

The Next Generation of Coherent Optical

Advanced Coherent Toolkit for Super-channels

Infinera's new Advanced Coherent Toolkit enables operators to improve their fiber capacity-reach performance with Nyquist subcarriers, SD-FEC gain sharing, matrix-enhanced phase shift keying (ME-PSK) modulation and other techniques. The toolkit is enabled by the Infinera optical engine, which combines large-scale photonic integrated circuits (PICs) and FlexCoherent™ Processor ASICs, two key technologies that enable 500 Gb/s and Terabit super-channel transmission and help operators scale intelligent transport networks.

A Brief History of Coherent Technology

Coherent technology began to be deployed in long-haul optical networks around the world in approximately 2010. It allows higher data rates (e.g. 100 Gb/s vs 10 Gb/s) to be sent over long-haul (typically >2,000 kilometers) optical transmission networks, compared to the historical modulation and detection technique of intensity modulation with direct detection (also sometimes referred to as non-return to zero or on/off keying), which had been widely used for several decades for rates of 10 Gb/s and lower.

Modern coherent detection involves the incoming phase and amplitude modulation information being digitized before being sent to a high performance digital signal processor (DSP). Digitizing the received signal requires an extremely high-speed analog-to-digital converter (ADC) capability. These techniques have been enabled by significant advances in electronics.

Meanwhile, substantial advances in photonics have enabled the delivery of super-channels, an evolution in dense wavelength division multiplexing (DWDM) in which multiple coherent optical carriers are combined to create a unified channel with a higher data rate, which is brought into service in a single operational cycle. Commercial super-channels (as opposed to academic experiments) make use of multiple laser sources implemented as large-scale photonic integrated circuits (PICs), delivering 500 Gb/s and beyond on a single line card. The key value of the super-channel approach is to enable an operational scalability (in terms of higher line card capacity) that is not practical with a single wavelength approach. This scalability is highly valued in the long-haul and subsea markets.

In the first coherent super-channel era, the DSP in the receiver allowed us to conquer impairments such as chromatic dispersion and polarization mode dispersion. As we move toward the second coherent super-channel era, digital processing and signal manipulation techniques are added to the transmitter, in addition to introducing enhanced receiver-based techniques. The new Infinera Advanced Coherent Toolkit (ACT) combines developments in both electronic and photonic integration in the Infinera optical engine. It is a core Infinera philosophy that integration must occur in both the optics and the electronics in order to maximize the value of coherent super-channels.

Infinera's Advanced Coherent Toolkit

Coherent detection combined with digital signal processing has led to a new and exciting paradigm in optical fiber communications as it allows for a substantial improvement in system capacity and functionality. Optical networking, and in particular the use of DWDM technologies like super-channels, is an optimal way to combine advanced functionality with the efficient transport of extremely large amounts of data over long-haul networks.

Infinera has pioneered the integration of hundreds of photonic functions, including lasers, modulators, waveguides and other optical components, into large-scale PICs, as well as the use of semiconductor manufacturing processes for PICs. PICs provide significant flexibility and efficiency benefits when integrated into DWDM systems.

Meanwhile, electronic function integration has been progressing as CMOS (complementary metal-oxide semiconductor) technology continues to improve. As feature sizes have shrunk and design tools improved over the years, the maximum complexity (and hence functionality) possible in an application specific integrated circuit (ASIC) has grown from thousands of gates to several hundreds of millions. This level of integration delivers higher processing power in terms of GBaud (symbol rate) and bits per symbol, thereby allowing higher order modulation formats and coherent detection, ultimately resulting in better capacity-reach performance.

Infinera combines large-scale PICs with coherent ASICs, two important technologies for 500 Gb/s and terabit super-channel transmission. In the first coherent era, Infinera's transmitter modulators were driven directly, and the optical impairments resulting from transmission were compensated for in the receiver by Infinera's FlexCoherent Processor. When this technology was introduced into the market, it enabled the move from 10 Gb/s to 100 Gb/s per channel, a tenfold increase in fiber capacity, and at the same time increased the typical optical reach from about 2,500 kilometers to about 4,500 kilometers. Infinera's latest FlexCoherent design introduces transmitter-based processing and enhances receiver-based capability. This is illustrated in Figure 1, in which the transmitter modulators are now driven by the combination of an advanced DSP and a digital-to-analog converter (DAC), which improves spectral shaping. Thanks to advances in ASIC technology, all transmitter and receiver functionality can be integrated into a single FlexCoherent Processor chip within the optical engine. This new design, combining electronic and photonic enhancements, introduces new capabilities, enabling operators to improve their fiber capacity-reach performance.

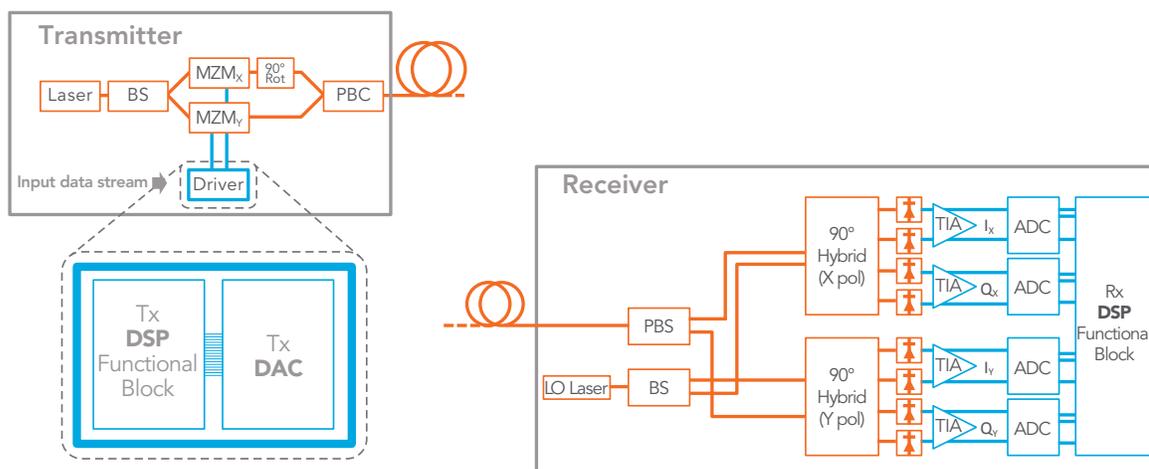


Figure 1: Infinera FlexCoherent™ TX/RX Block Diagram

These new capabilities are a part of the Infinera Advanced Coherent Toolkit (ACT), and include:

- Nyquist subcarriers
- Soft-decision forward error correction (SD-FEC) gain sharing
- Matrix-enhanced phase shift keying (ME-PSK)
- High-gain SD-FEC
- Flexible channel spacing

The following sections describe the key capabilities within the Infinera ACT and are powered by the Infinera optical engine.

Nyquist Subcarriers

In a conventional super-channel, multiple coherent optical carriers are implemented on a single PIC, on which each laser produces a single modulated carrier. By using the advanced functions of Infinera’s FlexCoherent DSP and DAC, each optical carrier can be further synthesized into multiple Nyquist subcarriers that are closely spaced to each other (see Figure 2).

The term “Nyquist” is borrowed from Nyquist-Shannon sampling theorem, a fundamental principle in telecommunications and signal processing, which establishes a sufficient condition for a sample rate that permits a discrete sequence of samples (digital) to capture all the information from a continuous-time signal (analog) of finite bandwidth. Nyquist WDM has the advantage of not requiring frequency-locked carriers, so independent lasers can be used. This technique, which has been used widely in radio transmission, results in a lower effective baud rate for a given resulting data rate. The effect in optical transport networks, as highlighted in Figure 2, is a dramatically improved tolerance of non-linear impairments. This is achieved through optimizing the subcarrier baud rate to minimize the combined interaction of the various nonlinear effects such as self-phase modulation, cross-phase modulation, cross-polarization modulation and four-

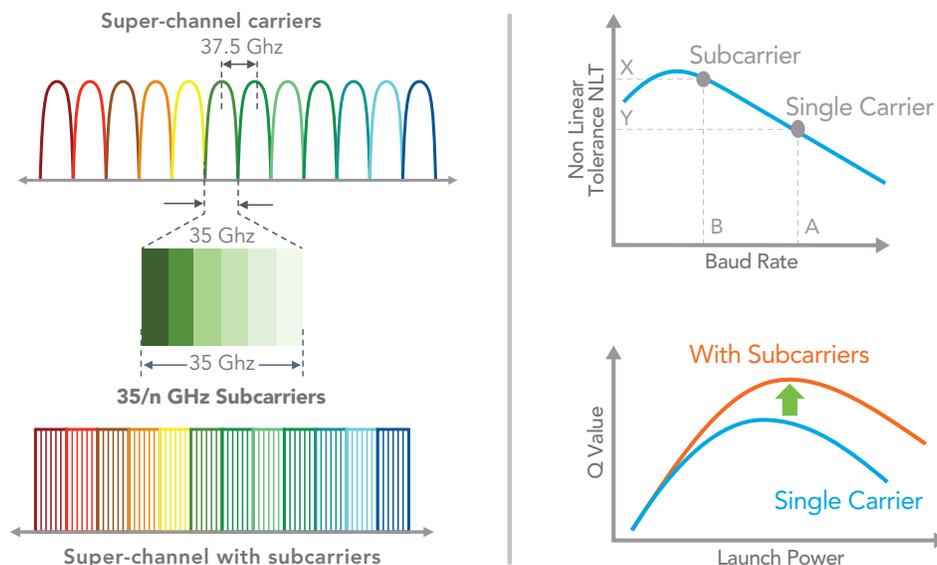


Figure 2: Nyquist Subcarriers

wave mixing. Increased tolerance against non-linear channel impairments translates to increased reach and capacity across the fiber. Implementing these techniques requires an advanced level of sophistication both in the electronic (DSP) layer and in the photonic layer. Infinera remains a pioneer in enabling these techniques through the optical engine, which combines the FlexCoherent ASIC and the large-scale PIC, and leads the industry in having validated the use of subcarriers in a super-channel implementation.

Soft Decision Forward Error Correction Gain Sharing

Because the constituting carriers of a super-channel traverse the same optical path, a unique opportunity exists for joint digital signal processing of multiple super-channel carriers that mitigates the negative performance impact of non-linear effects such as self-phase and cross-phase modulation. Using SD-FEC gain sharing, the FEC output from two channels can be mathematically combined so that the stronger channel can be used to enhance the quality factor or Q-value of the weaker channel. Benefits of gain sharing include increased capacity and/or increased optical performance. A given channel may be able to operate at a higher order of modulation than would be possible without gain sharing. A channel that could be modulated at polarization multiplexed 3QAM (PM-3QAM), for example, would deliver 50% more capacity than if it was necessary to use PM-BPSK.

Performance of Weak Channel Increased thru Gain Sharing with Strong Channel

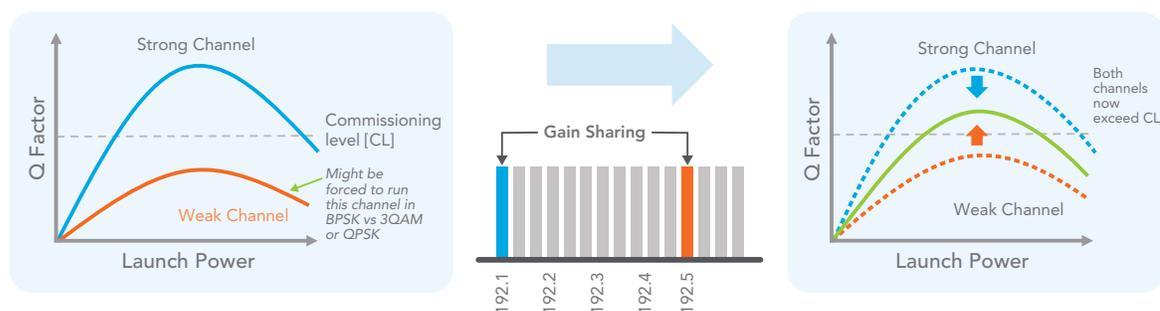


Figure 3: SD-FEC Gain Sharing

Figure 3 illustrates the benefit of SD-FEC gain sharing for a sample link where the non-linear penalty is sensitive to the wavelength of operation. Paired channels are placed strategically so that a channel with high nonlinearities and low Q-value can be made usable by the better performing channel or even bumped up to a higher modulation format with high spectral efficiency. SD-FEC gain sharing is part of the Infinera ACT and is utilized as a non-linear mitigation strategy for coherent super-channel transmission that results in substantial improvement in transmission capacity.

Matrix-Enhanced Phase Shift Keying

Infinera has been a pioneer of software-selectable modulation formats (FlexCoherent), in which the type of modulation can be chosen to optimize a given link for fiber capacity and reach. The modulation type with the longest reach is PM-BPSK, which has been used on cables of > 9,000 kilometer spans without regeneration. An enhancement to this modulation scheme is matrix-

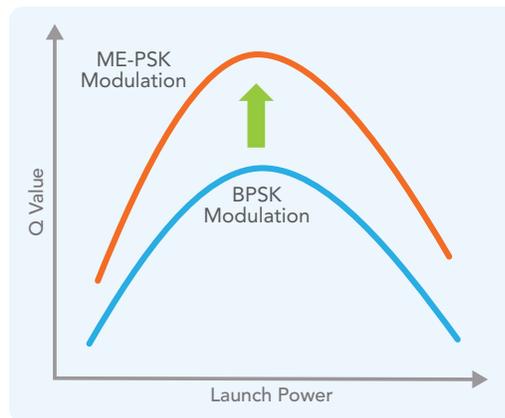


Figure 4: Matrix enhanced phase shift keying (ME-PSK)

enhanced phase shift keying (ME-PSK), which provides the same spectral efficiency of BPSK with the same baud rate and channel spacing. However, it uses a modulation constellation with enhanced coding techniques, resulting in increased Q-value as highlighted in Figure 4. This translates into increased reach and performance of channels at a lower optical signal-to-noise ratio (OSNR) than BPSK. The ability to activate or deactivate the matrix-enhanced mode of operation is yet another flexibility parameter of the Infinera ACT that customers can use to optimize capacity and reach over a given fiber.

High-Gain Soft Decision-Forward Error Correction

Forward error correction has been an integral part of optical transmission for more than a decade to drastically improve the Q-factor for a given channel. Figure 5 shows the tradeoff that must be made when choosing the size of the FEC overhead.

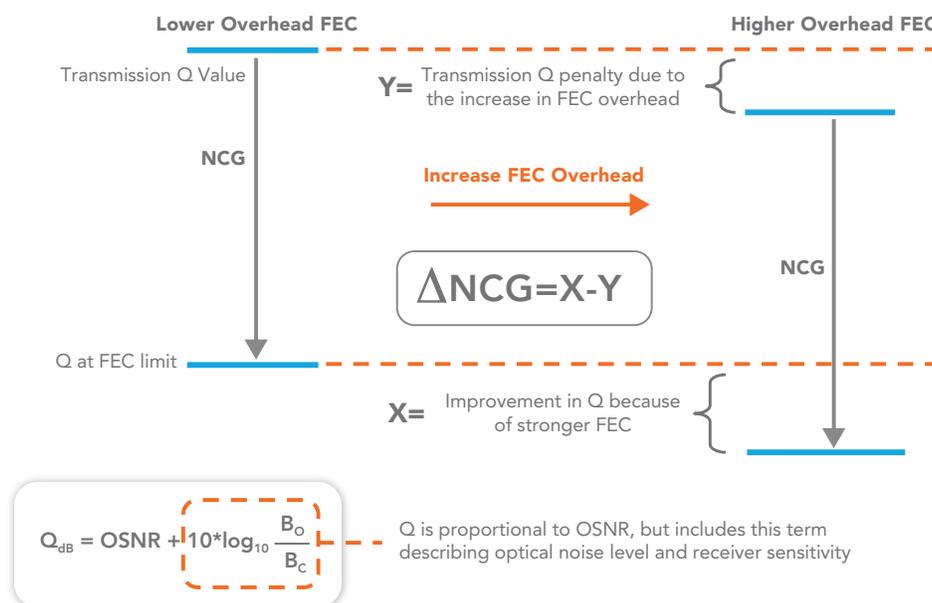


Figure 5: High Gain SD-FEC

On the left we see a lower-overhead FEC and the difference between the transmission Q value, and the Q at the limit of the FEC's ability to correct bit errors is referred to as the net coding gain (NCG). The bigger the NCG the better. On the right we see a higher-overhead FEC, and the value, X, at the bottom of the chart illustrates the improvement in Q as a result of a stronger FEC. However, the Y value at the top of the chart shows the transmission penalty we incur because the larger FEC overhead is actually more bits that we have to transmit. These additional bits will also have a negative impact on spectral efficiency. Infinera's advanced FEC algorithm enables optimized SD-FEC gain for low latency or higher optical reach applications.

Flexible Channel Spacing

Another feature available with the Infinera ACT is fine granularity of optical channel spacing. ITU-T G.694.1 recommendation defines a flexible frequency grid, as opposed to the fixed DWDM channels of the past. To take advantage of this and the spectral efficiency gains of Nyquist subcarrier operation, it is possible to tune the baud rate for a given set of carriers or subcarriers to deliver more or less spectral efficiency. Increasing channel spacing reduces inter-channel nonlinearities such as cross-phase modulation. More capacity can be realized with higher order modulation format at slightly increased spacing. For example, using QPSK with a channel spacing of 40.625 GHz provides better performance than QPSK with 37.5 GHz channel spacing and better spectral efficiency than 3QAM with 37.5 GHz, thus providing another intermediate step in the tradeoff of capacity with reach. Flexible channel spacing can be applied to carriers within a super-channel, a fraction of a super-channel or to the whole of a super-channel in order to maximize the available spectrum and thus boost the fiber capacity.

Summary

Coherent super-channels have proven their value and established a clear place as an optimal technology in the long-haul core network. Moving super-channels into the second coherent era, in which sophisticated signal processing is carried out in both the transmitter and the receiver, can offer long-haul and subsea network operators a new level of flexibility to maximize the capacity and reach for a given network link. Infinera's Advanced Coherent Toolkit, comprising comprehensive modulation and compensation techniques such as Nyquist subcarriers, SD-FEC gain sharing, ME-PSK, high-gain SD-FEC, and flexible channel spacing, enables the tuning of parameters for carriers and subcarriers in the super-channel in order to maximize the overall reach and capacity of the fiber.

Infinera combines innovation in electronics, with FlexCoherent Processor ASIC technology, and photonics, and with large-scale PIC technology, to provide superior performance for network operators.

With these advanced offerings, Infinera continues to pioneer the next generation of coherent technology and enable operators to harness the maximum capacity for a given reach from new or existing subsea and long-haul terrestrial cable systems carrying super-channels.



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