WHITE PAPER

The Ultimate Guide to Nyquist Subcarriers

Coherent optical transmission has delivered a dramatic enhancement in the capacity-reach product for long-haul and subsea cables. The first wave of coherent systems reached the market around 2011 and delivered a tenfold increase in capacity, with 10 gigabit [10G] wavelengths becoming 100G wavelengths. The first wave of coherent systems located all of the digital processing power in the receiver. Today, a second wave of coherent systems has both transmitter- and receiver-based processing, and can deliver around 30 times the capacity of non-coherent technology.

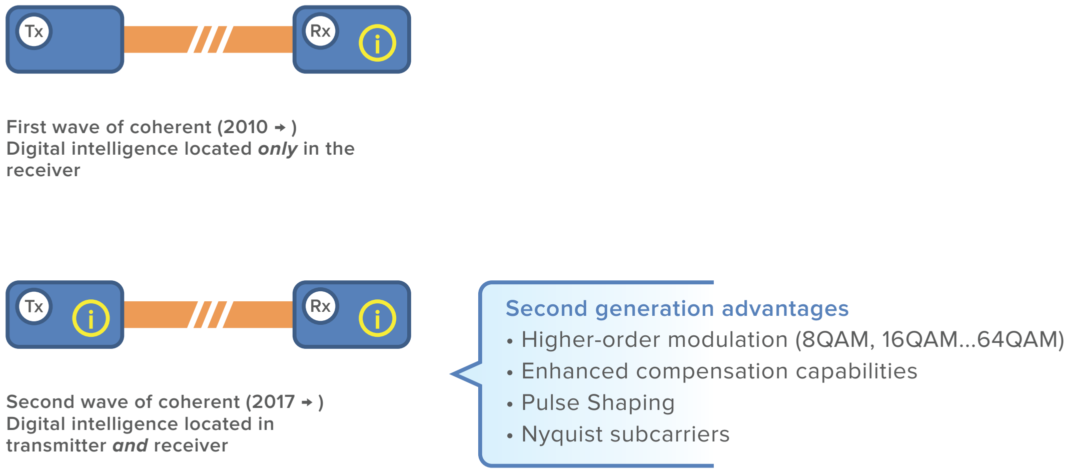

Figure 1: The first and second waves of coherent processing

The key advantages of transmitter-based processing are the delivery of higher-order modulation beyond quadrature phase-shift keying (QPSK), enhanced impairment compensation, pulse shaping and the ability to implement Nyquist subcarriers.

Infinera's fourth-generation Infinite Capacity Engine (ICE4) optical engine is an example of leading-edge coherent optical performance, and one of the critical differentiators in ICE4's long-haul and subsea performance leadership is the implementation of Nyquist subcarriers. This paper explains what these are and why they can dramatically enhance optical performance – especially in higher-baud-rate systems.

Baud Rate and Scaling

The idea of scaling to meet growing demand for capacity at ever-lower costs is a common theme in the optical transmission market. However, it is useful to clarify exactly what the scaling objective is. Here are three obvious objectives:

- Increasing the data rate per wavelength, transponder or appliance
- Increasing total fiber capacity
- Increasing optical reach

Much of the focus for coherent optical system vendors is to leverage advances in application-specific integrated circuit (ASIC) processing speed to increase the rate at which optical symbols are sent along the fiber – in other words, increasing the baud rate of transmission. At first glance this approach seems to offer significant benefits, because sending twice as many symbols per second (for a given modulation type) will double the data rate per wavelength or per transponder. This should have a very positive effect on the cost per bit and operational scalability for this transponder design.

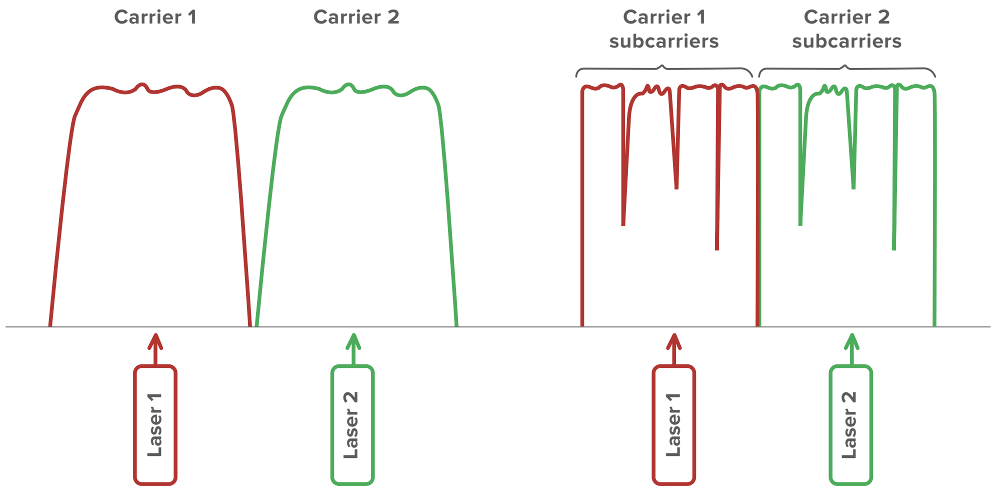

Figure 2a Figure 2b

However, doubling the baud rate will actually double the spectral width of the signal, which means there is no improvement in spectral efficiency, and overall higher baud rates suffer greater optical penalties, which tend to reduce optical reach. So increasing baud rate alone cannot achieve all of these objectives.

The use of Nyquist subcarriers can help to overcome some of the drawbacks and implementation barriers of higher baud rates.

What Is a Subcarrier?

In a conventional optical carrier, a single laser produces a signal that occupies a contiguous band of spectrum, known as the optical carrier. In other words, a carrier is the contiguous output from an individual laser (Figure 2a).

In a coherent implementation with transmitter-based processing, it is possible to mathematically shape the single-carrier signal so that it will occupy the minimum amount of optical spectrum, known as Nyquist pulse shaping. Many vendors implement pulse shaping to enhance spectral efficiency, but Infinera's ICE4 optical engine is unique because it uses Nyquist shaping to digitally divide the optical carrier into multiple subcarriers (Figure 2b). The number of subcarriers can be selected to optimize optical performance – in ICE4, four subcarriers are used.

The critical advantages that a subcarrier implementation delivers include:

- Linear impairment tolerance – especially for chromatic dispersion (CD)
- Non-linear impairment optimization
- Enhanced spectral efficiency via tighter channel spacing

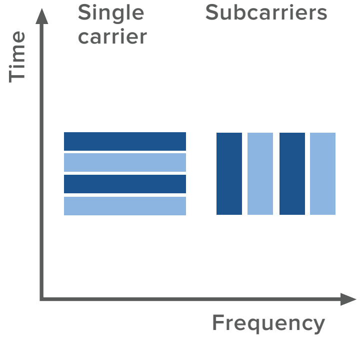

Figure 3a

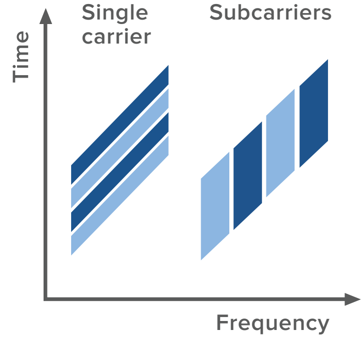

Figure 3b

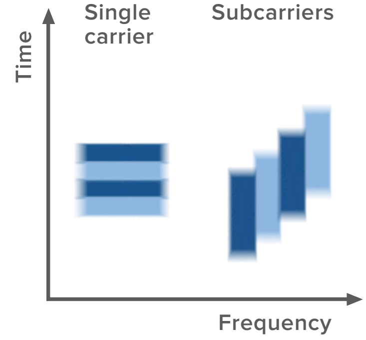

Figure 3c

Subcarrier Advantage: CD Compensation Tolerance

One of the technological advantages of coherent transmission is the ability to compensate for chromatic dispersion electronically, rather than by using dispersion-compensating fiber. Adding transmitter-based processing in second-generation coherent means that even the accumulated dispersion from modern transoceanic cables can be cancelled out completely. But this compensation comes with a penalty.

Figure 3a shows the transmission of a series of four symbols, in which a single carrier will transmit the symbols in the time domain while a subcarrier implementation uses the frequency domain. Figure 3b shows how these symbols are dispersed to the same amount, and Figure 3c shows how they are compensated in the coherent detector. The width of each subcarrier is 1/4 of the width of the single-carrier signal, which means it experiences 1/16 as much chromatic dispersion (the magnitude of CD increases with the square of the baud rate). In addition, compensation processing can be performed in parallel processing circuits – something that is easier to implement in a modern ASIC than increasing the serial processing rate.

In Figure 3c, when the subcarrier signal has been compensated, the residual skew between subcarriers is easily corrected and is a further advantage in terms of processing power.

Subcarrier Advantage: Non-linear Tolerance

Non-linear impairments, such as self-phase modulation (SPM), cross-phase modulation (XPM) and four-wave mixing (FWM), are the primary reason why higher-order modulation formats, such as polarization-multiplexed (PM)-64 quadrature amplitude modulation (QAM), have dramatically

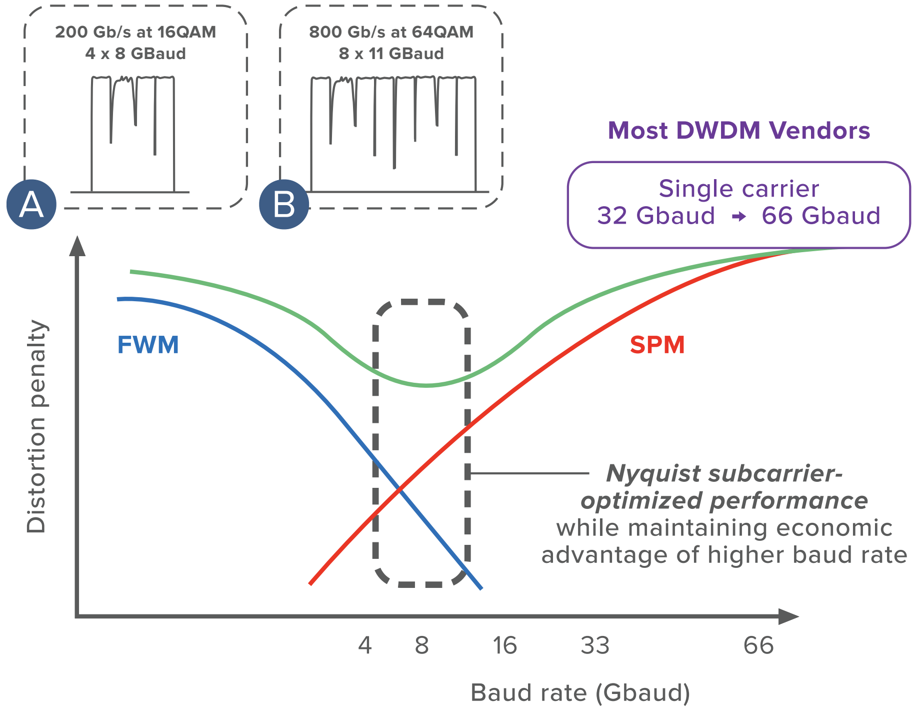

Figure 4: Total distortion penalty

shorter reach than PM-QPSK or PM-16QAM. The chart in Figure 4 shows total distortion penalty, with an aggregate of FWM and SPM on the vertical axis, and baud rate on the horizontal axis.

In order to increase the data rate on a single-carrier implementation, most dense wavelength-division multiplexing (DWDM) vendors are forced to use very high single-carrier baud rates – from 32 gigabaud (GBaud) and upward. As this chart shows, while FWM will reduce as baud rate increases, SPM actually rises. The result is a non-linear "sweet spot" between about 4 and 16 GBaud.

Infinera's ICE4 technology delivers up to 200 gigabits per second (Gb/s) per carrier using 16QAM modulation at about 32 GBaud. As Inset A in Figure 4 shows, ICE4 uses four subcarriers to ensure that the effective baud rate stays within the sweet spot.

The sixth-generation Infinite Capacity Engine, ICE6, can deliver up to 800 Gb/s per carrier using constellation-shaped 64QAM at 88 GBaud. But by doubling the number of subcarriers to eight, as shown in Figure 4 Inset B, this signal remains in the non-linear sweet spot.

Subcarrier Advantage: Tight Channel Spacing

It might be tempting to assume that a subcarrier implementation will have the same, or even worse, spectral efficiency than a single carrier. In fact, the opposite is true – the ICE4 subcarrier implementation has delivered up to 30 percent more capacity than competing single-carrier implementations. In a recent subsea trial, the end result was over 6 terabits per second (Tb/s) of additional fiber pair capacity made available for revenue-generating services. This tight spacing advantage is actually derived in two ways.

Reduced Roll-off

The first advantage comes in the form of a reduced roll-off factor. In a Nyquist-shaped carrier, the ideal situation would be a carrier width in gigahertz (GHz) equal to the baud rate – so a 32 GBaud carrier would have a width of 32 GHz. However, a coherent implementation has to recover its synchronization clock from the leading edge of the carrier, and the result is that these carriers will have a wider "shoulder" of up to 20 percent of the width of the carrier. This additional carrier width is known as the roll-off factor.

In a subcarrier implementation such as ICE4, clock recovery for the entire carrier can be achieved using just one inner subcarrier. So this inner subcarrier will have a 20 percent roll-off factor, while the other three carriers can have a roll-off factor as low as 2.5 percent.

Figure 5 shows how this can reduce carrier width from 38.4 GHz to 34.2 GHz.

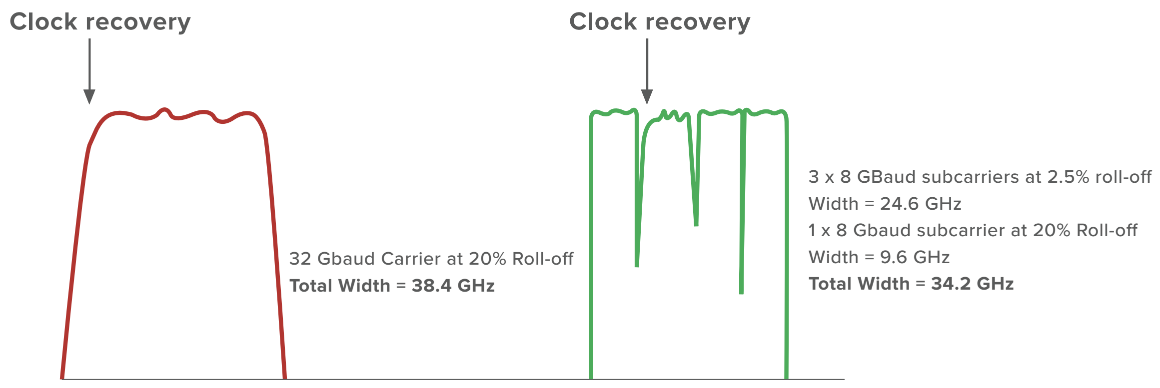

Figure 5: Roll-off reduction using inner subcarrier coherent clock recovery

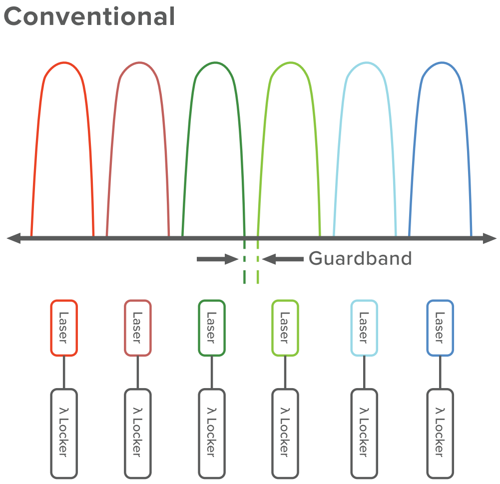

Figure 6a: Conventional transponders use separate wavelockers

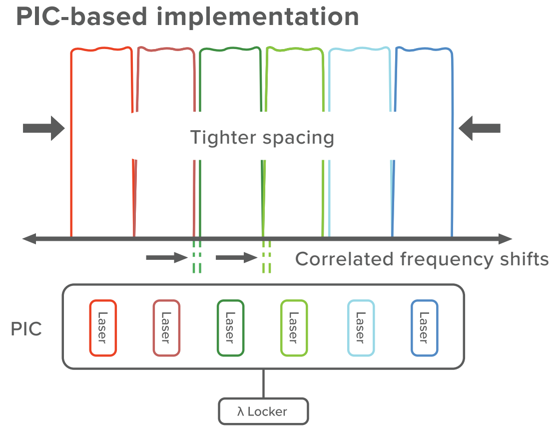

Figure 6b: Six-carrier large-scale PIC implementation with single wavelocker

PIC-based Advantage for Wavelocker

DWDM transponders make use of a wavelocker to control the drift in the carrier caused by temperature fluctuations in the environment around the laser. This is necessary to avoid interfering with neighboring carriers. In a traditional transponder implementation (Figure 6a), these wavelockers are individual devices, and have a certain level of accuracy. Carrier spacing may need to be increased to account for this accuracy.

ICE4 is a large-scale photonic integrated circuit (PIC) implementation with six lasers on the same chip, all sharing a single wavelocker (Figure 6b). While the accuracy of this wavelocker is similar to that of a single-carrier transponder's, the drift between carriers on the same PIC is extremely small. Note that this set of carriers from the same PIC is known as a super-channel. Carrier spacing within the super-channel can be reduced, while the spacing between super-channels would be similar to a single-carrier transponder.

Tight Channel Spacing Advantage

In full-fill networks, such as those used by internet content providers, tight channel spacing delivers the maximum possible capacity. This was demonstrated with record-breaking trans-Atlantic capacity (26.2 Tb/s) and spectral efficiency (6.21 bits [b]/second [s]/hertz [Hz]) over the MAREA cable in late 2018. The capability holds true over even longer distances, such as over the 10,500-kilometer Seabras-1 cable, which was closed using PM-8QAM modulation at 4.5 b/s/Hz spectral efficiency.

If a service provider prefers to trade full-fill capacity for additional reach, then ICE4's programmability in baud rate and carrier spacing allows them to do this. By reducing regeneration locations in a long-haul network, both capital and operational expenditure can be significantly reduced.

Summary

Nyquist subcarriers are a key enhancement to the latest generation of coherent technology. Subcarrier implementations like ICE4 and ICE6 overcome the drawbacks of single-carrier, high-baud-rate operation to deliver industry-leading optical performance.

In extensive field trials, and with almost two years of subcarrier-based deployments, Infinera has found a typical gain of around 0.8 decibels in the optical budget using subcarriers versus single carriers.

Moreover, as the industry looks toward 100 GBaud transmission, it appears that a subcarrier approach will be essential, and Infinera's lead in this area is likely to increase.

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