a wide variety of polarization properties and shapes



While coherent communications leverages two orthogonal polarizations (X and Y), with each carrying half the signal's data rate, once these two polarizations are combined and exit the optical engine, their electro-magnetic fields combine to create a wave with a single polarization shape, as illustrated by the example in Figure 15 where the blue and green polarizations combine to create the circular red polarization. The X and Y polarizations can combine to create polarizations with a wide variety of properties. In addition to digital compensation for the distortion aspect (different power levels on each polarization) of PDL in the DSP, ICE6 further mitigates PDL by digitally controlling the combined X+Y polarization properties of each subcarrier at the transmit end in order to minimize the impact of repeater, WSS, and other asymmetries. Even if the PDL could have been tolerated without this mitigation, it avoids the extra SNR penalty that would have resulted from higher PDL.

Additional features for spectral efficiency and fiber capacity

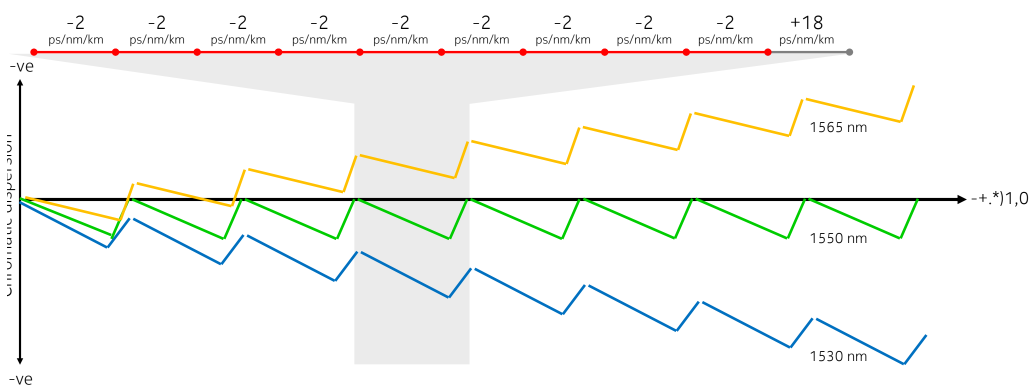
ICE6 provides a number of additional features that can help to maximize spectral efficiency in submarine applications. These include a tight roll-off factor, super-channels, an overhead-efficient Ethernet framing mode, and a shared wavelocker that reduces the guardband requirement between each pair of ICE6 wavelengths. Though not a common submarine requirement, L-band versions of both ICE6 and ICE6 Turbo provide the option of C+L with a total of 9.6 THz of spectrum, which also provides a useful option for scaling terrestrial backhaul capacity.

Maximize performance in all submarine cable types

Dispersion managed

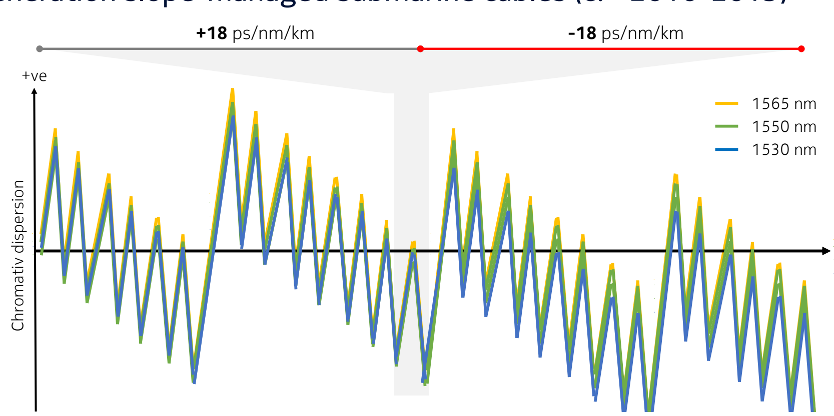
Dispersion-managed submarine cables mixed positive- and negative-dispersion fibers and were widely deployed between approximately 2000 and 2015, back in the pre-coherent days when chromatic dispersion could not be compensated for digitally. Leveraging non-zero dispersion-shifted fiber (NZDSF), the first generation of these cables, deployed between approximately 2000 and 2010, used approximately nine lengths of fiber with chromatic dispersion of -2 ps/nm/km for every one length of +18 ps/nm/km, as shown at the top of Figure 16. However, due to the previously discussed frequency-dependent nature of chromatic dispersion, there are large variations in chromatic dispersion across the C-band. As shown in Figure 16, 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 16. First-generation dispersion-managed submarine cables (c. ~2000-2010)



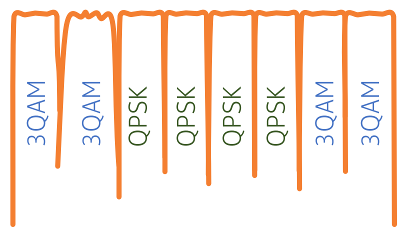
Deployed between approximately 2010 and 2015, the second generation, commonly referred to as “slope managed,” typically alternated positive-dispersion fiber (+18 ps/nm/km) with negative-dispersion fiber (-18 ps/nm/km). As shown in Figure 17, while chromatic dispersion was a little higher at the center frequencies (~1550 nm) relative to the first generation, across the C-band differences in chromatic dispersion were minimized.

Figure 17. Second-generation slope-managed submarine cables (c. ~2010-2015)



However, in the coherent era, low chromatic dispersion creates a key challenge for dispersion-managed cables. Low chromatic dispersion increases the likelihood that symbols on different wavelengths propagate together and changes the refractive index of the fiber at the same time through the Kerr effect, causing nonlinear effects such as cross-phase modulation (XPM). These cables can therefore benefit greatly from the low nonlinear penalties of ICE6's 4D and 8D modulation formats. Hybrid 4/3QAM, shown in Figure 18, and conventional QPSK may also have a role to play on these cables. These fibers will also typically benefit from ICE6's lower baud rate modes, PDL mitigation, SD-FEC gain sharing, and high-gain 33% FEC option.

Figure 18. ICE6 also supports frequency-domain hybrid 4/3QAM with 3.5 bits per symbol



Widely deployed for submarine applications from around 2015, G.654 fibers have a large pure silica core that results in lower loss, lower latency, and lower nonlinearities. They also have high positive chromatic dispersion, which is a benefit for coherent transmission as discussed previously. For example, Corning's widely deployed G.654.D Vascade® EX3000 has an effective area of ~153 µm2, loss of 0.154 dB/km, and chromatic dispersion of +21 ps/nm/km, with figures for G.652.D fiber (based on specifications for Corning's SMF-28® Ultra) commonly used in terrestrial networks shown for comparison in Table 1.

Table 1. G.654.D comparison with G.652.D fiber

	G.654.D (Vascade EX3000)	G.652.D (SMF-28 Ultra)
Effective area	153 µm^2 (typical)	~80 µm^2 (typical)
Loss	0.15 dB/km (typical)	≤ 0.18 dB/km (typical)
Chromatic dispersion	≤ 22.4 ps/nm/km	≤ 18 ps/nm/km

These submarine cables are optimized for high capacity per fiber pair, which is achieved through spectrally efficient modulation and high wavelength power. While large effective area and high chromatic dispersion reduce the nonlinearities that result from high power levels to an extent, nonlinearities can be further reduced by ICE6's LC-PCS with its super-Gaussian distribution option and advanced nonlinear compensation circuitry. These fibers can also benefit from ultra-high baud rates, Nyquist subcarriers, extensive programmability, SD-FEC gain sharing, Ethernet framing mode, and the shared wavelocker.

Space-division multiplexing

Transoceanic submarine cables evolved from two to between four and eight fiber pairs per cable following a philosophy of maximizing spectral efficiency (i.e., capacity per fiber pair). Since 2020, new space-division multiplexing (SDM) cable systems are increasing the number of fiber pairs in the cable to between 12 and 24, and this is likely to rise even further in the future. However, each fiber operates with less electrical power available for amplification and therefore a lower individual fiber capacity, but with the additional fibers increasing the total bandwidth capacity of the cable system beyond what was previously possible on earlier cable systems with fewer but higher-power fiber pairs. As these SDM cable systems run at relatively low wavelength power levels, low system SNR at the receiver is a key challenge. LC-PCS with a "regular" Gaussian distribution (i.e., not super-Gaussian) is an ideal solution to this challenge. A regular Gaussian distribution provides a larger Euclidean distance between the constellation points relative to super-Gaussian, and therefore has higher tolerance to ASE noise from the repeaters.

Unrepeatered and festoon

Unrepeatered and festoon scenarios differ from the previous three scenarios in that there are no repeaters (submarine amplifiers) in the wet plant. Depending on whether the fiber is dispersion managed or uncompensated and the length/loss of the fiber, different ICE6 features may be required. For example, very long spans can require both high wavelength transmit power and powerful amplification at both ends, which can create challenges in terms of both nonlinearities and linear (ASE) noise. The most challenging scenarios may require 4D or 8D modulation formats, lower baud rates, the 33% overhead FEC option, and SD-FEC gain sharing.

Summary

Nokia's ICE6 and ICE6 Turbo include a comprehensive toolkit that make them ideal for submarine applications. These tools include an ultra-high but tuneable baud rate, LC-PCS with a super-Gaussian option, Nyquist subcarriers, specialized 4D and 8D modulations, SD-FEC gain sharing, extensive programmability including 400+ line modes, bandwidth virtualization, PDL mitigation, and multiple additional features that help to maximize spectral efficiency. Submarine network operators can pick and mix from this toolkit to maximize performance for any submarine cable type, including dispersion managed, uncompensated, SDM, and unrepeatered/festoon.

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