The Evolution of DWDM Optical Networks

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***Abstract*—The first significant recommendation on Dense Wavelength Division Multiplexing, ITU-T G.692, was published in 1998. Since then, several updates and further recommendations have been published to support evolving channel spacing, fiber types, optical interfaces and higher data rates. In this article, we review the evolution of the technology, the changes in the recommendations to adapt to them and, in this context, the response of our partner PacketLight to the challenges posed by these new demands.**

***Keywords*—DWDM, Optical Networking, L-band, flex grid, 800 Gbps transceiver, PacketLight**

I. INTRODUCTION

The first major recommendation on Dense Wavelength Division Multiplexing (DWDM), ITU-T G.692 [1], was issued in 1998. Since then, multiple updates have emerged to support evolving channel spacing, fiber types, optical interfaces, and higher data rates (100, 400, 800 Gbps). This paper reviews the technological evolution, related recommendation changes, and the responses given by our partner, PacketLight, addressing the new challenges.

II. DWDM OPTICAL NETWORKS

A. Optical Transceivers

The evolution of optical transceivers can most clearly be observed through the various iterations of the IEEE 802.3 standard. [2] By the time the G.692 recommendation was introduced in 1998, 1 Gbps optical interfaces (GBIC) were already available. In 2001, we witnessed a form-factor transition: alongside GBICs, the similarly 1 Gbps SFP modules emerged. From 2002 onwards, 10 Gbps XFP modules became available, their size reduced to that of SFP modules by 2006, leading to the introduction of SFP+ modules. These SFP+ modules soon supported transmissions at 25 Gbps in addition to 10 Gbps. That same year, QSFP modules were introduced, combining four SFP channels (4 × 1 Gbps), followed by the enhanced QSFP+ modules (4 × 10 Gbps) in 2009.

The era of high-speed optical transceivers began with the development of CFP modules in 2010. These relatively large modules were specifically designed for relatively large 100 Gbps networks. Rapid technological advancements subsequently allowed for size reduction, resulting in the emergence of CFP2 and CFP4 modules. PacketLight products operating within DWDM systems typically use CFP2 modules. In 2014, QSFP28 modules were introduced, combining four 25 Gbps channels to deliver 100 Gbps bandwidth. QSFP56 interfaces emerged by 2018, utilizing four 50 Gbps channels to achieve 200 Gbps transmission.

Figure 1 illustrates modules of various bandwidths plotted against their years of introduction. Based on trend line fitting, it is evident that the development of optical modules currently follows an exponential trend.

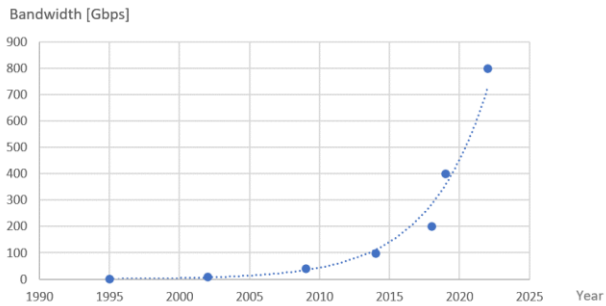

FIGURE 1 - Growth trend in optical transceiver bandwidth

In addition to increasing bandwidth, optical modules have also seen significant reductions in size and power consumption, enabling the manufacture of high port-density, low-power DWDM equipment. [8]

B. Recommendations and Standards

Several organizations strive to develop recommendations and standards for DWDM technology and its associated areas, including the International Telecommunication Union (ITU), the Institute of Electrical and Electronics Engineers (IEEE), and the Telecommunications Industry Association (TIA). This article focuses primarily on DWDM channel allocation and economic utilization, highlighting a few relevant recommendations from this perspective.

The G.692 recommendation [1] mentioned in the Introduction defines interface parameters for systems with four, eight, and sixteen channels, operating at nominal spans of 80, 120, and 160 km, at speeds up to STM-16 (~2.5 Gbps). A frequency grid anchored at 193.1 THz with channel spacings of 50 and 100 GHz was established for central frequency selection. The 193.1 THz network reference frequency was chosen partly to avoid favoring an absolute frequency reference (AFR) based on any particular material, especially as the recommendation explicitly indicated at the time that AFR parameters were still under study. [1, p. 18]. The channel spacing was predetermined to be an integer multiple of 25 GHz, considering factors such as the EDFA amplification spectrum and capacity. The goal was to leverage the technology optimally without imposing constraints for specific applications while accounting for technological limitations. Based on these considerations, the minimal channel spacing initially discussed was 125 GHz and 150 GHz, but ultimately, channel spacings of 100 GHz and 50 GHz were included in the recommendation, providing adequate flexibility to meet application requirements outlined in G.692.

The standard specifies nominal center frequencies between 192.1 THz and 196.1 THz, noting that frequencies beyond these limits might be utilized due to future development of multi-channel systems [1, p. 16].

Recommendation G.694.1 (06/2002) [3] specifically addresses the DWDM frequency grid, reducing the previously defined minimum spacing of 25 GHz by half. Thus, nominal center frequencies are defined with allowable spacings of 12.5 GHz, 25 GHz, 50 GHz, 100 GHz, or integer multiples thereof, still anchored at 193.1 THz. The recommendation references the C and L wavelength ranges [3, p. 2], and consequently, the listed channel center frequencies fall within the 1530 to 1625 nm range.

The 2012 amendment of the recommendation introduced *flexible channel allocation*. Practically, it allows any slot whose nominal center frequency in THz is given by the formula

$$\lambda_k = 193.1 + n \times 0.00625 \qquad (1)$$

where n is an integer. The slot width adheres to the previously established relationship of

$$12.5 \times m, \qquad (2)$$

where m is a positive integer. This amendment offers significant freedom in channel usage but also presents challenges to manufacturers aiming to create interoperable solutions with other vendors.

C. Channel Numbering

Recommendations deliberately avoid providing guidance for simplified DWDM channel labeling; they use nominal center frequency and fixed channel spacing for identification in fixed allocation mode, or slot width in flexible mode. In everyday practice, a shorter labeling system emerged as a convenience, adopted by various forums and vendors. Since recommendations tie channels to frequencies, and channel widths expressed in wavelengths differ despite identical frequency widths, numbering tied to frequency is practical.

One common notation uses the middle two digits of the six-digit nominal center frequency expressed in GHz. For example, the channel at 190100 GHz is labeled as channel 1, and the base channel at 193100 GHz is labeled as channel 31. In a 50 GHz grid, intermediate channels are denoted by fractional numbers; for example, the 193150 GHz channel is labeled 31.5.

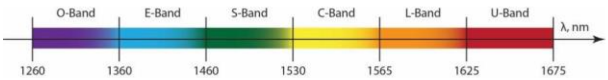

FIGURE 2 - Division of the wavelength range — Original; Extended; Short wavelengths; Conventional („erbium window"); Long wavelengths; Ultralong wavelength

Initially, recommendations designated the C-band (Figure 2) for DWDM, making labeling straightforward at first. The C-band includes 44 channels at 100 GHz spacing numbered from 16 to 59 and 87 channels at 50 GHz spacing numbered from 16.0 to 59.0, though descriptions found on the internet often differ, loosely defining wavelength band boundaries.

Some channels at the band boundaries extend into adjacent bands. For instance, with a 100 GHz grid spacing, 11% of channel 16 overlaps into the L-band, while 7% of channel 59 extends into the S-band. Similarly, with a 50 GHz grid spacing, channel 16 is entirely within the C-band, whereas 28% of channel 15.5 extends into the C-band, categorizing it within the L-band. Channel 59 remains fully in the C-band, but 35.6% of channel 59.5 is within the C-band, making it more suitable for the S-band.

G.694.1 recommendation anticipates future usage by dividing the L-band as well. However, previous numbering logic cannot be directly applied here. For instance, the 190000 GHz channel is labeled zero, 189900 GHz is channel 99, but the 187300 GHz channel cannot be labeled 73, as the 197300 GHz channel already uses this designation.

For 100 GHz and 50 GHz grid spacing, Nokia resolves this numbering issue by using the middle four digits for identification. The 193100 GHz reference frequency channel is labeled as 9310, 193150 GHz as 9315, and consequently, the L-band 184500 GHz channel could be labeled as 8450.

Some manufacturers created unique numbering schemes, differing from those mentioned above. For example, according to [4], the 191700 GHz channel is labeled as channel 19. Given that manufacturers label optical interfaces tuned to fixed frequencies by channel numbers, checking compatibility with corresponding frequencies is advisable.

The j2sw blog surprisingly reverses channel numbering, assigning numbers in ascending wavelength order [5]. The last C-band channel (previously 59, at 195900 GHz) becomes channel 17, progressing through the C and L bands up to the U-band channel with wavelength 1625.55 nm (184425.25 GHz) labeled as channel 143. The initial value (17) is scientifically unexplained, and the channel numbers cannot be directly derived from nominal center frequencies or corresponding wavelengths. However, this approach at least avoids negative channel numbers in the L-band.

Flexible channel allocations and the use of 25 GHz or 12.5 GHz channel widths further complicate numbering, making such attempts impractical. In these cases, it is advisable to reference nominal center frequencies directly.

D. Necessity for Development

Development is driven by several key factors [8]:

- Bandwidth Exhaustion: With widely used fixed channel spacing and low-bandwidth services occupying a single channel, optical fibers are utilized inefficiently. Older transponder cards often transfer only 10 Gbps of traffic over a 50 GHz DWDM channel. There is increasing demand for higher capacity on existing dark fibers, achieved economically and efficiently.
- Network Rigidity: Current networks employ fixed grid spacing, making them inflexible and incapable of adapting to dynamic capacity patterns. Flexible and scalable solutions with alternative frequency usage are essential.
- Security Threats: Optical fibers can be tapped in less protected areas, typically near distribution nodes or splicing points where cables are vulnerable. An attacker can expose and gently bend the fiber until light leaks from the core and cladding without significantly affecting active connection quality. Specialized tapping devices equipped with optical detectors can extract data without noticeable disruption by diverting as little as 1% of the transmitted light. Due to the increasing risk of data interception and breaches, there is growing demand for Layer 1 encryption [6].

E. *Challenges in Increasing Transport Capacity*

Primarily, applications drive the ever-growing demand for bandwidth, with artificial intelligence (AI) currently standing out. AI requires substantial data flows between data centers, positioning this application as a significant driver for technological progress.

Optimal upgrades minimize changes to existing infrastructure, ideally requiring no modification to fundamental elements such as optical cables and reconfigurable optical add/drop multiplexers (ROADM).

Energy consumption in data centers is considerable, and new equipment continuously demands rack space. Thus, after migration, the expectation is for equipment to occupy less rack space and use less energy per bit than before migration.

Manufacturers also face the challenge of maintaining lower per-bit costs than competitors. Additionally, their service responsiveness to market demands must be faster in order to remain competitive [8].

F. *Development of Fiber Capacity*

The evolution of fiber capacity relates directly to spectral efficiency. In 2002, typically 1 Gbps services were transponded to a single fiber, resulting in total fiber capacities below 100 Gbps. With the adoption of 400 Gbps optical interfaces, this capacity has risen to 25.2 Tbps. The development trajectory is illustrated in Figure 3. With the introduction of 800 Gbps interfaces and the extension into the L-band, total fiber capacity is projected to reach 51.2 Tbps by 2027 [8].

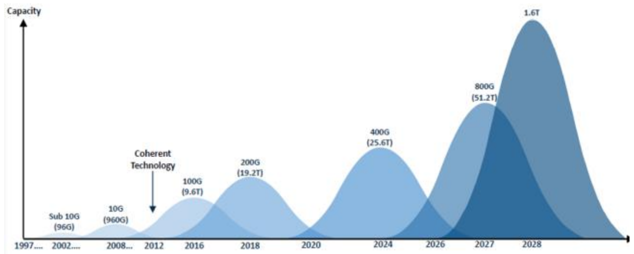

FIGURE 3 - Timeline of fiber/wavelength capacity. Each curve shows the typical bandwidth of the service transponded per channel, with the total capacity of the dark fiber in brackets below.

In the last decade, coherent optics technology has expanded beyond initial long-haul applications. Officially introduced into service provider networks in 2010, coherent optics have since firmly integrated into metro networks [7].

The evolution of fiber capacity is also evident in PacketLight's product development [8] (see Figure 4). In 2007, achieving an 800 Gbps throughput required 10 devices (10U), each transponding 10 Gbps services across 80 channels, maximizing available dark fiber capacity at the time. By 2012, with 100 Gbps modules, the same capacity needed only 8 wavelengths and 8 devices (8U). With the advent of 800 Gbps optics, just a single rack unit (1U) device can handle 10 × 800 Gbps transmissions. This progress results in substantial rack-space savings, significantly fewer lasers and optics, improved energy efficiency, and simplified operational management due to fewer wavelengths.

G. *Flex Grid*

DWDM channels were originally designated within the C-band and divided into fixed-width channels typically of 50 or 100 GHz. Manufacturers developed equipment supporting 80,

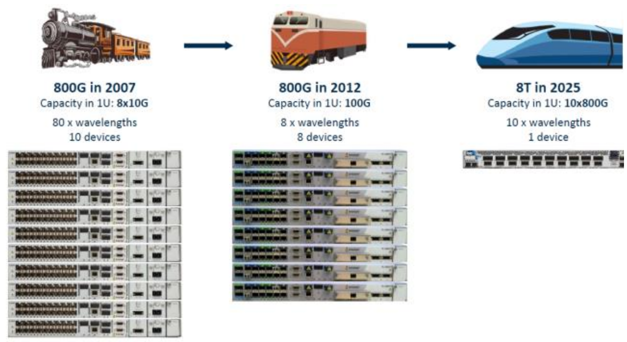

FIGURE 4 – Evolution of Fiber Capacity

88, or 96 channels at 50 GHz width or 48 channels at 100 GHz width (noting some channels overlap adjacent bands, as discussed in Section C).

Flexible channel allocation allows defining channels of varying widths within the optical spectrum according to requirements. As previously mentioned, the recommendation has permitted this flexibility since 2012. This is the specific capability, that enables efficient transmission of 100, 400, and 800 Gbps services and optimal utilization of the optics.

Implementing flexible channel widths requires upgrading existing infrastructure as follows [8]:

- Passive mux/demux devices and ROADMs must support variable-width spectrum slices.
- Network management systems must be redesigned.
- Tunable coherent DWDM optical modules capable of flex grid operation are required.
- Solutions for establishing protection paths in environments utilizing variable-width spectrum slices must be developed.

A 100 or 200 Gbps service comfortably fits within a 50 GHz wide channel, while a 400 Gbps service requires a 100 GHz wide channel, although current technology uses only three-quarters of this bandwidth (75 GHz). An 800 Gbps service thus requires a 150 GHz wide channel. These last two channel spacings are supported by recommendations, but their industrial implementation has not been common.

Figure 5 illustrates how using fixed channel spacings leads to significant waste of dark fiber capacity when transmitting services of different speeds simultaneously. In contrast, variable grid spacing allows these services to be efficiently packed together [8].

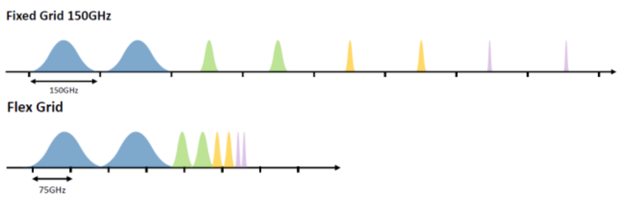

FIGURE 5 - Spectrum use for fixed and flexible grid spacing

If a network is prepared to support flex grid, later introduction of 1.6 Tbps optics will not require further infrastructure changes; these new services will coexist efficiently alongside 400 and 800 Gbps services.

H. Opening Up the L-Band

Another way to increase the bandwidth transmitted through optical fiber is by opening up additional frequency bands. DWDM technology currently uses primarily the C-band, due to optimal optical performance in this range, including lowest cable attenuation and lower OSNR, thereby reducing the number of required amplifiers [8].

The recommendation defines 48 channels of 100 GHz width in the C-band. With a fixed 75 GHz grid spacing, 64 channels could be used to transmit 64 services of 400 Gbps each, resulting in a total capacity of 25.6 Tbps (see Figure 6). The introduction of 800 Gbps optical interfaces does not increase dark fiber capacity, as 800 Gbps transmission requires double-wide (150 GHz) channels, indicating that the C-band has reached its capacity limit. The switch from 400 Gbps to 800 Gbps optics thus reduces the number of required channels and transceivers, enabling more compact equipment designs but not increasing total dark fiber capacity.

Utilizing the L-band unlocks additional optical spectrum in the fiber, effectively doubling the fiber's capacity.

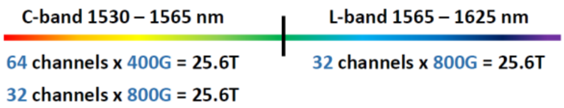

FIGURE 6 – Capacity of C and L bands

However, incorporating the L-band introduces several challenges [8]:

- Current systems must be upgraded to support L-band usage (ROADM, EDFA, multiplexer, optical transceivers).
- Optical limitations arising from simultaneous use of C and L bands must be overcome.
- Development of 800 Gbps optical modules that support the L-band is necessary.

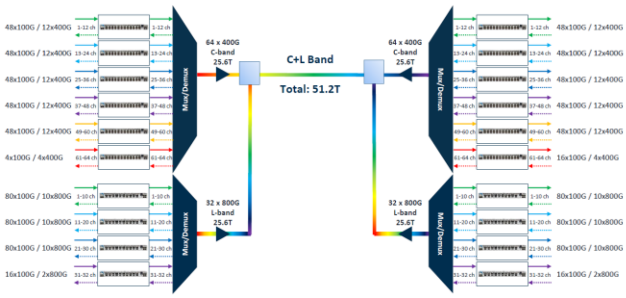

FIGURE 7 – L-band ecosystem

The simplified combined usage of C and L bands is illustrated in Figure 7. It shows that existing systems operating in the C-band can be expanded using C/L splitters along with equipment specifically designed for the L-band.

III. PACKETLIGHT NETWORKS

Founded in 2000, PacketLight Networks develops and manufactures DWDM and OTN devices for transporting data, storage, voice, and video services across fiber optic networks of varying purposes and distances.

A. PacketLight Devices Designed for 800 Gbps Transceivers

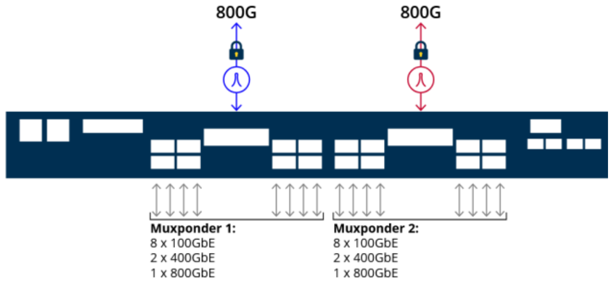

FIGURE 8 - PL-8000M Muxponder

PacketLight develops high-density, low-power DWDM equipment utilizing optical transceivers with MSA compliance. One of their latest products, the PL-8000M (Figure 8), is a 2 × 800 Gbps muxponder capable of multiplexing and transponding up to eight services per 800 Gbps DWDM channel, depending on bandwidth requirements. [9]

FIGURE 9 - PacketLight 10 × 800 Gpbs-os transzponder

At the time of writing this paper, their latest product—a 10 × 800 Gbps transponder (Figure 9)—was not yet commercially available [8]. Figure 7 illustrates how multiplexing the line outputs of such 8 Tbps devices can maximize dark fiber capacity.

B. Layer 1 Encryption

The necessity of Layer 1 encryption was discussed in Section II.D. PacketLight's solution transparently encrypts either all traffic transmitted through the fiber or only selected services, with low latency while maintaining full bandwidth. It also monitors connection performance, thereby detecting and alerting potential eavesdropping attempts (see Figure 10). [8]

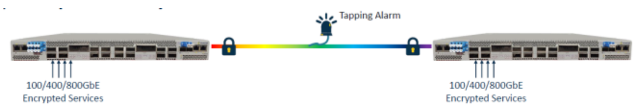

FIGURE 10 - PacketLight 1

Layer 1 encryption is a built-in capability of most PacketLight devices, activated through an appropriate licence. Technical specifications include:

- GCM-AES-256
- Diffie-Hellman key exchange
- SHA-384 authentication
- Quantum Key Distribution (QKD) support (previously discussed in another RelNet article). [10]

C. Redundancy

PacketLight devices provide several redundancy solutions [8]:

- Full hardware redundancy (Figure 11): Data is transmitted across two separate dark fiber paths, each terminated by dedicated hardware elements, offering protection against single points of failure.

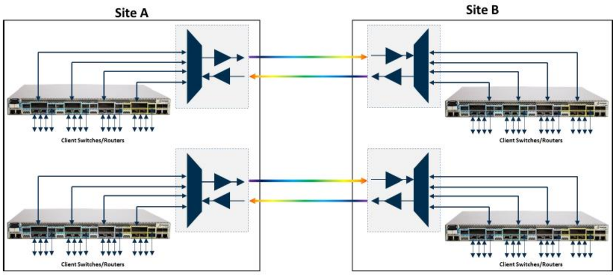

FIGURE 11 – Full hardware redundancy

- Optical path protection (Figure 12): Given that optical fiber failures are more common than DWDM hardware failures, this solution uses optical switches (OSW) to duplicate signals onto two fiber paths (working and protecting paths). The DWDM device detects fiber failures and switches to the backup path within 50 ms. This approach is significantly more cost-effective than full hardware redundancy and offers sufficient reliability for many use cases.

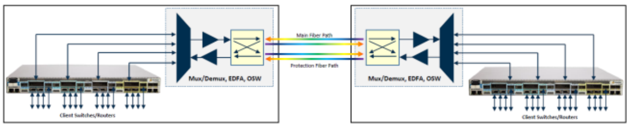

FIGURE 12 – Fiber path protection

IV. Summary

As a result of the exponential development of optical transceivers, we can now design systems with 400 and 800 Gbps modules. Effective transmission of these high-speed services requires adjustments to existing recommendations to ensure compatibility between various vendors and products. This has led to the definition of flexible spectrum usage and the opening of the L frequency band for DWDM applications. Reliable data transmission over optical networks necessitates Layer 1 encryption and appropriate redundancy solutions.

Abbreviations

DWDM – Dense Wavelength Division Multiplexing
GBIC – Gigabit Interface Converter
SFP – Small Form-factor Pluggable
XFP – 10 Gigabit Small Form-factor Pluggable
QSFP – Quad Small Form-factor Pluggable
CFP – C Form-factor Pluggable
AFR – Absolute Frequency Reference
EDFA – Erbium-Doped Fiber Amplifier
ROADM – Reconfigurable Optical Add-Drop Multiplexer
OSNR – Optical Signal-to-Noise Ratio
MSA – Multi-Source Agreement
QKD – Quantum Key Distribution
OSW – Optical switch

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