WHITE PAPER

Infinera®

FlexCoherent™ Modulation for the Terabit Age

Coherent super-channels have demonstrated a 30-fold increase in spectral efficiency and a 200-fold increase in operational scalability, as compared to classic 10 gigabit per second (G) direct detection technologies. In this whitepaper, we explain how the latest wave of technology, based on higher-order modulation and transmitter-based compensation techniques, has developed, satisfying continuing increases in Internet demand.

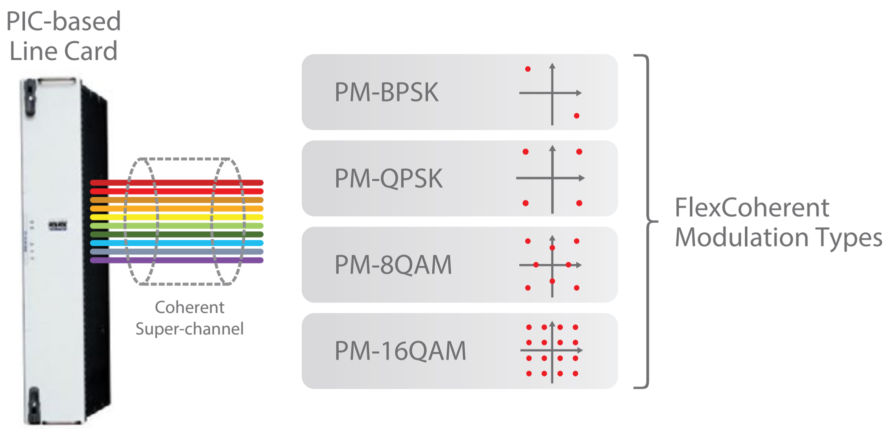

Figure 1: FlexCoherent Modulation Types

The Success of Coherent Super-channels

As Infinera explained in a separate whitepaper, a super-channel is an evolution in DWDM in which multiple coherent optical carriers are implemented on a single line card, brought into service in a single operation, and seen by higher-layer services as a single pool of digital capacity[1] as shown in Figure 1, above. Recent advances have taken coherent super-channels to a new level of scale, allowing up to 2.4 terabits per second (T) of capacity to be turned up in a single operational cycle.[8]

Coherent technology[2] allows us to massively increase spectral efficiency and, when it is combined with powerful soft-decision forward error correction (SD-FEC),[3] we can increase reach and deal with challenging, high polarization mode dispersion (PMD) fiber installations.[4]

Combined with flexible grid[5] technology and polarization-multiplexed quadrature phase-shift keying (PM-QPSK) modulation, it has been possible for some time to achieve up to 12T in the extended C-band of conventional optical fiber. With new higher-order modulations, even higher capacities can now be achieved.

However, there is no single form of coherent modulation that works best in all circumstances. In 2011, Infinera pioneered our FlexCoherent modulation capability, in which different modulation types can be configured on the same physical line card, and in 2016 we extended this flexibility to add new modulation types, including matrix-enhanced phase-shift keying (ME-PSK) and higher order PM-8QAM (quadrature amplitude modulation) and PM-16QAM,[7] also shown in Figure 1.

Higher-order Modulation

Higher order phase/amplitude modulation techniques carry more bits in each modulation symbol. Figure 2 shows the capacity-reach data for all the FlexCoherent modulation types.

As an example, 16QAM initially appears to be a very attractive modulation technique because each compound symbol (i.e. the sum of X and Y polarizations) carries eight bits. Accordingly, 16QAM can deliver up to 26.4T of fiber capacity.

However, optical fiber is a non-linear medium and so the total power of any individual modulation symbol is effectively capped by the non-linear threshold. Exceeding this non-linear threshold has a major impact on reach, caused predominantly by cross phase modulation (XPM).[6]

Modulation	Bits per symbol (X+Y Pol)	Extended C-Band Capacity [1]	Typical Reach [2]
ME-PSK [3]	2	6.4T	>12,000
BPSK	2	6.4T	12,000
PM-3QAM	3	9.6T	9,000
PM-QPSK	4	12.8T	6,000
PM-8QAM	6	19.2T	2,500
PM-16QAM	8	26.4T	1,150

[1] Assumes extended C-band and flexible grid
[2] Assumes G.652 fiber with at least 2 dB system margin
[3] ME-PSK provides the same spectral efficiency, baud rate and channel spacing of BPSK with enhanced coding techniques to deliver increased reach and performance at a lower OSNR

Figure 2

A specific modulation symbol will have a power limit. For example, 16QAM carries twice as many bits as QPSK in that symbol, and this results in a lower optical signal-to-noise ratio (OSNR).

Moreover, Figure 3 shows that the tolerance for receiving a 16QAM signal is significantly more challenging than a QPSK signal. Notice that the phase angle between two adjacent symbols with the same intensity value is much larger on QPSK than 16QAM. As a result, we see that, compared to QPSK, 16QAM can deliver up to twice the capacity on a given fiber, but at the cost of delivering one-sixth of the optical reach.

The example set forth in Figure 3 implies that 16QAM will be limited to short-reach, metro and small regional deployments where regular signal regeneration can be provided. In these circumstances, we believe that Infinera's unique ability to offer low-cost regeneration and to convert from one modulation format to another on a "hop-by-hop" basis will be a significant competitive advantage for service providers.

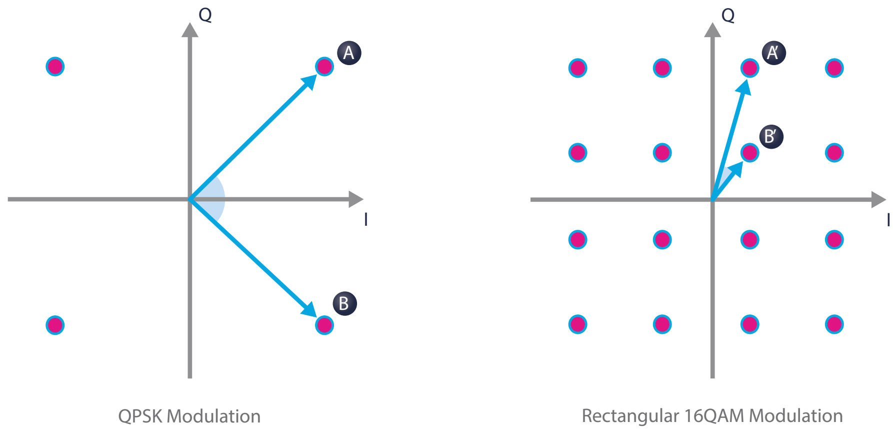

Figure 3: QPSK and 16QAM Modulation

The Optical Sweet Spots: 3QAM and 8QAM

In the range of FlexCoherent modulation types, there are two that stand out in terms of offering an intermediate step as network designers strive to optimize their link capacity and reach.

PM-3QAM

While the specific details of Infinera's 3QAM implementation are confidential, at a high level, Infinera believes the effect will be similar to transmitting one of the polarization states using BPSK and the other using QPSK, and then reversing this for the next symbol. In other words, each compound symbol carries a total of three bits, and the non-linear penalty is intermediate between BPSK and QPSK.

3QAM is incredibly useful in submarine deployments because it allows network designers to close links that are too long for QPSK, but without suffering the 50% reduction in capacity as a consequence of using BPSK.

This increase in useful capacity was first demonstrated by Infinera and Telstra over Segment 5 of the Asia-America Gateway cable between California and Hawaii, where 3QAM showed it could increase the useful capacity of the cable by 50% compared to competitive BPSK solutions.

PM-8QAM

While 3QAM offers a useful intermediate modulation in submarine deployments, 8QAM offers a similar capability for terrestrial networks. Figure 2, on page 3, shows the tradeoff between fiber capacity and reach for all of the FlexCoherent modulation techniques. By adding 3QAM and 8QAM to the modulation options Infinera offers a vital set of intermediate steps for fiber capacity optimization.

As an additional dimension of flexibility, Infinera's Bandwidth Virtualization technology allows the modulation technique to be switched hop-by-hop across the network in order to optimize the entire traffic matrix on the network.

What Kind of Fiber?

As DWDM vendors strive for greater capacity, a number of hero experiments and field trials have been, and continue to be, performed to illustrate progress in this area. It is important for network designers to understand that the headline capacity achieved in these trials may not be realized in an actual network deployment. The major factors involved in this disparity are the type of fiber used in the trial and the lack of an end-of-life system margin in the fiber budget.

The majority of the world's fiber today complies with one of two ITU-T standards: either G.652 or G.655. There are multiple variations within these standards, but in simple terms, the differences between these fibers come down to attenuation, dispersion, and effective area.

Figure 4[6] shows the performance of QPSK, 8QAM and 16QAM for both G.652 and G.655 fiber types. G.652's higher dispersion value means that the non-linear penalty is lower, which translates to somewhat better reach compared to G.655.

Note that newer fibers are being developed, and because these new fibers tend to be more expensive than existing fibers, such newer fibers are initially scheduled for deployment in new submarine fiber routes.

The new fiber types are engineered with a lower attenuation, typically 0.16 decibels (dB) per kilometer (km), and a larger effective area, typically around 112 square microns versus 80 square microns for G.652. Lower attenuation means that a signal of a given power can travel further along the fiber before amplification is required. Larger effective area means that the power density of an optical signal (which is the limiting factor for the onset of non-linear effects) is lower because the power of the signal is spread over a larger area. Together these characteristics

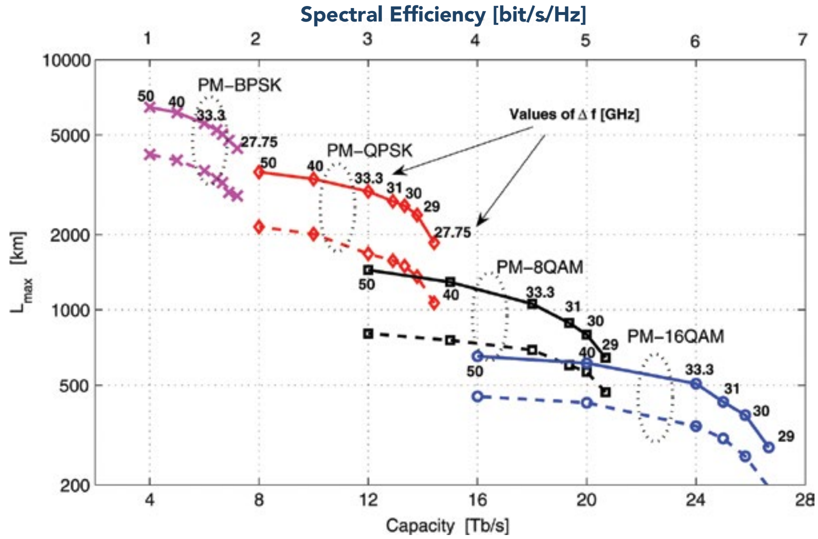

Figure 4

Maximum reach with bit error rate of <4.10-3 versus capacity in the C-band (bottom axis) and spectral efficiency (top axis) for PM-BPSK (crosses), PM-QPSK (diamonds), PM-8QAM (squares) and PM-16QAM (circles). Lines are obtained connecting simulation results. Solid lines refer to standard single-mode fiber (SSMF) and dashed lines refer to non-zero dispersion-shifted fiber. The corresponding values of Δf in gigahertz (GHz) are shown at the SSMF points.

mean that these new fibers may deliver 16QAM reach that is up to 50% further than G.652 fiber. However, such new fibers are not the fibers that service providers have in the ground today.

Aside from the fiber type, field trials and hero experiments often operate without any additional margin in their transmission budget. Service providers will typically demand a 2dB margin (though this will vary on a case-by-case basis) in order to ensure that fiber repairs or other factors can be tolerated during the lifetime of the fiber and reliable transmission will be maintained.

Note that the values quoted in Figure 2 and in the rest of this whitepaper are based on G.652 fiber and a 2 dB system margin.

Summary

Coherent transmission has transformed the long-haul optical market and delivered more than a 30-fold increase in the capacity-reach product compared to 10G intensity modulation/direct detection (IM-DD). Coherent super-channels have made this technology operationally scalable, allowing up to 2.4T of capacity to be turned up in a single operational cycle.

Since there is no one-size-fits-all modulation technique, Infinera's FlexCoherent technology provides service providers the ability to optimize each link in their network under software control and thus avoid the complication of individual line card types for spares management.

Specific FlexCoherent modulation techniques may offer particular advantages. PM-3QAM, for submarine networks and PM-8QAM, for terrestrial networks, provide a vital intermediate step so that service providers can squeeze the maximum capacity from their fiber assets.

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