WHITE PAPER

Maximizing Reach-capacity in Optical Networks with WaveLogic 5 Extreme DSP Innovations

Advanced algorithms implemented in coherent optical Digital Signal Processor (DSP) design have enabled the deployment of 800G-capable optical transport systems—offering unprecedented reach-capacity capabilities and better network economics. In addition to programmable capacity rates, 800G coherent DSP multi-baud technology is a key enabler for efficient network upgrade paths for some legacy 100 GHz fixed-grid line systems—whether for 600G metro-regional or 400G long-haul links—and for maximizing spectral efficiency for certain submarine applications.

This paper explains the algorithms developed and employed in Ciena's WaveLogic™ 5 Extreme (WL5e) which underpin the performance characteristics of this latest generation of 7 nm FinFET-based coherent optical DSP. These include nonlinear Probabilistic Constellation Shaping (PCS), 4-carrier Frequency Division Multiplexing (4FDM) or Nyquist subcarriers, and throughput-optimized Forward Error Correction (FEC).

WaveLogic 5 Extreme
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Nonlinear Probabilistic Constellation Shaping (PCS)

Coherent optical transmission over single-mode fiber (SMF) uses the phase, amplitude, and polarization state of light to encode information. Bits are encoded into constellation symbols and the combination of constellation type and symbol rate (baud or symbols/second) determines the maximum bit rate. Simpler, lower-order constellations have fewer bits/symbol, like QPSK which has 2 bits/symbol, or 4 bits/dual-polarization symbol. More complex, higher-order constellations have more bits/symbol, like 64QAM which has 6 bits/symbol, or 12 bits/dual-polarization symbol total. Higher-order constellations can carry more bits for a given symbol rate.

Highlights

- Advanced DSP algorithms enable adjustable line rates from 200G-800G for capacity optimization across any distance
- Nonlinear PCS employs symbol sequence weighting to improve transmission
- 4FDM (Nyquist subcarriers) improves tolerance to fiber nonlinearities
- Throughput-optimized FEC enables more capacity per wavelength or extends reach in long-haul transmission

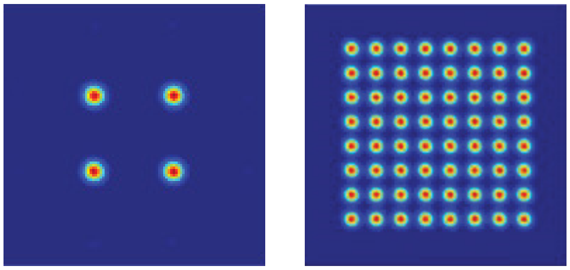


Figure 1. Comparison of lower- and higher-order constellations

The distance between constellation points determines the noise tolerance of the signal. Higher-order constellations have a smaller spacing between the individual points of the constellation and are more susceptible to noise and nonlinearities which impact signal transmission.

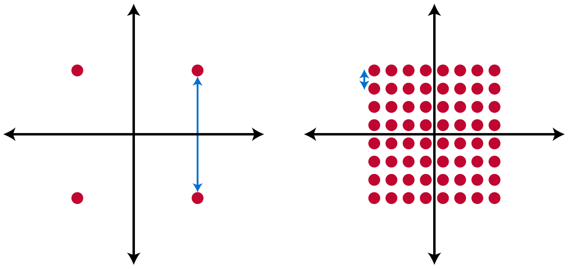


Figure 2. Distance between constellation points for lower- and higher-order constellations

PCS is a technique used to improve signal propagation in the fiber by the selective transmission of certain constellation points more often than others. Performance can be greatly improved with appropriate choice for the probability of using each constellation point. Applying higher probability weighting to the inner points of the constellation means that, compared to a uniform constellation where points are used with equal probability, the number of bits/symbol—and therefore capacity—is reduced. This is done in exchange for improved noise tolerance which maximizes reach.

Figure 3 illustrates the difference between a uniform 64QAM constellation without PCS where every symbol is sent an equal number of times on average, and one with PCS where the low-energy symbols at the center of the constellation are sent more often. Assuming the average power of the transmitted optical signal is equal in both cases, the use of PCS results in a larger distance between constellation points on average, providing more noise tolerance and greater reach.

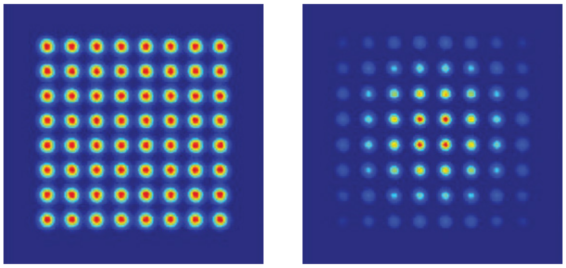


Figure 3. Constellations with and without constellation shaping

However, not all PCS algorithms are the same. Published PCS algorithms primarily address linear impairments resulting from fiber transmission. The proprietary nonlinear PCS employed in WL5e applies probabilistic shaping to mitigate both linear and nonlinear impairments. This is achieved by applying PCS not just to individual constellation points, but to specific sequences of constellation points. In other words, it is not just the distribution of constellation points that matters, but also the patterns of sequential symbols. Nonlinear PCS involves choosing only the best patterns of sequential symbols which further reduces nonlinear penalties and improves system margin for a given throughput.

The diagram in Figure 4 illustrates this concept as a bucket containing a very large number of potential symbol sequences which are then sorted by performance.

- Better performing sequences use more low energy symbols, and minimize interference between symbols and with other wavelengths, providing the highest tolerance to linear and nonlinear impairments
- Lower performing sequences use more high energy symbols, generate more interference between symbols and with other wavelengths, and suffer more from linear and nonlinear impairments

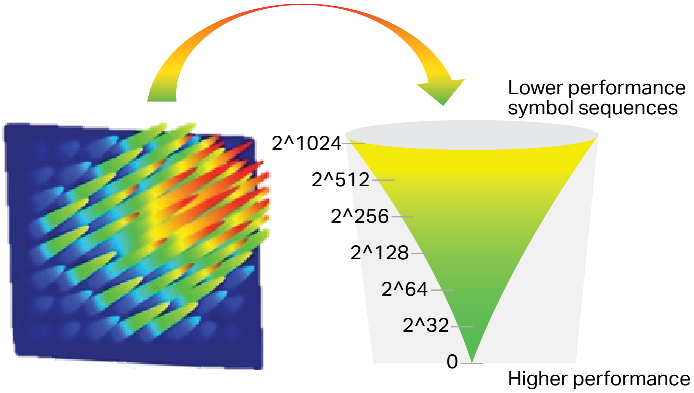
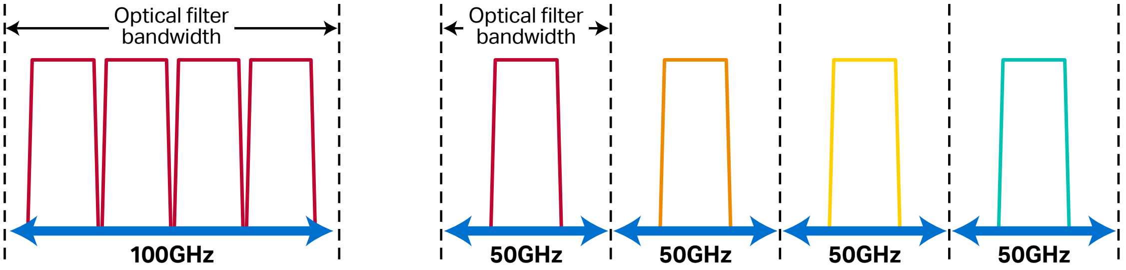


Figure 4. Distribution of constellation symbol sequences



Electrical FDM (Nyquist) subcarriers
- 1 laser
- 1 modulator
- All subcarriers within one filter bandwidth

Optical carriers
- 4 lasers
- 4 modulators
- Optical filters for each carrier

Figure 5. Electrical/Nyquist subcarriers versus optical carriers

Selective use of a subset of these additionally weighted symbols is traded off against the required line capacity (bits) to maximize fiber transmission performance. The implementation of nonlinear PCS in WL5e allows for more than 1 dB of additional performance compared to solutions where PCS is not employed at all.

4-carrier Frequency Division Multiplexing (4FDM)

Frequency-Division Multiplexing (FDM) is a generic term for any multi-carrier grouping—multiplexing—in a transmission band. For coherent optical technology, it generally refers to electrically generated signals using only one coherent laser and modulator, not to optically generated signals using two or more coherent lasers and modulators. The purpose is to allow for closely grouped, lower-rate subcarriers without having to allow spacing for separate optical filtering. This is also known as Nyquist subcarrier modulation.

4FDM is the use of four subcarriers within one optical channel or wavelength. The high-baud transmitted signal is spread across four lower-rate subcarriers, with each carrier having a lower baud.

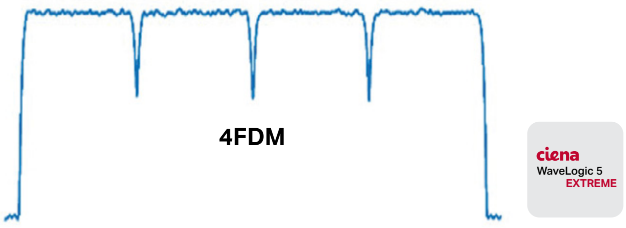


Figure 6. WaveLogic 5 Extreme 4-carrier FDM spectrum

In a single coherent modem, with a single set of high-speed optics, the four symbol streams across the frequency range spanned by the modem are created in the digital logic core of the coherent DSP chip. Susceptibility to nonlinearities for each sub-carrier is greatly reduced relative to a single high-baud signal. This in turn maximizes reach-capacity for a given link. An additional benefit of this approach is the avoidance of the cost, space, and power dissipation burden of using parallel optics to achieve a similar effect, as shown in the optical carrier example illustrated in Figure 5.

Advances in coherent DSP design leverage smaller semiconductor process technologies geometries—7 nm FinFET in the current volume production generation—to support the implementation of these algorithms in very compact, power-efficient chip packages. The advances also include pushing the capabilities in speed and performance of the analog front end, the digital-to-analog converters (DAC), and analog-to-digital converters (ADC) on the line or fiber side of the DSP. The high-speed DACs on the transmit side have enough analog bandwidth to efficiently convert and transmit the four, digitally generated FDM subcarriers towards the optics. Likewise, the ADCs on the receive side have sufficient bandwidth to resolve the incoming 4FDM signal.

The use of 4FDM is a field-proven technology with WL5e enabling the propagation of high capacities over very long distances.

High-performance Coherent in CMOS: Foundational Technology for WDM Optical Networking
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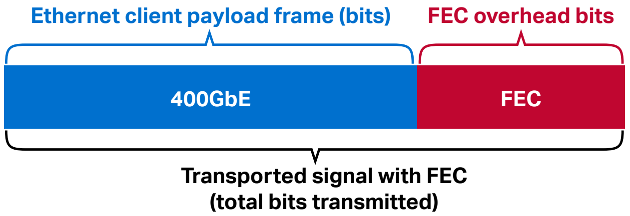
Throughput-optimized Forward Error Correction (FEC)

An objective of optical transmission is the transportation of revenue-generating information, or payload, from a transmitter to a receiver without error. Noise caused during propagation results in errors at detection. Longer propagation results in more noise, which ultimately results in more errors. FEC enables the correction of these errors up to a threshold number. This is done by performing mathematical operations on payload bits and sending the result of these operations with the payload in the form of overhead bits. At the receiver, detected payload and overhead bits are processed to recognize and correct payload errors. The ratio of overhead bits to total bits transmitted is referred to as the FEC overhead and is often quoted as a percentage. For a given payload, the higher the FEC overhead, the greater the raw data rate required of the transmitted signal. For example, the payload might be a 400GbE client data signal from a router where the transmission is WAN transport across a metro region, or even across a trans-continental network.



$$\text{FEC Overhead (\%)} = \left[\left\{\frac{\text{Total bits}}{\text{Payload bits}}\right\} - 1\right] 100$$

Figure 7. FEC overhead

There is a long history of FEC in transmission and a wide variety of FEC solutions and performances. Basic FEC schemes, such as Reed-Solomon codes, apply minimal additional encoding and correct for a small number of errors or lower error rate. More advanced codes requiring more overhead can correct a much larger number of errors or higher error rate. The high-performance, proprietary FEC design developed by Ciena for WL5e is unmatched by any other FEC design and operates with an overhead that is optimized for the data rate of each payload it is configured to transport. The optimization guarantees lowest FEC power dissipation and highest tolerance to error-producing noise.

Some FEC types are Hard-Decision FEC (HD-FEC) where the algorithm makes a discrete choice between a 1- or a 0-bit based on limited use of the available information. More advanced algorithms are based on Soft-Decision FEC (SD-FEC) where the algorithm assigns a probability of a one or a zero to a bit. This makes better use of available information in the correction processing. With better error correction, reach and/or capacity are greatly improved. Ciena's experience with high-performance FEC design over multiple WaveLogic coherent optical DSP generations is one of the key contributing factors to the significant performance leap in WL5e.

Another aspect of design which adds to FEC efficiency is throughput-optimization. In coherent transmission, bits are grouped into symbols. Coherent transmission capacity, or payload bit rate, has increased over each generation by means of higher baud, or symbol rate, and use of constellations with higher number of bits per symbol. Such constellations have smaller inter-symbol spacing. The ability to correct bit errors for these more complex constellations also drives the need for more efficient FEC algorithms. Throughput optimization chooses the best overhead for each throughput or payload bit rate. At any given choice of baud and throughput, the optimization is the best compromise of two processes.

First, as the FEC overhead increases, error correcting capacity goes up—but so does the total bit rate. As the total bit rate increases, the inter-symbol gap of the constellation decreases, and there are more errors to be corrected. Eventually the rate of increase of errors due to shrinking inter-symbol gap exceeds the rate of increase of FEC error correcting capacity. At this point, any further increase in overhead will reduce the error correcting capacity of the FEC.

Second, as the FEC overhead decreases, the total bit rate decreases and the errors per payload bit decrease due to expansion of the inter-symbol gap. At the same time, the error correcting capacity of the FEC also decreases. If the FEC overhead is too low, the rate of reduction in error correcting capacity falls below the rate of reduction of errors from reduced total bit rate. Once again, the error-correcting efficiency of the FEC is compromised.

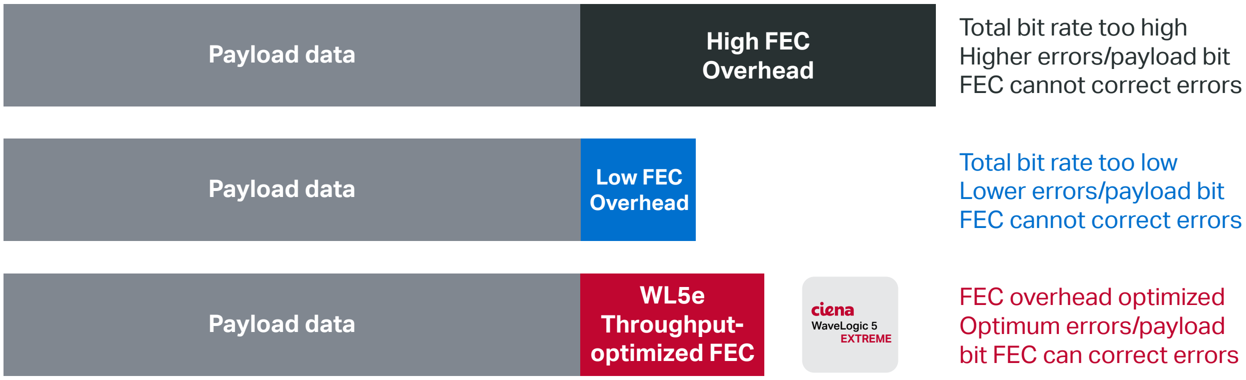


Figure 8. Comparison of FEC overhead rates for a fixed baud

Careful matching of the FEC overhead to the throughput is required to optimize efficiency. WL5e achieves this objective. The result is very efficient transmission that is robust against errors and which supports propagation over for very long distances.

Combined use of advanced algorithms for maximum reach-capacity

The implementation of nonlinear PCS, 4FDM, and throughput-optimized FEC in the latest generation of WL5e has paved the way for new strides in optical network efficiency. Whether from the perspective of capacity over a given link—up to 800 Gb/s—or the ability to transport client signals up to 400GbE any distance, transport systems based on this technology are enabling operators to realize cost savings in the operation of their networks. As the industry approaches the Shannon-limit (the theoretical maximum capacity over a defined fiber medium), DSP designers have met the challenge for increasing network bandwidth with great efficiency through improvements in field-proven advanced algorithms for mitigating fiber nonlinearities.

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