INFINERA
INFINITE CAPACITY ENGINE

Innovation on Fast Forward

infinera®

THE INFINERA INFINITE CAPACITY ENGINE (ICE) family of optical engines delivers cloud scale capacity for Infinera Intelligent Transport Networks. Powered by the advanced electronics in Infinera's FlexCoherent® digital signal processors (DSPs) and the cutting-edge photonics of Infinera's photonic integrated circuits (PICs), ICE offers network operators the combined benefits of scalable multi-terabit super-channel capacity and industry-leading capacity-reach performance from metro to subsea distances.

With each new generation of ICE, delivered on a rapid cadence to keep pace with capacity demands, Infinera delivers new levels of optical performance that are designed to enable network operators to increase capacity and service agility while lowering total cost of ownership (TCO). ICE is innovation on fast forward.

In 2016, Infinera introduced the first Infinite Capacity Engine, known as ICE4 because it built on three prior generations of optical engine innovation. ICE4 was the industry's first integrated terabit-scale optical engine. ICE4 powers a broad range of Infinera products, from the compact, disaggregated Cloud Xpress 2 and XT Series meshponders to the DTN-X XTC family, serving a wide variety of metro, long-haul and subsea applications.

In 2018, Infinera announced a new Infinite Capacity Engine, ICE5, the industry's first 2.4 terabit per second (Tb/s) optical engine. ICE5 delivers step-function improvements in capacity, density and power efficiency that target the highest-scale applications, such as data center interconnect and fiber-deep architectures for mobile 5G and cable distributed access.

	ICE4	ICE5
Maximum capacity per wavelength	200 Gb/s	600 Gb/s
Base optical engine, number of wavelengths	6 wavelengths	4 wavelengths
Base optical engine, maximum capacity	1.2 Tb/s	2.4 Tb/s
Maximum capacity per fiber (C-Band)	27.6 Tb/s	approximately 40 Tb/s
Supported modulations	BPSK thru 16QAM	QPSK thru 64QAM
Transmission symbol rate	flexible, 17-33 gigabaud	flexible, 33-66 gigabaud
Built-in encryption support	Yes	Yes

Table 1. ICE Generations at a Glance

Table 1 shows the ICE4 and ICE5 specifications at a glance.

Looking ahead, Infinera is already developing the next Infinite Capacity Engine, ICE6, targeted to provide higher performance and value to network operators so they can continue to scale their networks to address the relentless growth in bandwidth demand.

Addressing Exponential Bandwidth Demand

THE INSATIABLE DEMAND for bandwidth continues to drive the need for network scale. By 2020, over 20 billion devices are expected to get connected as the Internet of Things (IoT) becomes

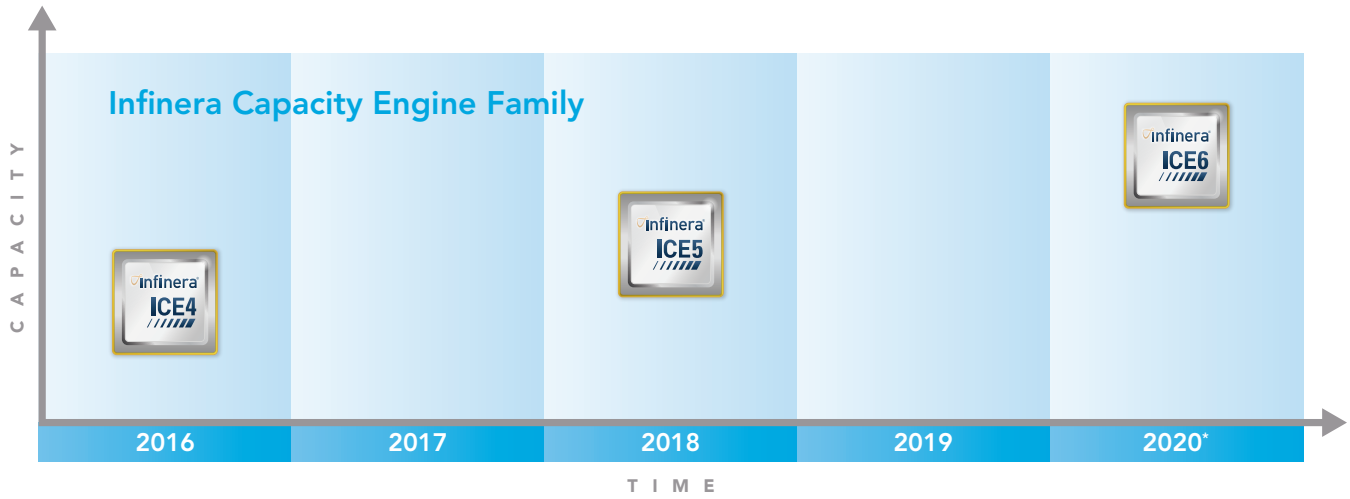

Figure 1: The Infinite Capacity Engine Family

*projected release date

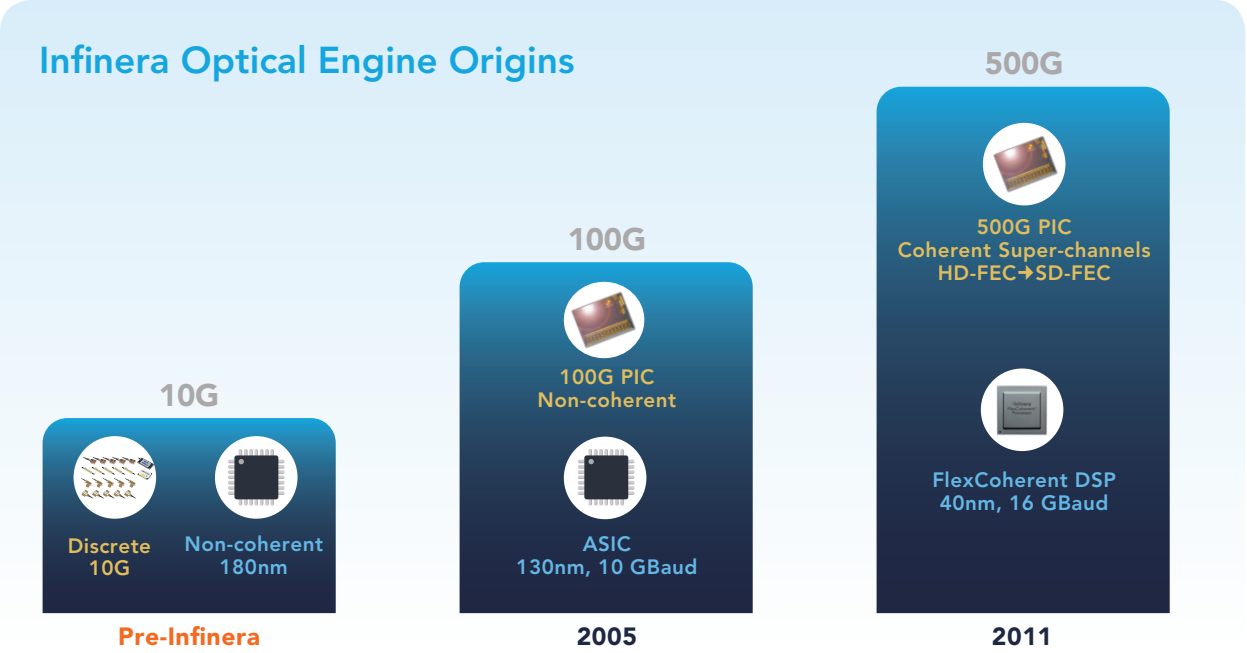

Figure 2: Infinera Optical Engine Origins

pervasive. Mobile video usage is forecast to multiply 13 times over from today, while 70% of businesses are expected to be cloud-enabled by 2020. This exponential growth in bandwidth has compelled network operators to invest in highly scalable wavelength-division multiplexing (WDM) technology, in which multiple optical carriers travel in parallel over a single fiber pair. However, in spite of the tremendous capacity of current WDM technology, new levels of scale, flexibility and reliability are continually needed to handle this tremendous onslaught of data traffic.

Before ICE: A History of Optical Engine Innovation

Super-channels are a recent WDM innovation in which several optical carriers are combined to create a composite line-side signal of the desired capacity that can be provisioned in one operational cycle. Infinera pioneered the use of super-channels in optical transport network platforms in 2005 with the introduction of the world's first large-scale PIC. This PIC transformed the 10 gigabit per second (10 Gb/s) transport market, which had historically relied on discrete optical components to build WDM systems. These discrete optics-based systems consumed tremendous power and rack space and required more modules and fibers, resulting in greater operational complexity. The first-generation PIC introduced a step function in network bandwidth economics by combining over 60 different functions into a fingernail-sized pair of chips, while provisioning 100 Gb/s of capacity in one operational cycle. In addition to photonic functions delivered using the PIC, transport platforms use electronic functions in the form of DSPs/application-specific integrated circuits (ASICs) to process network traffic.

The Infinera DTN platform, designed with the first-generation PIC and DSP/ASIC, achieved impressive success by capturing 10 Gb/s market share leadership a few years after its introduction. In 2009 the second-generation PIC was introduced, dramatically improving performance to support ultra-long-haul terrestrial and subsea applications. The next step function in transport performance was delivered in 2011 with the introduction of the 500 Gb/s PIC and the FlexCoherent DSP/ASIC as key elements of the Infinera DTN-X platform. This was the third generation of the PIC technology, with five 100 Gb/s channels, effectively delivering a 500 Gb/s super-channel, as shown in Figure 2. The FlexCoherent DSP provided coherent detection technology for the super-channel, tremendously increasing the capacity-reach performance of the DTN-X. Similar to the Infinera DTN platform, the Infinera DTN-X platform found much success, capturing 100 Gb/s market share leadership the first quarter after it began shipping.

The Infinera Infinite Capacity Engine

In each ICE generation, Infinera incorporates new innovations in both the DSP and PIC, which are tightly coupled to create an engine designed to improve performance rapidly from one generation to the next.

Cutting-edge Photonics

Infinera PIC technology has clocked over two billion field hours, lighting up over two million kilometers of fiber. The PIC technology within the Infinera Infinite Capacity Engine integrates several hundred optical functions, including tuneable lasers, photodiodes, nested Mach-Zehnder modulators, demodulators, splitters, combiners, attenuators and amplifiers. The PIC is designed to support multiple parallel channels, is engineered on the monolithic Indium Phosphide (InP) substrate and supports the creation of up to multiple terabits of capacity along with modulation, multiplexing and in-chip amplification functions. This implementation leverages the same fundamental technology as in earlier PIC generations, enabling Infinera to continue to build unique InP design, manufacturing and testing capabilities to continue to advance the state of the art. Monolithic InP, a naturally lasing material at certain temperatures, continues to be a superior material for integrating active and passive optical functions, for distances longer than a few kilometers (km), while providing multi-terabit-scale performance, as compared to other co-packaging or hybrid approaches that use silicon photonics.

Figure 3 illustrates the photonic integration advantages of ICE4, which delivered greater simplicity, reliability and lower power than comparable optical systems available when it was introduced. With its unique technology and expertise, Infinera expects to sustain comparative integration advantages in the ICE5 and ICE6 engines and beyond.

Advanced Electronics

The FlexCoherent DSPs in ICE are designed to deliver sophisticated digital signal handling, with transmitter-based (Tx) processing and enhanced receiver-based (Rx) capability, industry-leading coherent performance and complementary features to enhance network security and availability.

Advanced Coherent Toolkit Several advanced technologies incorporated into the FlexCoherent DSP, including many that are unique to Infinera, work together with the goal of maximizing

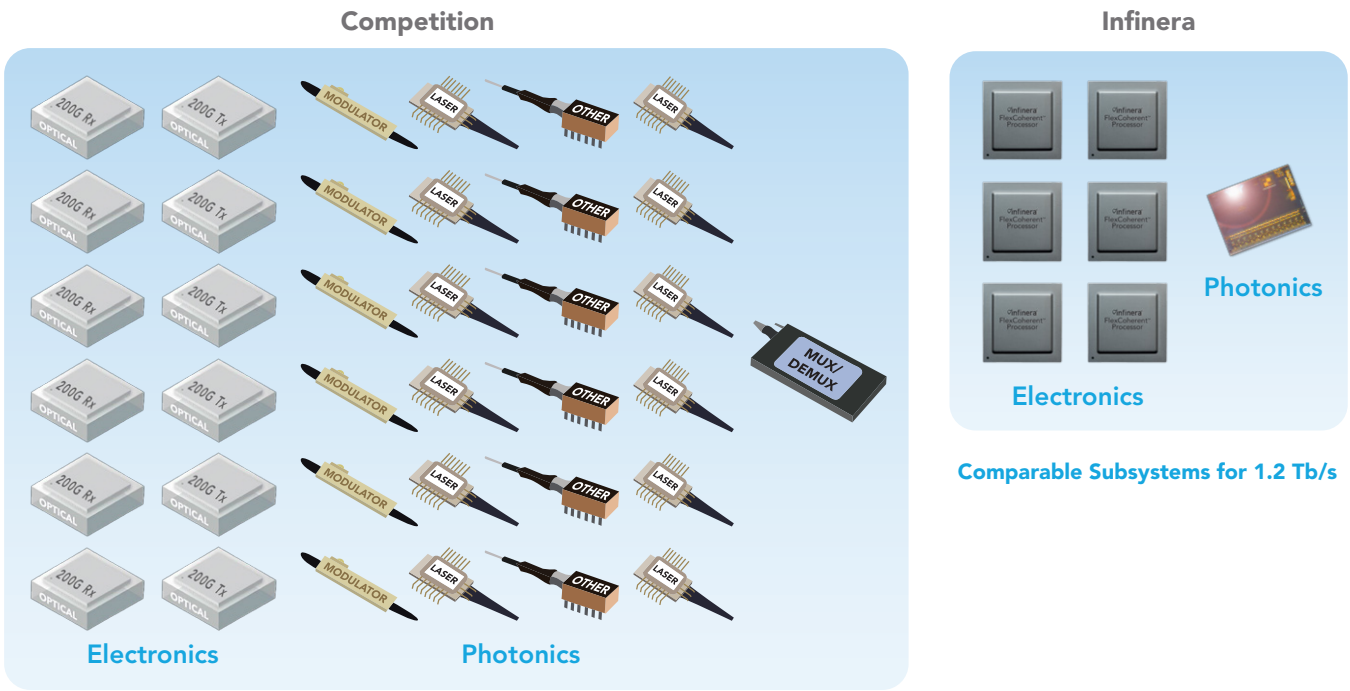

Figure 3: ICE4 Photonic Integration Advantages

Advanced Coherent Toolkit
• Nyquist subcarriers
• Advanced, flexible modulation
• Flexible baud rate
• Flexible and tight channel spacing
• SD-FEC gain sharing
• Non-linear compensation
• Lightning protection

Table 2: Advanced Coherent Toolkit

capacity-reach performance (the maximum capacity achievable for a given transmission distance) and operational scalability, driving down network operators' total cost of ownership. We refer to this group of technologies as the Infinera Advanced Coherent Toolkit (ACT).

In ICE4, ACT technologies have been proven to deliver record-breaking capacity-reach performance in real-world deployments from metro to subsea distances. Examples of ICE4 record milestones include:

- 27.6 Tb/s fiber capacity over metro-to-regional distances in the extended C-band on conventional fiber. With planned ICE4 L-band optical engines as part of a complete C+L solution, fiber capacity can be approximately doubled to over 50 Tb/s.
- 18.2 Tb/s fiber capacity over a subsea link exceeding 10,000 km, approximately 50% higher spectral efficiency than available alternatives.

In future ICE generations, it is envisioned that the Advanced Coherent Toolkit will continue to grow, employing the latest coherent optical innovations to help operators increase capacity-reach performance in their networks, and thus drive down total cost of ownership.

For more in-depth explanation of these technologies see these Infinera white papers:

- ***The Next Generation of Coherent Optical***
- ***Super-Channels: DWDM Transmission at 100Gb/s and Beyond***

Encryption Security is becoming increasingly important for operators, with many looking to encrypt network traffic. In-flight network traffic encryption at the optical transport networking layer, Layer 1, provides strong protection against snooping or altering, and all Infinera Infinite Capacity Engines support this capability at wire rate with 100% payload throughput at multi-terabit scale. ICE supports ultra-low latency while encrypting in bulk mode or per service, providing tremendous flexibility to the network operator. The traffic is encrypted using Advanced Encryption Standard (AES) 256-bit keys, while the keys themselves are exchanged using the highly efficient 521-bit elliptical curve Diffie-Hellman (ECDH) mechanism. ICE also supports fast, hitless key rotation, a key requirement for many cloud-based service providers. Internal policies and processes within providers may require key rotation, or compliance mandates may dictate that keys are rotated as well.

- **In-flight integrated encryption**
- **Bulk and per service**
- **Strong AES 256-bit key encryption**
- **Hitless key rotation**
- **521-bit elliptical curve DH key exchange**

- **Ultra low latency**
- **100% payload throughput**
- **Protocol-agnostic**

ICE Enables Cloud Scale Networking

The power of an Infinite Capacity Engine is fully realized as part of an Infinera Intelligent Transport Network that incorporates other cloud scale technologies and features, shown in Table 3.

Cloud Scale Networking Technologies
• Instant Bandwidth
• Instant Network
• Sliceable super-channels
• Future-proof flexible grid open line systems
• Open ICE transmission over third-party line systems
• Cloud automation

Table 3: Cloud Scale Networking Technologies

LIGHTNING PROTECTION

With the ICE4 engine, Infinera also introduced a unique capability to protect against lightning-related outages that impact coherent transmission over aerial fiber. A wide range of network operators employ at least some aerial fiber in their networks due to its cost and availability. However, when the first coherent transmission systems were deployed, operators and suppliers such as Infinera discovered a new failure mode in aerial fiber due to lightning-induced state of polarization (SOP) transients that overwhelmed the coherent detection circuitry, resulting in outages that could last seconds or minutes. Some routes in lightning-prone areas experience dozens or even hundreds of outage events per year. Short-term workarounds helped to reduce the frequency and severity of outages, but a complete solution was not available until Infinera introduced ICE4.

The ICE4 DSP incorporated innovative circuitry to enable very fast SOP tracking and achieved 100% protection against all known or observed lightning events. Infinera's solution took advantage of its Nyquist subcarrier technology, without which complete protection would have been far more difficult to achieve. As a result, the ICE4 solution for 100% lightning protection is unmatched in the industry.

As with the Advanced Coherent Toolkit, many of these technologies are unique to Infinera, in part because they build on the unique capabilities of ICE. They can be enabled individually or in combination to create complete network solutions that enable network operators to achieve high service agility and fast time to revenue with low total cost of ownership. To learn more about them, refer to these Infinera resources:

- ***Infinera Instant Bandwidth (brochure)***
- ***Infinera Instant Network (brochure)***
- ***Future-proof Open Line Systems for Cloud Scale Networks (white paper)***

Summary

The Infinite Capacity Engine family of optical engines delivers scalable multi-terabit super-channel capacity and industry-leading capacity-reach performance from metro to subsea distances. With each new generation, ICE incorporates cutting-edge innovations and step function increases in capacity, enabling network operators to scale their networks and keep pace with relentless bandwidth demand.

ICE: Innovation on Fast Forward.

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