Nokia PSE-V Coherent Solutions Beyond the Limit

Industry leading performance, spectral efficiency, and flexibility for 5th generation coherent optics

White paper

Part of Nokia's WaveFabric Elements portfolio of optical components and subsystems, the Nokia PSE-Vs and PSE-Vc are the industry's most advanced coherent digital signal processors (DSP), powering the next generation of Nokia high-performance, high-capacity transponders, packet-optical interfaces, and data center interconnect (DCI) platforms. Supporting 2nd generation probabilistic constellation shaping, enhanced FEC, fine granularity baud rates, and reduced power consumption, the new PSE-V family sets industry benchmarks for optical performance, capacity, and flexibility.

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Introduction

In 2018, Nokia developed probabilistic constellation shaping (PCS) for use in the 4th generation Photonic Service Engine 3 (PSE-3) digital signal processors (DSP). This revolutionary technology enhances performance to near theoretical limits, while at the same time reducing optical networking costs. In testament to its significance and power, nearly every other DSP vendor has announced plans to add PCS capabilities in their future products. As the industry leader in the innovation and development of coherent high-speed optics, Nokia took the performance of light to the limit – the Shannon Limit.

With the introduction of the 5th generation coherent DSP family, Nokia is moving beyond the limits. The PSE-V product family supports higher wavelength capacities over longer distances, further reducing network costs and power consumption. In addition, the low power PSE-Vc enables pluggable coherent optics, with the DSP integrated within the module.

The Nokia PSE-V product family incorporates several key enhancements, including enhanced 2nd generation PCS technology, improved FEC coding, granular baud rate tuning, and finely adjustable channel spacing. These innovations result in improved performance, flexibility, and lower operator's cost per gigabit.

5th Gen Digital Signal Processors

Optical networking suppliers are starting to introduce 5th generation DSPs, with support for baud rates in the range of 90 Gbaud. Modulation is used to encode digital ones and zeros into symbols that are then transmitted over the fiber at the baud rate, or symbol rate. Higher order modulations, such as 16QAM or 64QAM, encode more bits per symbol, but with a tradeoff of shorter optical reach compared to lower complexity modulations, such as QPSK or 8QAM. Due to the capacity versus optical reach trade-off in coherent optics, high capacity 250G – 400G wavelengths have traditionally been limited to metro applications, with lower order modulations utilized on 100G - 200G long haul (LH), ultra-long haul (ULH) and subsea wavelengths.

By supporting higher baud rates, the PSE-V enables the best of both worlds - high wavelength capacities over very long distances. Overall wavelength capacity is based on the modulation format (#bits/symbol) multiplied by the baud (or symbol) rate. Increasing the baud rate to 90 Gbaud, allows use of lower order modulations formats suitable for LH/ ULH distances, while supporting high capacity 400G wavelengths.

No formal industry definition exists for what constitutes a 5th generation" DSP, but the generally accepted criteria includes:

- 33 – 90 Gbaud rates
- Probabilistic Constellation Shaping
- Advanced SD-FEC
- Nyquist filtering
- 400G capacity over LH/ULH distances
- DSP options supporting various cost, size and power-optimized pluggable interfaces

Along with the introduction of 5th generation coherent DSP chips, the Optical Interoperability Forum (OIF) has defined a new optical interface standard for 400G interfaces operating at distances up to 120 Km, referred to as 400ZR. As these interfaces become available, they are expected to have a major impact on metro edge and data interconnect (DCI) networks.

400ZR Industry Impact

The planned introduction of 400ZR optics is already having a dramatic impact on optical network planning, particularly for metro edge and DCI applications. The new 400ZR standard defines an interoperable, pluggable, 400G coherent module for distances up to 120 Km that incorporates the DSP inside the module. Integration of the coherent DSP into optical modules has long been an industry objective but has only recently become viable with the availability of low power 7nm CMOS technology.

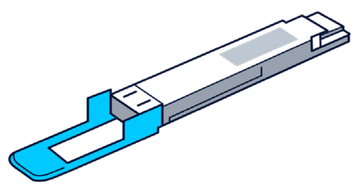

Figure 1. 400ZR module in a QSFP-DD form factor

The small size, low cost, lower power and pluggable form factor, make 400ZR/ZR+ an ideal solution for short reach high-capacity transport applications. Many high capacity edge applications will migrate from platform-based transponder line cards to 400ZR/ZR+ pluggables as these new modules become available from optical systems vendors such as Nokia as well as third parties.

For these applications, 400ZR/ZR+ optics obviate the need for the maximum wavelength capacity modes of the latest generation of coherent DSP’s. The maximum capacity that can be transported over a single wavelength achieves only limited optical reach, restricting its usefulness in real world applications.

As an example, at 90-95 gigabaud rates, 800G wavelengths require 64QAM modulation. But this very high order modulation severely limits the optical reach to one or two spans, or roughly 200 km, and consume greater than 100GHz of spectrum. While these maximum capacity wavelengths could be used on certain short reach point-to-point networks, this application will likely be dominated by 400ZR/ZR+ optical modules due to their 1) lower costs, 2) lower power, 3) pluggable form factor, and 4) interoperability (in the case of ZR) - with only a slight penalty in spectral efficiency.

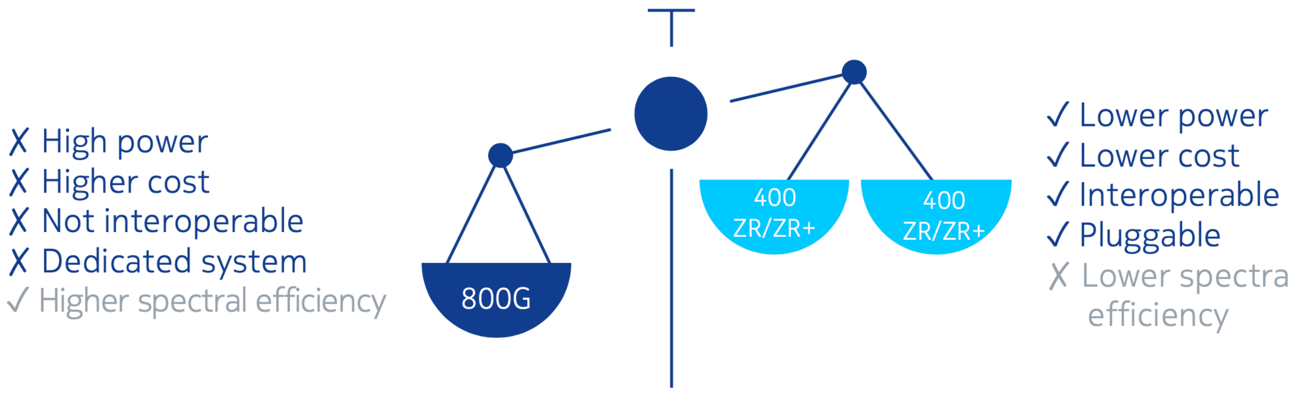

Figure 2. High rates suitable only for short distances can't match the economics of 400ZR/ZR+

PSE-V product family

The Nokia PSE-V product family consists of the high-performance PSE-Vs (super coherent) and low power PSE-Vc (compact) coherent digital signal processors. Supporting two PSE versions ensures transponders, DCI interfaces, and coherent pluggable modules can be optimized for performance, power, size, and application.

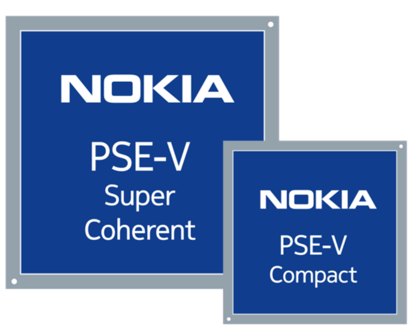

Figure 3. Nokia PSE-Vs and Vc coherent DSP's

The PSE-Vs supports up to 800G wavelengths and is optimized for high performance applications, such as 400G wavelengths over regional, long haul, and ultra-long-haul routes. The PSE-Vs incorporates Nokia's latest technology innovations, including 2nd generation probabilistic constellation shaping, enhanced FEC, and fine baud rate granularity.

The PSE-Vc is optimized for lower power, smaller sized modules and pluggables, where high capacity and high port density are needed, but with more modest rate/reach expectations. The lower power PSE-Vc is ideal for pluggable optics with integrated DSP, such as CFP2-based modules supporting multi-haul rates and reaches from 400G regional to 200 long haul, and smaller modules supporting the more feature and distance limited specifications of 400G regional to 100G long haul, and the loosely defined 400ZR+ category.

Ultimately, the by engineering DSP's of varying performance packaged into modules of different form-factors and power envelopes, lowest cost per bit, particularly at 400G rates, can be delivered across applications from single span metro to ultra long-haul.

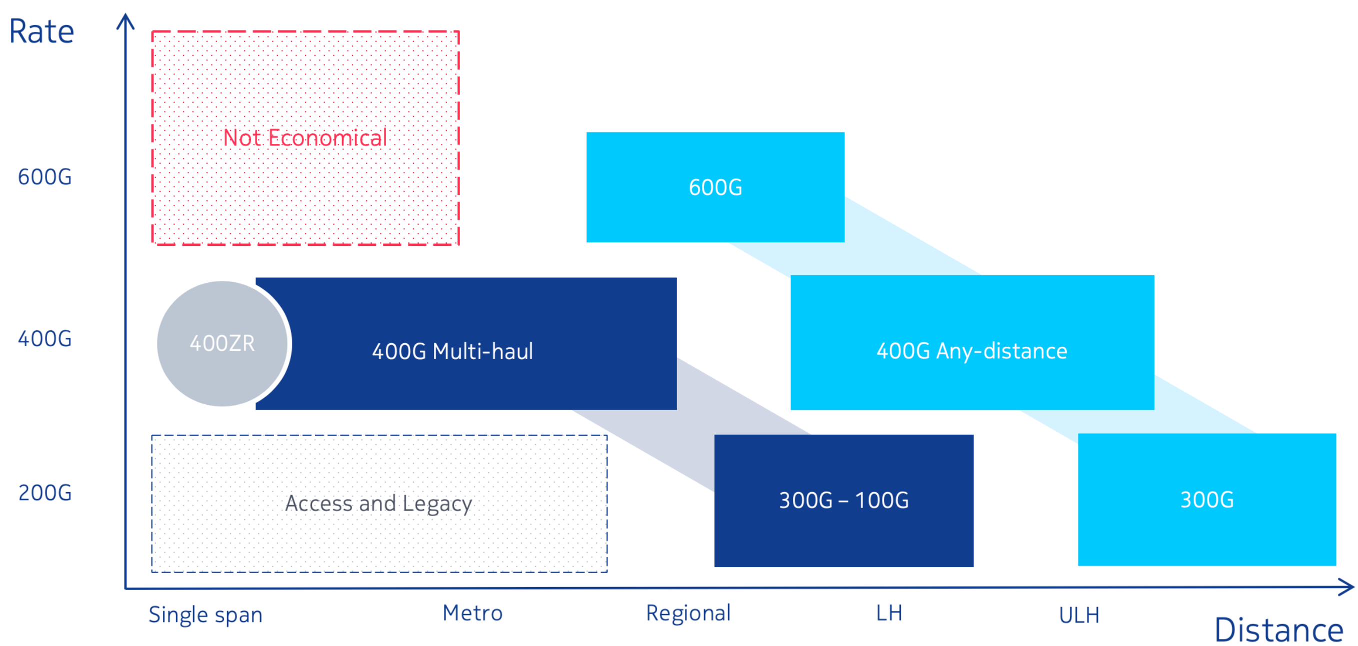

Figure 4. Next generation DSP's and modules will focus on delivering 400G in the most economical fashion

Scaling light beyond the limits

For any given optical communications channel, there is an upper limit on the rate at which information can be transmitted. This theoretical limit was defined in Claude Shannon's renowned paper "A Mathematical Theory of Communications" written in 1948 while a researcher at Bell Labs. Since then, the upper capacity limit of a communications channel has been known as the Shannon Limit or Shannon Theorem.

In optical networking, modulation is used to convert digital ones and zeros into symbols that are transmitted over fiber. Higher-complexity modulations, such as 16QAM or 64QAM, increase overall capacity by encoding more bits per symbol, but with a tradeoff of diminished optical reach. A key objective in optical networks is to maximize the amount of data transported over each optical route, which is typically achieved by using variable baud rate, multi-modulation transponders. In 2018, Nokia introduced a new generation of PSE coherent DSPs with the industry's first probabilistic constellation shaping (PCS) technology. PCS wavelength shaping yields significant performance improvements in both wavelength capacity and optical reach.

With the introduction of the Nokia PSE-V super-coherent DSP, Nokia is adding several key enhancements to further increase performance, optical reach, and flexibility, including:

- Higher baud rates (+90 Gbaud)
- Gen2 PCS algorithms
- Fine baud rate granularity
- Enhanced FEC

400G Anywhere

One of the key benefits of the new PSE-V coherent DSP product family is the addition of higher baud rates (90+ Gbaud). By increasing the baud rates, lower complexity modulations can be used to achieve longer optical distances, while still supporting high wavelength capacities

The higher baud rates on the PSE-Vs, enable 400G wavelengths to be transported over any optical network from metro (150 Km) to long haul (2,500 Km) to subsea (> 5,000 Km). Higher rate wavelength capacities can be used in metro applications, but many of these short-reach networks are expected to rely on PSE-Vc based optical modules.

Gen2 Probabilistic shaping

Probabilistic constellation shaping (PCS) is an optimization technique applied to modulation symbols, resulting in significant optical performance improvements. Standard modulation formats such as 16QAM use all constellation points with equal probability. PCS algorithms intelligently adapt which constellation points are used, and how often, to optimize the capacity and performance to the optical characteristics of each route. Probabilistic shaping improves optical reach performance, by approximately 1 dB, or roughly 25%.

Conventional, square modulation formats result in a performance gap to the Shannon Limit, because Shannon's theorem is based on a Gaussian noise model. Probabilistic shaping transforms a square constellation pattern into a Gaussian-like shape, providing an improved fit to the Shannon Gaussian model, resulting in performance gains.

While constellation shaping concepts have been known for many years, Nokia was the first vendor in the optical networking industry to develop these techniques for use on high-speed optical wavelengths.

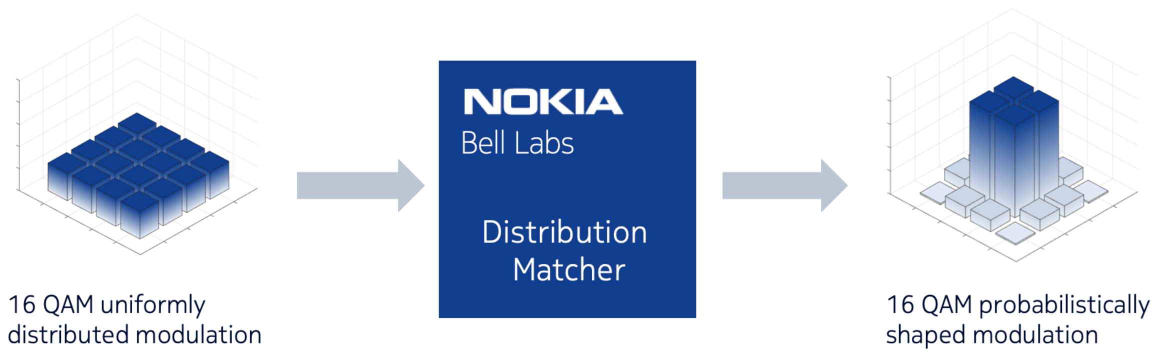

Figure 5 Nokia's patented distribution matching algorithm shapes a uniformly distributed square constellation into a probabilistically shaped constellation

A key technology in all PCS algorithms is the distribution matcher (DM), which transforms a sequence of uniform data bits into Gaussian-shaped symbols. It's the shaping of the square constellation points into a Gaussian form that provides the PCS performance improvement, also known as the shaping gain. While several mathematical techniques exist to perform this transformation, including Constant Composition Distribution Matching (CCDM), most of these are not well-suited for real world ASIC implementations. The PSE family uses a Nokia Bell Labs developed and patented distribution matching algorithm that achieves near optimal Gaussian shape yet is easily realizable within the ASIC.

With the PSE-Vs, Nokia has enhanced the distribution matching algorithm, further refining the Gaussian shape of the resulting constellation. The PSE-V incorporates improvements to the shaping function over larger block sizes, resulting in a more optimal Gaussian modulation shape, delivering incremental performance improvements.

Fine Baud Rate Granularity

When building optical networks, a key objective is maximizing the amount the data transported over each optical route. Wavelength capacity is defined by the baud rate and modulation format. Previous DSP generations provided wavelength optimization by supporting multiple baud rates (33, 44, 62 Gbaud) and modulation formats (QPSK, QAM-8, QAM-16, QAM-64). By adjusting each of these “dials”, wavelength capacity could be maximized at any distance, resulting in the familiar capacity versus optical reach staircase graphs.

Probabilistic constellation shaping enables even finer capacity adjustments, since the shaping function permits finely variable adjustments of the number of bits encoded per symbol. However, even with PCS, some granularity still exists since the shaping is applied to square modulations (QAM-16) over a fixed number of constellation points, along with granularity due to real world ASIC implementations.

With the PSE-V, Nokia is introducing fine granularity baud rate adjustments. When combined with probabilistic shaping, these fine granularity baud rate adjustments allow fine tuning of wavelength capacity at any optical reach. Since the baud rate is directly related to the wavelength channel size, the highly granular baud rate adjustment also allows much finer control of channel sizes, a key benefit for subsea applications.

Enhanced FEC

Forward error correction (FEC) algorithms are applied to wavelengths to ensure robust, error-free end-to-end communications. The photonic industry primarily relies on strong, modern FEC code referred to as Low Density Parity Check (LDPC) codes. These LDPC FEC codes, combined with soft decision iterations, provide very robust 11.5 – 12.5 dB net coding gains.

Additional FEC bytes are added to the transmit signal, allowing the receiver to detect and correct any transmission path errors. While the LDPC codes perform very well, historically they’ve required 20 – 25% overhead.

The PSE-V utilizes a new, stronger type of spatial coupled low density parity check (SC-LDPC) code. These new Nokia SC-LDPC codes provide coding gains similar to previous generations, but requiring only 15% overhead compared to the roughly 25% of previous generations. Reducing the FEC overhead allows use of stronger PCS shaping, yielding improved shaping gain performance.

Network cost savings

A recent Nokia study compared the capacity and WDM transponder requirements of a network composed of 5th generation PSE-V based wavelengths to those based on the 4th generation PSE-3 DSP.

The Nokia study was based on two network models, the 75 node Continental US backbone network (CONUS) shown in Figure 6, and the G50 German backbone network model shown in Figure 7.

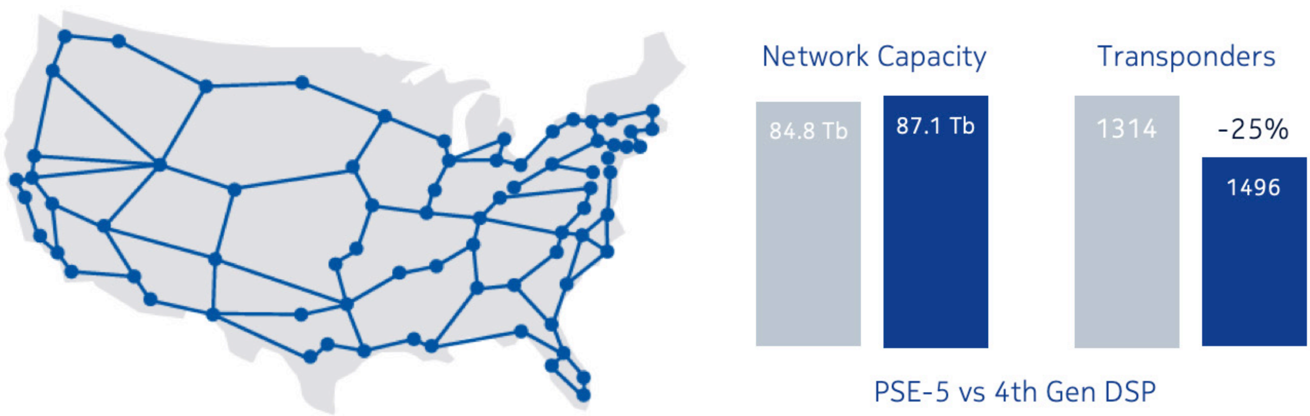

Figure 6. CONUS network model

The overall network capacity was approximately the same for both the new PSE-V and previous generation DSP on both models, which is expected as both DSP generations incorporate Nokia's advanced probabilistic shaping and operate close the theoretical limits. However, significantly fewer number of PSE-V based transponders are needed to support the capacity levels on both models.

The PSE-V higher baud rates enable higher capacity wavelengths over longer distances, resulting in 25% fewer transponders on the CONUS model. The fewer number of PSE-V based transponders results in direct cost savings of the transponders themselves, as well as secondary savings in space and power associated with the lower equipment requirements (fewer cards, shelves, etc.)

The German G50 backbone network model produced similar results, with essentially flat network capacity, but requiring 17% fewer PSE-V based transponders. The shorter distances in the G50 network produced a slight anomaly on total network capacity, where the 4th generation PSE offered a slightly better "fit" to this specific network model.

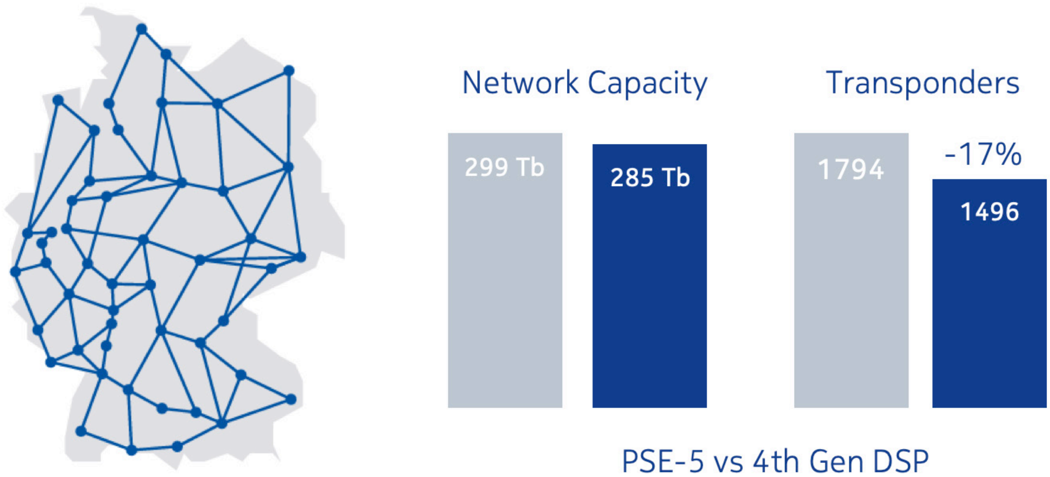

Figure 7. German G50 network model

Summary

Nokia is the industry leader in the innovation and development of coherent high-speed digital signal processors, including key technologies such as probabilistic constellation shaping (PCS). First introduced in 2018 in Nokia's PSE-3, PCS has been universally recognized as critical to achieving high levels of network performance and is being adopted by future generations of DSP's throughout the industry. Nokia has incorporated enhanced 2nd generation PCS into the Nokia PSE-Vs, along with higher baud rates, higher wavelength capacities, stronger FEC implementations, along with support for pluggable applications on the PSE-Vc. The Nokia PSE-V coherent DSP product family – **taking light beyond the limit.**

Abbreviations

1. ASIC Application specific integrated circuit
2. CCDM Constant composition distribution matching
3. CONUS Continental United States backbone reference network
4. dB Decibel
5. DM Distribution matcher
6. Gbaud Giga-baud
7. GHz Giga-hertz
8. DCI Data center interconnect
9. DSP Digital signal processor
10. FEC Forward error correction
11. Km Kilometer
12. LDPC Low density parity check
13. LH Long Haul
14. QAM Quadrature amplitude modulation
15. OIF Optical interoperability forum
16. QPSK Quadrature phase shift keying
17. OSNR Optical signal-to-noise ratio
18. PCS Probabilistic constellation shaping
19. PSE Photonic service engine
20. SC-LDPC Spatially coupled low density parity check
21. SD-FEC Soft decision forward error correction
22. ULH Ultra-long haul
23. WDM Wavelength division multiplexing

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