Introducing the 6th Generation of Optical Networking – Carrier and Spatial Division Multiplexing (CSDM)

Introduction

Since the inception of optical networking almost four decades ago, the achievable capacity within an optical fiber has grown consistently at around 30-40% CAGR reflecting the enormous growth in demand for data traffic, driven by society's continuing and prevalent requirement for more data intensive connectivity. Historical optical networking developments to date can be neatly categorized into five distinct transmission generations (Figure 1):

The total fiber capacity achievable in early optical networking generations (1, 2 and 3) was determined by the interface rate supported by a single transceiver, which grew over this period at a rate of more than 50% per year. The introduction of the EDFA enabled the 4th generation in networking, made span-by-span regenerated systems obsolete, and led to the development of WDM and DWDM systems that saw the achievable fiber capacity grow at approximately 40% per year for the next decade. Continued improvements in DWDM capacity through higher interface rates in the 4th generation became limited by the impact of chromatic and polarization mode dispersion, and further capacity gains through the addition of more DWDM signal wavelengths reached a limit imposed by the achievable EDFA gain-bandwidth.

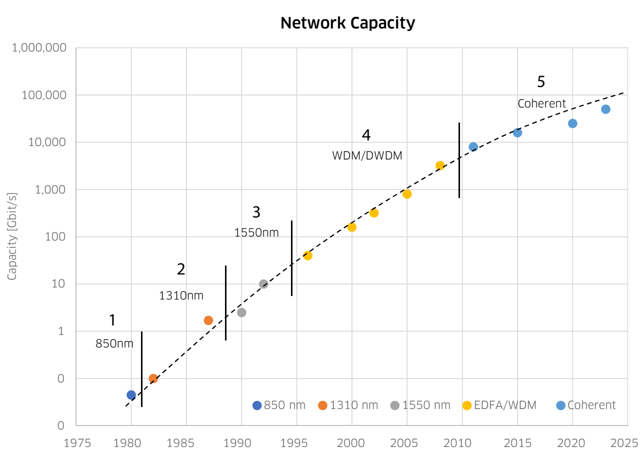

Figure 1: Five generations of optical networking

This led to a need for improved spectral efficiency, which was enabled by the transition to the 5th generation of optical networking, with the introduction of coherent transmission technology in 2009. The coherent transmission generation has seen successive modulation density and baud rate improvements that have led to increases in coherent interface rates and capacity growth rates of nearly 20% year on year.

We are however, approaching several simultaneous practical limitations in our ability to expand optical networking capacity using 5th generation technology.

Generation	Timeframe	Fiber Capacity	Technology Enabler
1	1980	45 Mbps	850 nm, MMF, single wavelength, regeneration
2	1982-1987	100 Mbps-1.7 Gbps	1310 nm, SMF, single wavelength, regeneration
3	1987-1997	2.5 Gbps-10 Gbps	1550 nm, SMF, single wavelength, regeneration
4	1997-2011	40 Gbps-3.2 Tbps	WDM/DWDM, EDFA, dispersion managed
5	2011- present	8 Tbps-50 Tbps	Coherent, amplified DWDM

The Shannon Limit

The first of these is a fundamental limitation in the amount of information that can be packed into an optical fiber, commonly referred to as the Shannon limit. This impending limitation, which is widely recognized and understood across the industry, is a significant milestone in optical networking and states that, for a given transmission length, there is a finite limit to the amount of information that can be encoded within the available optical spectrum. Figure 2 shows how this limitation translates into achievable capacity in the C band as a function of transmission reach.

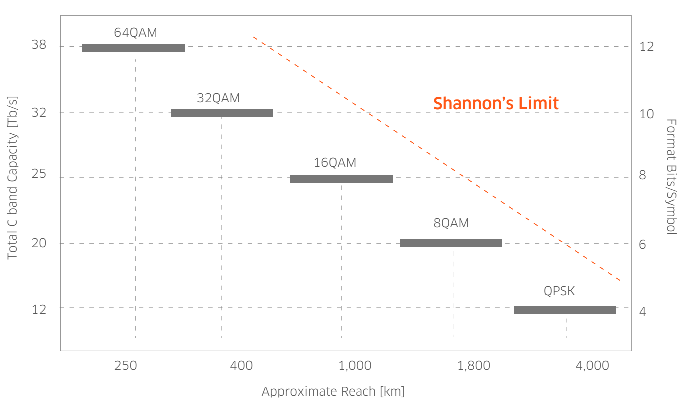

Figure 2: C-band fiber capacity limit as a function of transmission reach

As an example, for a transmission distance of 1,000 km there is a fundamental capacity limit in the C band of 25 Tb/s. Network solutions are being developed and deployed that have expanded the usable amplified optical spectrum to include both the C and L bands, allowing capacity in a single fiber to scale by an additional factor of two, but it is generally accepted that there is no currently practical amplification technology that can enable the expansion of the usable spectrum in a fiber beyond the C+L band (for example, into the S, E, and O bands).

Increasing Coherent Interface Rates

Since the start of the 5th generation (coherent), interface rates have increased consistently, resulting in reductions in $/Gb amounting to approximately 20% year-on-year as shown in Figure 3. During this time, transceiver baud rate has increased, doubling from 32 GBd to 64 GBd with a further, more recent doubling of baud rate from 64 GBd to 128 GBd.

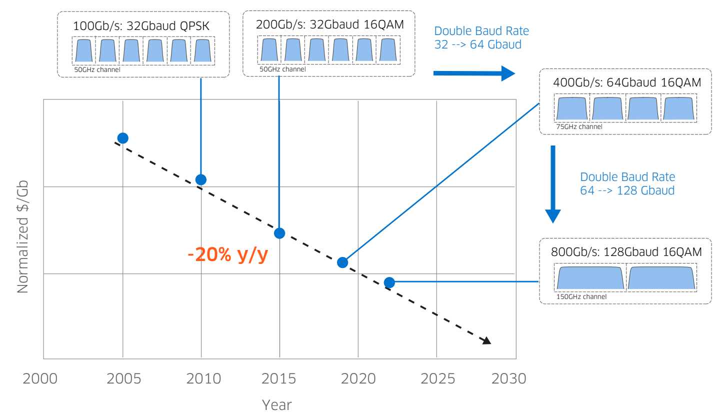

Figure 3: Evolution of coherent interface rates and resulting $/Gb

Scaling baud rate beyond 128 GBd demands higher analog bandwidth for all photonics, electronics, and RF interconnect. Doubling the baud rate again from 128 GBd to 256 GBd will be a significant technical challenge and so 256 GBd may be where baud rate scaling reaches a practical limit. This technological limitation on baud rate scaling is rapidly approaching.

Given that capacity continues to grow exponentially, the interface rate must continue to increase over time as has been the case historically in order to maintain similar year-on-year reductions is $/Gb, and ensure cost effective capacity growth. With baud rate scaling reaching a practical limit, a new generational approach is required to continue to scale coherent transceiver capacity.

The 6th Generation of Optical Networking: CSDM

Spatial Division Multiplexing (SDM)
Having exhausted the usable bandwidth of an optical fiber, the industry has begun exploring capacity expansion through the deployment of multiple independent fibers, multiple fiber cores constructed within a single fiber, and multiple propagation modes within a multimode fiber. This approach is known as spatial division multiplexing (SDM) since each fiber/core/mode occupies a different path in space. While multimode fiber SDM options remain the subject of academic research, multi-core fibers are starting to be commercially deployed in subsea applications, where available repeater volume limits the number of standard single-mode fiber pairs that can be supported. In terrestrial optical network applications, where no such volume limitations exist, deployment of multiple independent fibers remains the most practical approach to scaling network capacity, by increasing the number of fiber pairs utilized from 2 to 4 to 8 etc.

The 6th generation of optical networking requires the development of ROADM and EDFA transport systems that can support SDM transmission across multiple fiber pairs per physical route without linearly scaling cost, size, or power of the solution.

Carrier Division Multiplexing (CDM)
With spectral efficiency saturating for a given reach as predicted by the Shannon limit, increasing coherent transceiver interface capacity requires an increase in signal bandwidth. This has been achieved to date by scaling baud rate. Given that the achievable baud rate of coherent transceivers is rapidly approaching a technological limit due to practical RF limitations, scaling signal bandwidth in the 6th generation will require the use of multiple, closely spaced coherently modulated optical carriers starting with 2 and increasing to 4, then 8 in subsequent transceiver iterations. This approach to coherent transceiver capacity scaling can be referred to as carrier division multiplexing.

Combined, these two approaches enable capacity scaling as shown in Figure 4 and collectively defines the 6th generation of optical networking namely, carrier and spatial division multiplexing (CSDM).

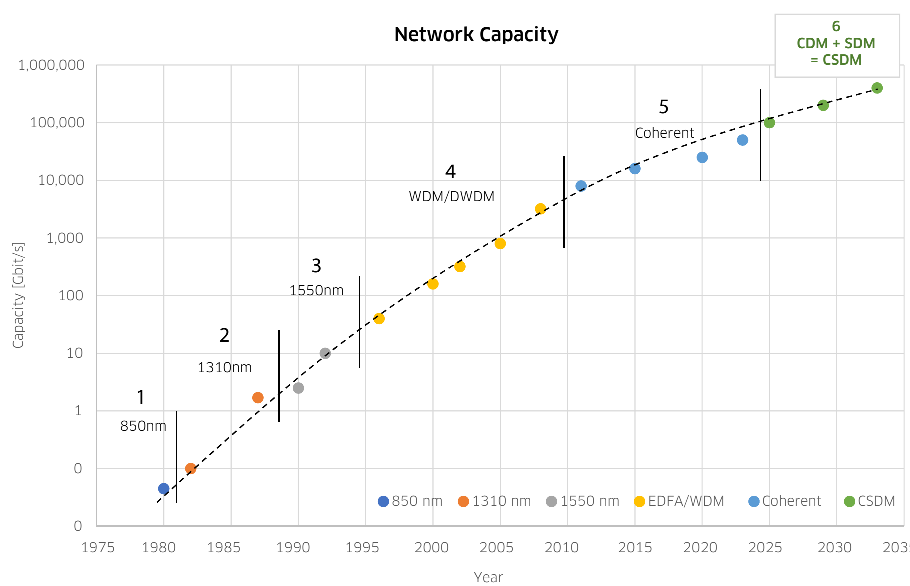

Figure 4: CSDM, the 6th generation of optical networking

Key Innovations Enabling CSDM: The 6th Generation of Optical Networking

Spatial Division Multiplexing (SDM) in ROADM Networks
Historically, network capacity growth has been supported by innovations in transceiver technology. Interface rates improved consistently across the five generations as shown in Figure 4, with each generation making more efficient use of the available spectrum in the fiber at a lower $/bit. With the Shannon limit approaching rapidly, and network traffic demand continuing to approximately double every two to three years, capacity growth can only be achieved going forward by expanding the available optical spectrum (amplified bandwidth) at the same rate.

This approach to capacity growth is already occurring in networks today. For operators where deployed fiber is constrained or where fibers are leased, C+L band is being deployed, while in scenarios where deployed fiber is plentiful, multiple fiber pairs per route are being activated. The underlying problem with either of these approaches is that network cost scales linearly with capacity, such that achieving twice the capacity results in double the network infrastructure cost.

Addressing this issue to enable cost-effective capacity growth in the era of the Shannon limit, first with C+L band, and then by activating multiple fiber pairs per route, requires innovation in optical and photonic functional integration, with the ultimate goal of reducing the cost per unit bandwidth ($/THz) as capacity and amplified bandwidth scale. Figure 5 shows how ROADM networks must evolve, employing functional integration to ensure lower $/THz as capacity grows.

Today's ROADMs use a twin wavelength selective switch (WSS) per fiber pair. Many implementations deploy C-band WSSs only with 4.8 THz of bandwidth per fiber, but L-band WSSs are also available to enable twice the capacity per fiber. In today's networks, separate C- and L-band WSSs are deployed, resulting in twice the capacity, but at double the infrastructure cost.

Recent advances in liquid crystal on silicon (LCoS) and optical design technology have allowed the development of a Twin WSS that supports both the C and L bands in a single WSS module, supporting 9.6 THz of spectrum in a single device. This innovation in ROADM capability enables a doubling of supported capacity at a significantly reduced cost per unit bandwidth ($/THz).

Further capacity growth beyond the C and L bands will require the activation of multiple fiber pairs per route/direction and additional functional integration steps will be required to maintain a consistent reduction in $/THz. Twin WSS with integrated C+L band supporting 9.6 THz in a single device will evolve to quad WSS with integrated C+L band to support two fiber pairs per route for a total of 19.2 THz of amplified bandwidth per direction in a single device.

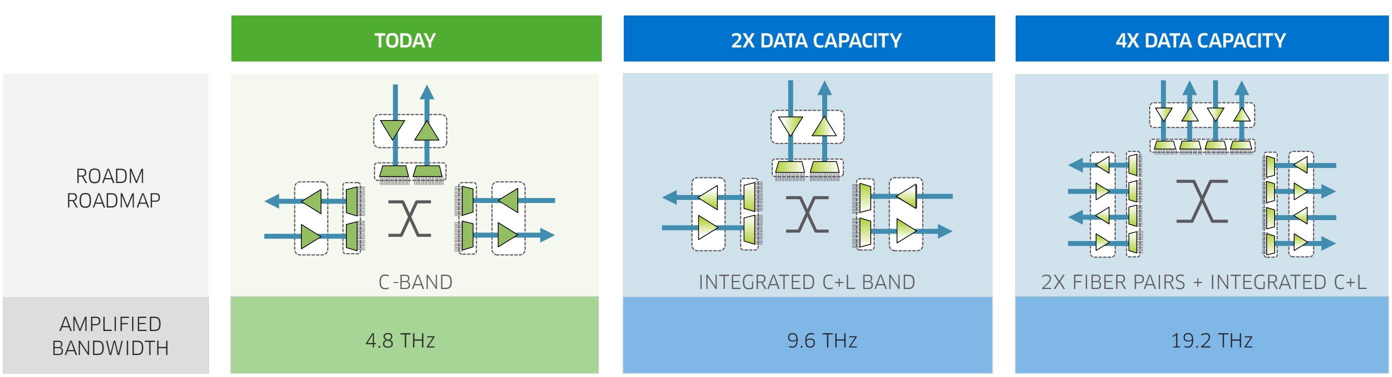

Figure 5: Evolution of ROADM networks for cost effective capacity growth

Carrier Division Multiplexing (CDM)

Since capacity continues to grow exponentially, coherent interface rates must continue to scale in order to maintain consistent reductions in $/Gb and ensure cost-effective capacity growth. With baud rate scaling reaching a practical limit, parallel carriers will be required to continue to scale interface rates as shown in Figure 6.

Today's coherent transceivers are reaching a practical limit in baud rate with respect to RF bandwidth and power dissipation achievable. The technology to enable baud rates up to 256 GBd is currently under development, but it is likely that this represents the maximum that can be achieved while meeting performance expectations within a reasonable power dissipation envelope.

Scaling interface rates beyond what is achievable with a single carrier will require innovation in photonic integration of lasers, modulators, and receivers to enable parallel carriers, while ensuring that $/Gb and power/Gb reductions are maintained as coherent interface capacity increases.

Conclusion

With traffic growing exponentially, nominally doubling every two to three years, and spectral efficiency and baud rate not keeping pace, a new 6th generation of optical networking, termed carrier and spatial division multiplexing (CSDM) will be required to provide a cost-effective means to support capacity growth.

Cost effective capacity growth in ROADM networks requires functional integration of C+L band in the first instance, evolving to integration of C+L band and multiple fiber pairs in subsequent WSS generations, while coherent transceiver interface rates need to continue to scale beyond practical baud rate limitations, requiring photonic integration of multiple parallel carriers.

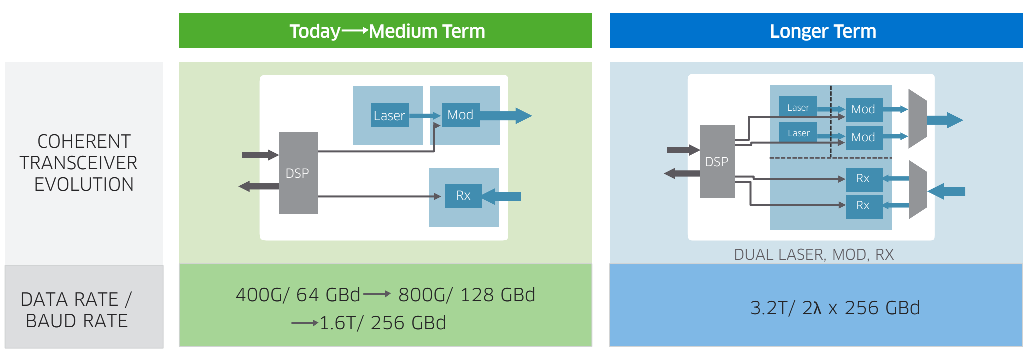

Figure 6: Coherent transceiver evolution to parallel carriers

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