Tactics for Deploying C-L CDC-F DWDM Systems

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1. Introduction

Since the COVID-19 crisis, the demand for broadband communication services has soared, with some providers experiencing as much as 30-50% increase in internet traffic. Network operators are searching for economical ways to increase capacity to keep pace with the demand of data-intensive services.

With Optical transmission systems growing exponentially every year, and operating close to the theoretical Shannon's limit, we often get challenged about what is next for scaling optical transmission.

In the recent years, from the traditional C- band (80 wavelengths with 50 GHz channel spacing) to the extended C- band (96 wavelengths with 50 GHz channel spacing) and then to the Super C- band (120 wavelengths with 50 GHz channel spacing), the industry has continuously expanded the scope of the C-band spectrum, improving the transmission capacity.

With the continuous growth of bandwidth intensive applications such as IP Video,4K streaming, cloud computing, gaming, AR & VR,5G, our network gets pushed to a limit where we cannot sustain further growth and bandwidth demands without deploying a new architecture with flexgrid capability, due to the shift to 100G & beyond. Clearly, Rogers had every reason to move past the legacy C-band only fixed grid optical networks. We understood that the optical spectrum needs to be expanded to C+L band. Expanding network deployment to the L-band is a cost-effective approach to enable operators to reduce operational expenditure (OPEX) for dark fiber/IRU leases.

Optical fiber deployment is slow and optical fiber resources are precious. The most effective way to address yearly network traffic growth is to reuse existing optical fiber resources and expand the spectrum of optical fibers to increase the single-fiber capacity.

Submarine cables too, carrying over 99% of international data traffic, are nearing its capacity limits. Operators are adopting advanced coherent optical transmission and L-band technology to boost data throughput without laying new cables, optimizing existing infrastructure to meet growing internet demands. This innovation is crucial for sustaining global connectivity.

This paper presents a discussion on the business drivers, technical strategy, challenges, and opportunities for C-L Colorless, Directionless, Contentionless-Flex Grid (CDC-F) Dense Wave Division Multiplexing (DWDM) system deployment at Rogers Cable. Finally, we compare C & C-L systems, and proving how the latter can increase the total system capacity on a deployed fiber.

2. What Next When C-Band Reaches its Limits?

The foundational layer of any high-capacity optical network is the photonic layer, which enables the efficient illumination of fiber by managing and directing wavelengths throughout the optical spectrum. Historically, Wavelength Division Multiplexing (WDM) systems have employed the C-band frequency range for the transmission of WDM wavelengths. Spanning roughly from 196.10 to 191.3 THz, which corresponds to wavelengths between 1530nm and 1565nm, the C-band offers a broad spectrum of 4800 Hz. Its widespread adoption can be attributed to the minimal fiber attenuation and the efficient performance of Erbium Doped Fiber Amplifiers (EDFA) within this range.

To meet the growing demands for bandwidth, operators have attempted to narrow the channel spacing and deploy higher-speed wavelengths within the C-band as shown in Figure 1. However, these efforts are constrained by the Shannon limit, which dictates the maximum capacity of the fiber.

Shannon's theorem sets a fundamental limit on the maximum achievable data rate over an optical channel.

The theorem states:

Channel Capacity (C) = B * log2(1 + S/N)

Where:

- C is the channel capacity in bits per second
- B is the bandwidth of the channel in Hz
- S is the average signal power in watts
- N is the average noise power in watts
- S/N is the signal-to-noise ratio (SNR)

By understanding Shannon's theory, optical network designers can optimize system parameters to maximize data rate and minimize errors, ensuring reliable and efficient data transmission over optical networks.

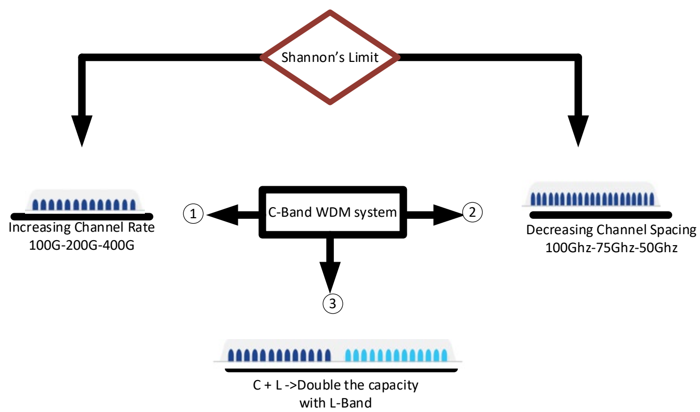


Figure 1 - Network capacity and spacing option.

In the past decade, the field of coherent digital signal processors (DSPs) and optical technology has seen significant progress, leading to substantial increase in capacity while simultaneously decreasing the cost per gigabit. For instance, the latest generation of coherent DSPs offers various baud rates, modulation schemes, and robust forward error correction (FEC), maximizing wavelength capacity across all distances, from urban networks to trans-oceanic cables. These advancements are complemented by Coherent-optimized Colorless Directionless Contentionless – Flex grid (CDC-F) Reconfigurable Optical Add-Drop Multiplexers (ROADMs), which adapt to the 200G–800G wavelength modes necessitated by these DSPs, accommodating new channel spacings such as 75 GHz, 87.5 GHz,112.5Ghz and beyond.

Yet, as modern transponders approach the Shannon limit, the potential for further enhancements in capacity and spectral efficiency within the C-band is becoming increasingly constrained.

Therefore, network operators seeking to expand their system's capacity can deploy WDM systems that incorporate L-Band capabilities alongside their existing C-band infrastructure, thus effectively doubling the network's throughput without the need for laying additional fiber. Various Optics bands and wavelength ranges are shown in Table 1.

Table 1 - Optical transmission frequency/wavelength ranges

Fiber Optics Band	Description	Wavelength Range in nm
O Band	Original	1260-1360
E Band	Extended	1360-1460
S Band	Short	1460-1530
C Band	Conventional	1530-1565
L Band	Long	1565-1625
U Band	Ultralong	1625-1675

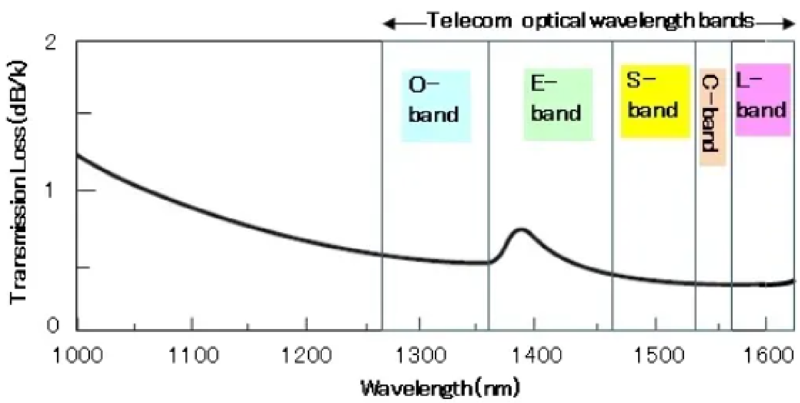


Figure 2 - Optical Communication wavelength bands and transmission loss.

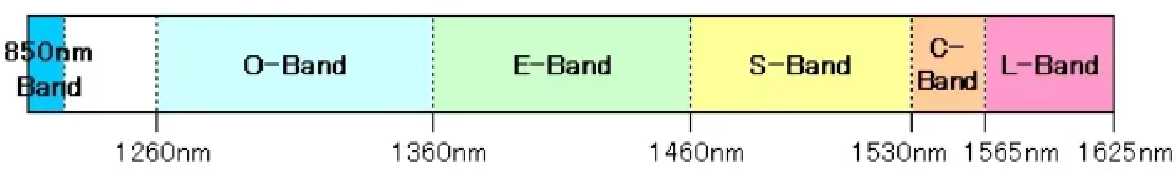


Figure 3 - Electromagnetic Spectrum and Optical communication wavelength.

2.1. The L-Band :1565-1625nm

The telecommunication industry is facing challenges with high-capacity routes where traditional methods are proving insufficient. To address this, the industry has turned to the L-band, an adjacent optical spectrum ranging from 1565nm to 1625nm, to enhance line capacity.

The L-band, or long wavelength band, is a segment of the electromagnetic spectrum that lies adjacent to the C-band, traditionally utilized to enhance the capacity of terrestrial DWDM networks. It is the second lowest-loss wavelength band.

The push towards adopting L-band technology is primarily driven by the ever-increasing demand for network traffic capacity. For network operators to consider the deployment of L-band solutions, these solutions must be straightforward to plan and implement. By leveraging the L-band, operators can effectively double the available optical spectrum as shown in Figure 4.

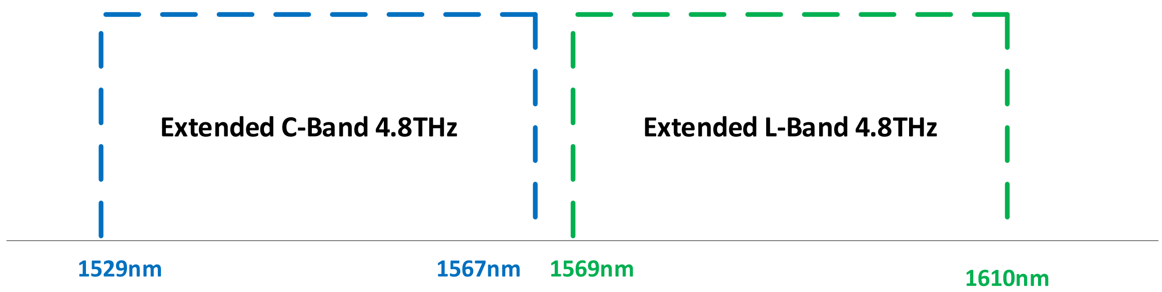


Figure 4 - Spectrum doubled to 9.6Thz with C+L-band.

When a network's existing capacity is maxed out due to continuous bandwidth growth, the next step is typically to light up additional fiber pairs. However, if the costs associated with deploying new fiber or leasing existing ones are exorbitant, network operators must look for alternative methods to unlock further capacity.

Additionally, it's crucial that the transition to L-band does not interfere with the existing C-band traffic. Both the C and L-bands are situated at the point of minimum attenuation in silica-based optical fibers, which coincides with the operational range of EDFAs. To effectively cover both the bands, networks require the installation of two distinct types of EDFAs at the amplifier sites as shown in Figure 5 below.

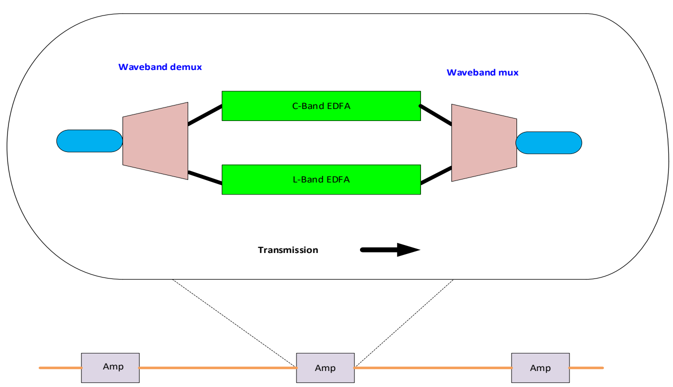


Figure 5 - C+L Band EDFA Configuration.

When a fiber optic cable transmits data using both C-band and L-band wavelengths, it's necessary to amplify them simultaneously. This is because an amplifier designed for C-band wavelengths would cause significant signal loss for L-band wavelengths, and the reverse is also true. Therefore, at each amplification point, the different wavelengths are separated, each is amplified on its own, and then they are combined again.

Additionally, as the wavelength of light increases, the optical fiber becomes increasingly susceptible to losses caused by bending. This sensitivity necessitates more meticulous installation practices to ensure that the fiber is not bent beyond its specified limits, which could lead to signal degradation.

2.1.1. L-Band Expansion to Submarine Cables

Submarine cables, the less visible yet vital components of global internet infrastructure, carry over 99% of international data traffic. As the demand for internet capacity continues to surge, these cables are nearing their capacity limits, posing a significant challenge for operators who are reluctant to lay new cables due to high costs and practical limitations. A decade ago, the terrestrial fiber industry encountered a similar predicament when the prevailing On-Off-Keying technology could no longer keep up with the growing bandwidth demands spurred by video streaming and other data-heavy applications. This led to a pressing need for innovation to enhance the existing fiber infrastructure without extensive physical expansion.

In response to this challenge, the industry shifted towards more advanced coherent optical transmission technology, which allowed for a significant increase in data throughput over the same fiber. Today, submarine cable operators are considering similar technological upgrades to boost the capacity of their underwater cables. This approach aims to optimize the use of existing infrastructure to meet the world's insatiable appetite for data, thereby avoiding the substantial costs and logistical complexities associated with deploying additional submarine cables. The evolution of these technologies underscores the continuous effort to push the boundaries of data transmission and the importance of innovation in sustaining the growth of global connectivity.

This shift is particularly evident in submarine communications, where L-band technology is being adopted to improve network capabilities beneath the oceans.

2.1.2. L-Band Limitations

Deploying L-band networks, however, incurs additional costs due to two main factors: higher fiber attenuation leading to increased power requirements and costs, and the lower production volume of L-band components compared to C-band components, which benefits from economies of scale. Despite these costs, the operational expenditure (OPEX) savings from using dark fiber leases or Indefeasible Rights of Use (IRUs) make L-band deployment a cost-effective solution for network operators looking to expand their capacity.

3. Optical Amplifiers

Modern variable gain amplifier modules with good noise figures and sufficient output powers are typically based on multiple gain stages. The pump lasers provide energy to the coils of erbium doped fiber that enable the optical amplification process, while the gain flattening filter (GFF) ensures a flat gain response over the entire operating region, compensating both the 1st and 2nd stage amplifiers. Optical amplifiers also generate some unwanted “optical noise”, along with amplifying the desired wavelengths. The amplifier noise accumulates with each ROADM and In Line Amplifier (ILA) node, decreasing the optical signal to noise ratio (OSNR) as the signal travels over longer and longer distances. Eventually, it’s the decrease in OSNR that limits a wavelength’s capacity and reach.

3.1. Erbium -Doped Fiber Amplifiers (EDFA) and Raman Amplifiers

An Erbium-Doped Fiber Amplifier (EDFA) consists of a coil of erbium-doped fiber, a coupler, and a pump laser. The role of the pump laser is to energize the incoming signals, while the erbium-doped fiber coil facilitates the transfer of this energy to the signal wavelengths. However, the inherent gain response of erbium-doped fiber coils is not perfectly uniform, leading to significant fluctuations in the gain profile. The ideal scenario for amplifiers is to maintain a consistent gain response throughout the entire range of operation.

Figure- 6 shows a typical EDFA amplifier in both C and L-band.
Table -2 shows the Gain Vs wavelength response of a typical EDFA amplifier.
Table -3 shows the Gain Flattening Filter C-Band.

Contemporary variable gain amplifier modules, known for their favorable noise figures and adequate output power, generally employ multiple amplification stages. These stages are energized by pump lasers that charge the erbium-doped fiber coils, which in turn, carry out the optical amplification. A Gain Flattening Filter (GFF) is utilized to achieve a uniform gain response across the operational spectrum, balancing the amplification across both the first and second stages. It's important to note that optical amplifiers inadvertently produce some "optical noise" while boosting the desired signal wavelengths. This noise tends to accumulate through each Reconfigurable Optical Add-Drop Multiplexer (ROADM) and In Line Amplifier (ILA) node, progressively reducing the Optical Signal-to-Noise Ratio (OSNR). Over extensive distances, this reduction in OSNR becomes the limiting factor for the signal's capacity and reach.

Amplification in optical networks often involves a combination of Erbium-Doped Fiber Amplifiers (EDFA) and Raman amplifiers, creating a hybrid system that enhances signal-to-noise ratio (SNR) due to the latter's superior noise figure.

A Raman amplifier is typically costlier, has better gain and lower noise figure compared to an EDFA amplifier, leading to higher OSNR. Raman amplifiers use the transmission fiber as the gain medium, while EDFA amplifiers use erbium-doped fiber as the gain medium.

This hybrid approach is prevalent, with companies like Rogers integrating Raman Amplifiers into nearly all long-haul routes with span losses exceeding 17dB. For uniform gain across both C and L bands, maintaining less than dB variation, configurations employing over five Raman pumps are utilized, please see Figure 7. Accurate modeling of the Raman amplification process is crucial during network planning, encompassing gain and noise figure specifications, to ensure the efficient design and operation of multi-band transmission systems.

Raman amplifiers offer several advantages in long-haul DWDM networks, such as distributed amplification, which uses the transmission fiber itself as the amplification medium, resulting in a lower noise figure and reduced nonlinear penalties due to lower launch power compared to Erbium-Doped Fiber Amplifiers (EDFA). This can lead to a 5-7dB improvement in Optical Signal-to-Noise Ratio (OSNR) over EDFA. However, there are also disadvantages to consider, such as the potential for higher costs and the need for complex engineering design.

Raman amplifiers can extend the reach of DWDM networks by reducing the number of required regenerations, but they may not always perform better than other amplifiers in all scenarios.

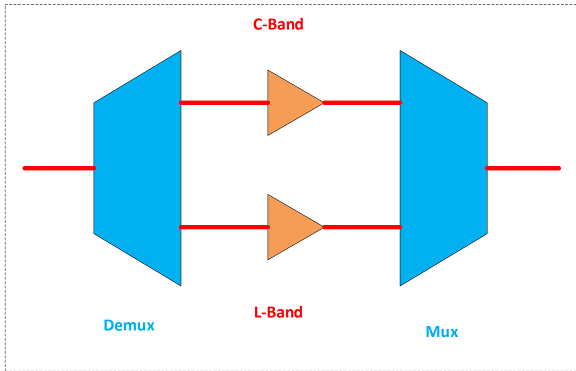


Figure 6 - Amplification options for C+L Band systems.

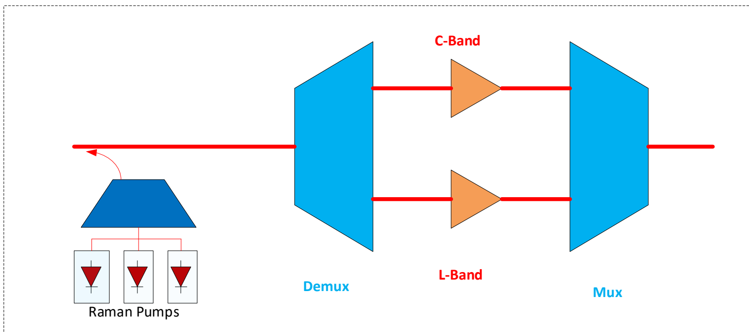


Figure 7- Hybrid EDFA/Raman with multi-pump Raman amplifiers.

Table 2 - Gain Vs Wavelength response of an EDFA Amplifier.

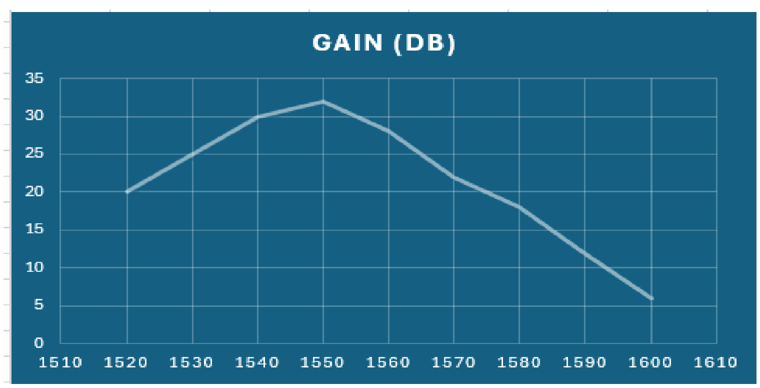
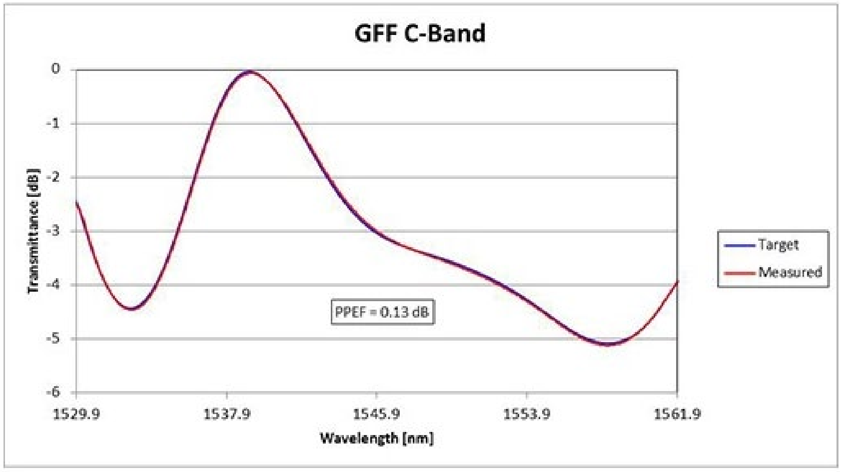


Table 3 - Gain Flattening Filter C-Band



4. Upgrading Network Infrastructure in a Flexible Way

There are multiple incentives for implementing C+L systems. The introduction of C+L band photonic line systems has allowed service providers to enhance their network's capacity twofold without surpassing the fiber capacity of their existing infrastructure. This approach has minimized or postponed substantial capital expenditures associated with fiber expansion, while also introducing new business models that leverage the increased spectral capacity. Additionally, it facilitates the provision of 400G services and higher, utilizing advanced baud rates and various modulation techniques.

A primary feature of C+L-band WDM systems is their ability to enhance network capabilities in a cost-efficient manner. These systems facilitate the integration of the L-band into pre-existing C-band networks, offering modular and adaptable upgrade paths that promote broader industry acceptance (C minus L system).

Operators often implement their C-band WDM systems, with independent C-band procedures. However, with the advent of C+L-band WDM systems, it becomes possible to incorporate L-band modules into current ROADM and ILA sites after the C-band capacity is maximized. This addition of L-band components occurs on an as-needed basis, eliminating hefty upfront costs and supporting a scalable upgrade model. Please see Option 1 of Figure 8.

For ILA sites, there are two strategies: operators may opt to install C+L ILA initially, which precludes the need for subsequent remote site visits and thus lowers operational expenses. When the need for L-Band capacity arises, operators can simply enhance their ROADM sites with the necessary L-Band components, ensuring uninterrupted service, as shown in Option 2 of Figure 8.

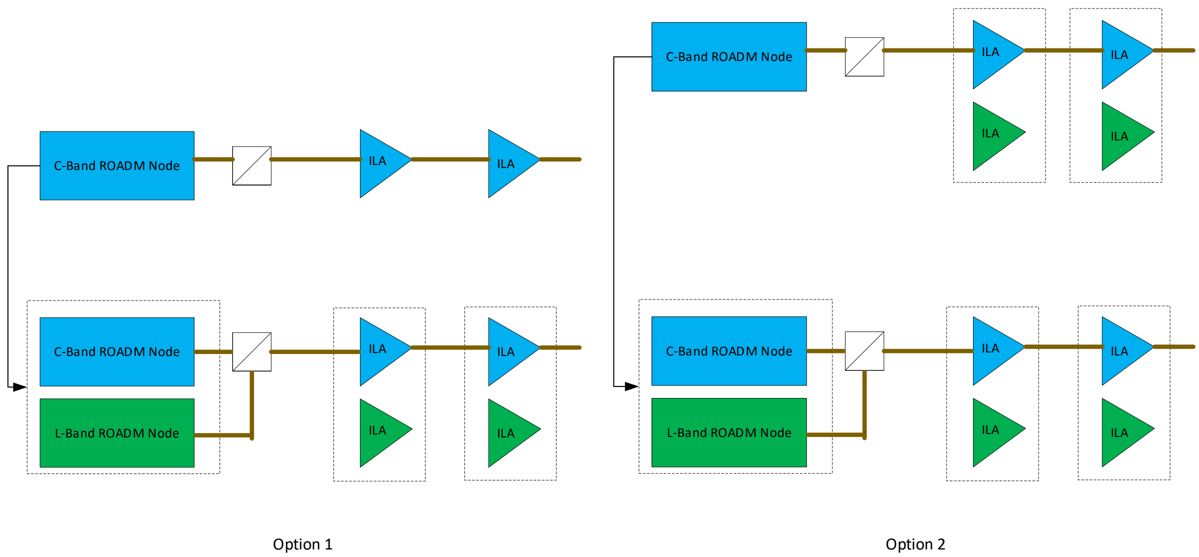


Figure 8 -Two options to upgrade ILA sites with C+L

Although the incorporation of additional optical components, such as splitters and couplers, are necessary to manage C and L band channels, a significant degree of integration of C and L band elements can be realized within the chassis. This integration enables the consolidation of multiple system functions, including controllers and monitoring systems, into a unified platform.

Consequently, we at Rogers decided to get ahead of the challenge by deploying optical networks that can provide maximum efficiency, higher performance, and better network reliability with C-L(C minus L) /CDC-F architecture. We deployed a network with C-band capability, along with a C+L combiner/splitter (that hosts the C and L– band filters) on day one, to enable us with an in-service upgrade to L-Band later.

5. Colorless – Directionless- Contentionless with Flex Grid (CDC-F) Systems

Colorless-Directionless-Contentionless with Flexible grid (CDC-F) Dense Wavelength Division Multiplexing (DWDM) systems represent a significant evolution in optical networking. These systems offer unprecedented flexibility and efficiency, enabling network operators to maximize the capacity of optical fiber.

CDC-F DWDM systems allow any wavelength to be added or dropped from any port without the need for manual reconfiguration, thus reducing operational expenses and improving service agility.

With CDC-F, network operators can remotely reconfigure wavelengths without the need for on-site visits, thanks to the **Colorless** feature that allows any wavelength to be added or dropped from any port. The **Directionless** capability facilitates the routing of wavelengths across any path in the network, enhancing network resiliency and simplifying operations. Moreover, the **Contentionless** feature ensures that multiple signals can share the same wavelength path without interference, optimizing network performance. Please see Figure 9 below.

The adoption of CDC-F DWDM systems is driven by the increasing demand for bandwidth and the need for more dynamic and resilient optical networks. As the volume of data traffic continues to grow, CDC-F DWDM systems provide a scalable solution to meet the future needs of data transmission.

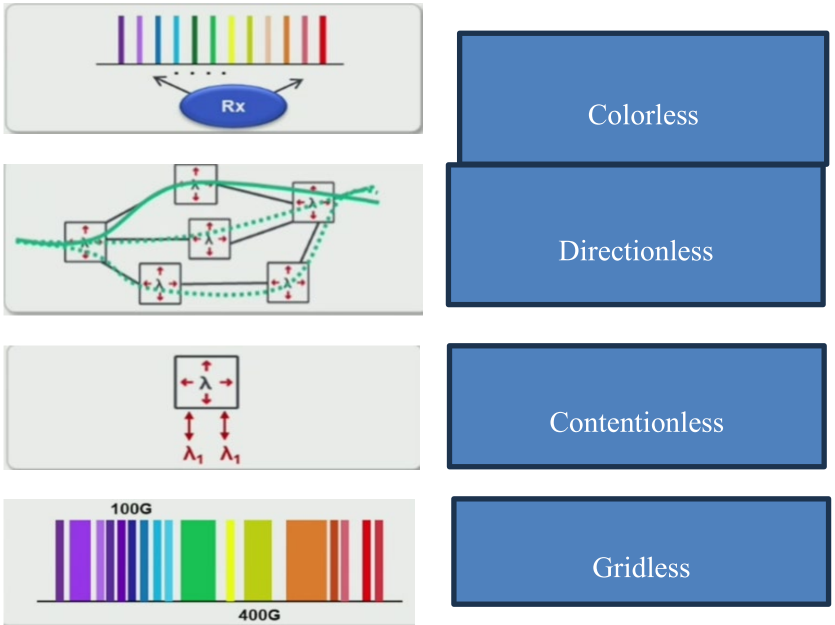


Figure 9 - CDC- Flex grid.

6. Criteria for deplying C-L/CDC-F DWDM architecture in Rogers

As optical engine spectral efficiency approaches the Shannon limit and spectral efficiency gains become harder to achieve, increasing a fiber's total capacity by utilizing C+L spectrum can provide a practical and cost-effective option for network operators.

In Rogers, C-L line systems will be deployed on main long-haul routes with high bandwidth requirements and anticipated high future growth rate.

Some key determining factors are:

- Availability of extra fiber pairs in the existing Rogers fiber plant.
- Fiber availability and cost of laying new fibers or leasing dark fibers from 3rd party.
- Space and power availability in hub sites, especially in third party sites.
- C-band (1550nm) and L-band (1625nm) fiber characterization.

7. System Components of C-L / CDC-F DWDM Architecture

Following are the system components:

1. Photonic shelves
2. C+L Combiner splitter
3. Integrated ROADM
4. Raman Amplifier (5 pumps)
5. Mesh Fiber Shuffle
6. Amplifier Arrays

7. Multicast Switch
8. Integrated C +L Wideband ILA
9. Wideband OTDR
10. Muxponder Cards

7.1. Key Functions of Each Component

7.1.1. C and L Coupler Splitter

The C and L Coupler Splitter hosts the C and L-band filters and the OTDR module. It consists of two or more input ports and two or more output ports. It combines the signals from the C band (1530-1563 nm) and L band (1570-1613 nm) inputs and splits them into two output ports, one for each band. This allows for the efficient use of optical amplifiers and minimizes signal degradation. It allows for wavelength multiplexing, demultiplexing and optical power splitting.

7.1.2. Integrated ROADM(IROADM)

The main components in an IROADM are Wavelength Selective Switch (WSS), Multiplexer/Demultiplexer, Optical Channel Monitoring (OCM), Optical Supervisory Channel (OSC), OTDR ports.

7.1.3. Raman Amplifiers(5 pumps)

Raman amplifier with five pumps can provide gain over the entire C + L -band. It provides improved noise figure and OSNR, enhanced gain flatness, increased reach, reduced repeater spacing, support for higher channel counts and density, as well as better performance in long and ultra haul networks.

7.1.4. Mesh Fiber Shuffle

It is used for fiber management between the IROADMs and Amplifier Arrays, using MPO cables. It gives an insertion loss of 0.7db between the MPO ports.

7.1.5. Amplifier Arrays

These are an array of fixed gain amplifiers, used to provide add and drop amplification for the Multicast switch (MCS) add/drop blocks. This pack is connected between the Mesh fiber shuffle and MCS Card.

7.1.6. Multicast Switch(MCS)

The Multicast Switch (can be of different options: 8 - 16, 16 - 15 etc.) provides Contentionless add/drop functionality, each card supports 16 channels add/drop capability from up to 8 degrees (for MCS 8 -16). Any MCS add/drop port supports any channel frequency to any degree.

7.1.7. Wideband In-Line Amplifier

The Wideband ILA is used in the ILA Configuration of C + L- band system. The pack consists of two gain modules, one in the C-band and another in the L-band.

7.1.8. Wideband Optical Time Domain Reflectometer(OTDRWB)

OTDRWB is used to characterize a fiber span prior to turning on service, especially to see if it is suitable for Raman amplification, to determine the location of a fiber break, or to monitor the fiber while services are running. It is designed for C + L-band optical lines, and operates at 1625nm, beyond the L-band wavelength range. Figure 10 shows the basic building blocks of a C-L CDC-F DWDM network.

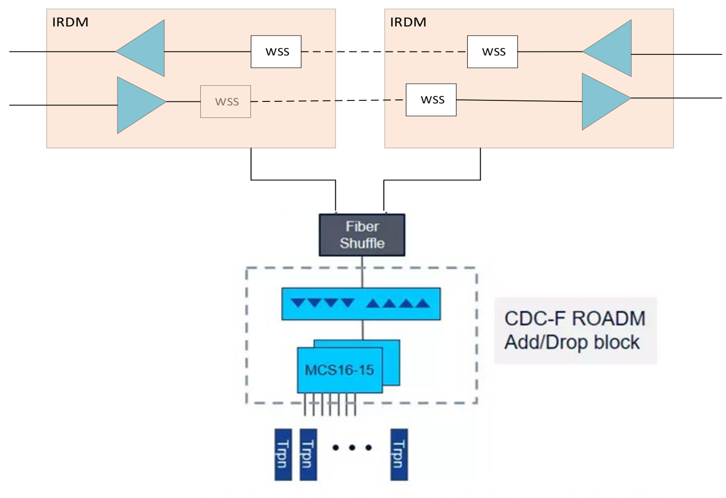


Figure 10 - C-L CDC-F DWDM Block Diagram.

8. Key Optical Technologies and Challenges on C+L Systems

In the C+L band expansion, the industry faces challenges in solutions such as wavelength adding or dropping control technology, wide-spectrum low-noise amplification, Stimulated Raman Scattering (SRS) in addition to linear effects (loss, chromatic and polarization mode dispersion).

8.1. Stimulated Raman Scattering (SRS):

Stimulated Raman Scattering (SRS) is a phenomenon in optical fibers wherein power transfers from shorter to longer wavelengths, leading to a spectrum-wide wavelength tilt. This can affect both C-band and C+L-band WDM systems. It involves the scattering of light within the fiber by silica's vibrational modes, which is notable at spectral frequencies around a few terahertz.

8.2. Low -noise amplification technology:

L-band EDFA has a higher noise figure and lower gain efficiency compared to C-band due to the weaker erbium absorption and emission coefficients at its wavelength. This results in lower gain, which is often offset by using longer EDF coils. However, L-band optical amplifiers (OAs) perform worse than C-band OAs. Wide spectrum low-noise amplification is crucial for C+L band expansion, and the Stimulated Raman Scattering (SRS) effect helps balance C and L band performance by transferring energy from C to L band.

8.3. Careful network planning & design:

It is a challenge during evolution from C-Band to C+L band in the future, if the network planning is not carefully considered in the early stage itself.

8.4. Spares management:

Separate C-band and L-band cards result in twice the number of cards and spares to manage and double the footprint at 3rd party locations where space is a premium.

9. Performance limiting issues on C+L WDM Networks

9.1. SRS Tilt management

In optical fiber communication, when signals of varying wavelengths are sent, the energy from signals with shorter wavelengths gets transferred to those with longer wavelengths, as shown in Figure 11. This energy shift is crucial for the system's entire lifespan because improper handling of signal add/drop can cause severe penalties to existing channels.

The C+L band not only increases the number of available wavelengths but also extends the bandwidth compared to the standard C band. This expansion leads to a more pronounced SRS effect, which particularly affects the power of shorter wavelengths, as shown in Figure 12. To counteract this, SRS control technology is employed within the C+L band spectrum expansion strategy, playing a pivotal role in maintaining system performance.

For single C-band systems, vendors counteract SRS tilt by enhancing the power of shorter wavelengths at each amplifier station, a process known as pre-emphasis. Amplifiers at each network node monitor and slightly adjust the power levels of shorter wavelengths to maintain flat wavelength spectrum across both the bands. As the network changes with the addition or removal of wavelengths, WDM systems dynamically adapt the SRS pre-emphasis. This dynamic, self-tuning SRS tilt management ensures that network operators do not have to manually address SRS tilt issues.

Thus, pre-emphasis and dynamic SRS tilt management in WDM systems are needed to achieve consistent power across all wavelengths.

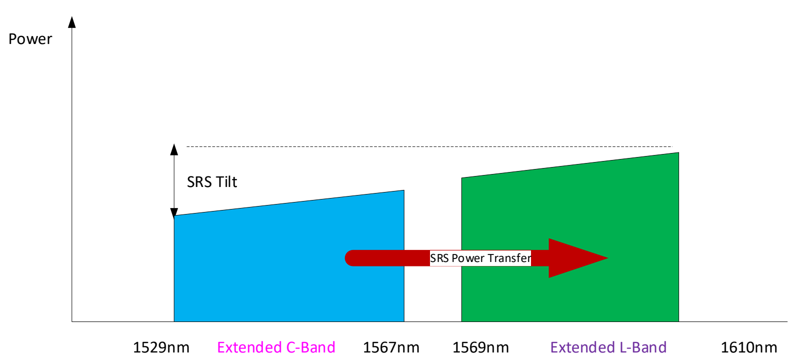


Figure 11 - Power shift from the C-Band to the L-Band due to the SRS effect.

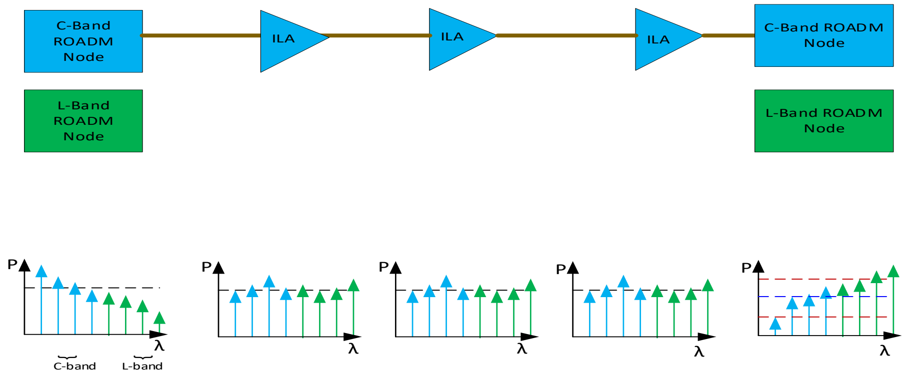


Figure 12 - Stimulated Ram Scattering (SRS)

9.1.1. Mitigate SRS effect.

Some vendors use a “Tilt profile” to adjust for SRS tilt, which is applied separately to C & L -Band amplifiers, each will have slightly different profile shapes, as shown in Figure 13. SRS tilt profiles are dynamically updated as channels are added or deleted and is dependent on the number of channels and fiber type.

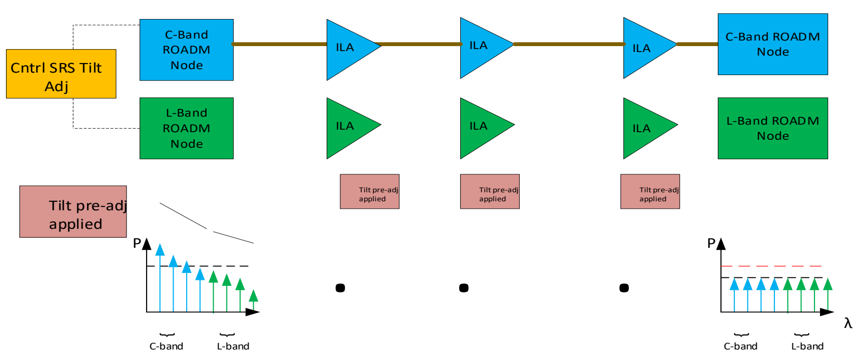


Figure 13 - Tilt profiles applied.

On noise loaded systems, SRS tilt compensation is still required, but the amount of tilt compensation remains constant. The SRS tilt compensation doesn’t vary, since Amplified Spontaneous Emission (ASE) noise loading fills all unused channels, simulating a fully loaded network. One issue of ASE noise loading on C+L WDM systems, especially as part of SRS compensation, is that it typically requires deployment of both C-band and L-band ASE noise sources as part of the initial deployment – even if a carrier initially only uses the C-band capacity. As a result, the initial network costs can be slightly higher when using ASE noise loading. In addition, if an ASE noise loading source fails there’s a risk of bit errors or traffic outages, unless the WDM network also supports C+L dynamic power management, as a back-up solution.

9.1.2. Channel tilt and Power settings in C +L system using software.

With some vendors, network element software can automatically adjust average launch power and tilt based on channel loading, which can compensate for non-linear imperfections and optimize the OSNR over the full C&L bands.

Software Control of Transmission - For Channel /power management

The software, which runs on the controller cards and collaborates with pack level control loops, leveraging inter-NE information exchange in path setup and algorithms, can achieve the following:

1. Per channel power control.
2. Ingress & Egress adjust for span loss compensation.
3. Spectrum power equalization.
4. Pre-tilt for linear effects.
5. Power adjustment for nonlinear effects.
6. Set channel target power based on modulation format and bit rate (technology type).
7. Service launching and deletion.
8. Greenfield commissioning of a network.

9.2. Impacts due to nonlinearities

Optical nonlinearities such as cross-phase modulation (XPM), four wave mixing (FWM) and self-phase modulation (SPM) are unwanted wavelength interferences and distortions. Nonlinearities result in a small reduction in overall OSNR performance, slightly reducing a network's capacity and optical reach. The amount of the nonlinearity penalty depends on several factors, including fiber type, number of active channels, channel spacing, route distance, and wavelength power levels. To ensure networks operate with their designed wavelength capacity and optical reach, vendor WDM simulation tools calculate the nonlinearity penalty and include it their overall OSNR budget for a network design.

9.3. Amplified Spontaneous Emission (ASE) Noise Loading

Another method of overcoming SRS tilt management over C and L-Bands is by "noise loading "of unused channels, which is a technique of loading unused optical channels with artificial optical noise power, mostly used in subsea systems, because of the constant power amplifiers used. This technique simulates a fully loaded WDM system, the network operates at full capacity with all channels occupied, either with actual traffic carrying wavelengths or with ASE noise channels, as shown in Figure 14. As new channels are added to the network, a noise channel is simply replaced by the "live" traffic carrying wavelength. Similarly, as "active" channels are deleted from the network, they are automatically replaced by ASE noise channels.

The ASE noise source is typically just a normal EDFA amplifier running without an input signal (open loop), which creates ASE optical noise at all wavelengths across the band.

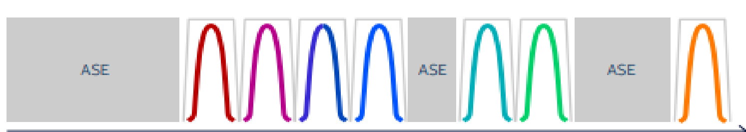


Figure 14 -ASE Noise Loading on unused channels.

9.3.1. ASE – Subsea Networks.

ASE noise loading is extensively used in Subsea networks, as the equipment resides under hundreds to thousands of meters of sea water. Repairing these underwater cables is not only costly, often exceeding a million dollars, but also time-consuming, as repair ships must travel to distant ocean locations to retrieve the optic fiber cable from the ocean bed and make the needed repairs.

Consequently, to mitigate the risks associated with high repair expenses and lengthy downtimes, subsea equipment is engineered for high redundancy, lowest failure rates, and streamlined amplifier designs that use as few components as necessary, reducing the likelihood of malfunctions.

The power management algorithms can be static, only needing adjustment during initial provisioning. Since the system appears always fully loaded, no additional optical power adjustments are required. Even with ASE noise loading, there are some failure scenarios where "dynamic power management" may be needed to ensure error-free operation.

9.3.2. ASE – Terrestrial Networks.

There has always been some industry interest in using ASE noise loading on terrestrial systems, however traditionally terrestrial systems relied on embedded 'dynamic power adjustment algorithms', which ensures flat gain response and constant per channel power levels using software or firmware control algorithms.

Both these methods whether ASE noise loading or dynamic power management using algorithms, work equally well in WDM networks. Optical power management algorithms automatically maintain constant per channel power levels, as any network changes occur due to wavelength additions or deletions. The algorithms make these adjustments by controlling optical amplifier power levels, which are running constantly in the background. These algorithms rely on additional circuitry built into amplifiers for monitoring total and per channel optical powers as well as for controlling the amplifier power levels. The hardware components can include optical channel monitors (OCM), control circuits, optical taps etc.

Even with noise-loaded systems, SRS tilt pre-emphasis is still required on both C-band-only systems as well as C+L-band WDM networks, but it is not dynamically adjusted as wavelengths are added or deleted to the network. Noise-loaded systems result in slightly higher upfront costs because both C-band and L-band noise-loading modules must be incorporated into the WDM system with the initial deployment. Also, in fault scenarios where a noise-loading module fails, the system still needs to perform dynamic SRS tilt adjustment to prevent service degradation.

9.3.3. Network restoration and ASE noise loading.

There is some industry misinformation suggesting ASE noise loading improves optical restoration times in WDM networks, which is not accurate. Noise loading should not have any impact on optical restoration times – on well-designed WDM nodes. After a network outage, ROADM nodes carefully control and manage the restoration of dropped channels to prevent power transients, which could cause bit errors on unaffected traffic-carrying wavelengths.

9.3.4. ASE noise loading versus Software algorithms.

There has been some industry discussion on whether ASE noise loaded systems provide a more accurate estimate of wavelength OSNR budgets, compared to relying on vendor WDM simulation tools. Since ASE noise loading fills all unused channels, the theory is that noise loaded systems provide static, known, operating performance, including all nonlinear penalties, that doesn't vary as channels are added or deleted. Historically on terrestrial WDM networks, dynamic power management algorithms provide per channel optical power and tilt management, while vendor WDM simulation tools calculate the OSNR budget and nonlinear penalties to ensure network performance remains constant regardless of the number of wavelengths operating on the network. Both approaches work equally well and result in approximately the same OSNR budgets and overall performance.

There are WDM industry vendors supporting both dynamic power management and integrated ASE noise loading options on their WDM Integrated ROADM systems, so carriers have the freedom to choose their network deployment preference.

10. Planning and Operationalization

This section discusses the lessons Rogers learnt in operationalizing C-L CDC-F DWDM system in Rogers Network. Since the deployment may be quite different than what other MSOs are used to, the intent for this section is to share some lessons learnt in our journey of operationalizing C-L CDC-F WDM systems that it may be helpful to other cable operators.

To assess the potential impact of fiber bends on C+L system deployments, we evaluated various long-haul fiber routes in Rogers' network with respect to bends, splice, and connector losses. The fiber plant has been characterized with Optical Time Domain Reflectometer (OTDR) at 1550 nm (C-band) and 1625 nm (L-band) wavelengths.

We considered all splices, connectors, and bends that exceeded a loss delta between C and L-band of 0.03 dB. There were some instances where the use of L-band warranted some additional remediation efforts, the vast majority did not. The most common issues detected by L-Band OTDR include non-reflective breaks, where the fiber may be cut or broken without reflecting light, making it challenging to determine the exact point of fault. Other typical problems are fiber loss, splice anomalies, connector reflections that can affect signal quality and integrity. We therefore concluded that using C+L systems rather than C-band only systems does not create a significant additional burden on the fiber plant testing.

Most optical vendors provide planning tools for designing and predicting an optical network link performance. Utilizing the available data, which includes gain, attenuation, and other parameters for all line system components like amplifiers, and taking into account the span loss, Polarization Mode Dispersion (PMD), and Chromatic Dispersion (CD) of the fiber systems, we successfully modeled the line system's behavior.

In order to access the potential impact of ASE line loading in Rogers, we tried to enable the ASE line loading throughout the span and ran few tests. It created unexpected operational complexity, by generating erroneous alarms that were difficult to troubleshoot, such as Low Gain-C or PWRMAXGAIN, though the Gain was within the set limits. So, we left the system software to do the channel power adjust and tilt automatically, based on channel loading. All the errors disappeared the moment we turned off ASE noise loading. While ASE Noise loading is more predominant in Subsea applications, terrestrial networks utilize dynamic power management algorithms running within each ROADM node to automatically adjust optical power levels and ensure optimal performance.

We also carried out path continuity tests (PCT) for testing out all the ports of an MPO cable assembly, connected between the Integrated ROADM (IROADM) cards and between IROADMs and the CDC-F add/drop blocks (Multicast switch (MCS)) for testing the degree-degree as well as degree to add/drop block continuity.

Path connectivity test (PCT) is a testing tool built into the network element software, it is intended to validate path connectivity between degrees and degree to add/ drop blocks of CDC-F configuration. PCT is run by the network element (NE). A pass/fail test of a path is determined based on a received power threshold for the specific configuration and connectivity.

We simulated different transponder platforms on various optical grids and frequency spacing, 62Gbaud signals and 75GHz frequency spacing ,86.04Gbaud signals and 87.5 GHz frequency spacing, 87.36Gbaud and 112.5Ghz spacing and observed critical network parameters such as OSNR margin, Pre-FEC BER, EOL Q- factor and margin. As the signal width increases, the line rate and the OSNR margin also improved. It is a trade -off between the spectral width and the line rate or capacity and the operator needs to carefully choose between the two in their networks.

We can achieve good data rates with flex grid compared to a fixed grid network by planning out the spectrum usage efficiently without any wastage.
Major challenges associated with a flex grid network are:

- Spectrum fragmentation.
- Channel count reduction.

For managing spectral widths and to minimize spectrum defragmentation, we selected and standardized a few spectral widths and created different buckets of these spectral widths in our network. Say for example, groups of 75GHz x 4= 300GHz, 87.5GHz x 4= 350Ghz and 112.5GHz x 4 =450Ghz, or multiple of these groups to avoid any spectrum wastage and its efficient usage.

Embedded OTDR for advanced fiber analysis is another key feature. This provides a complete OTDR loss profile during new link turn up(baseline) and can be used for future reference. Automatic OTDR trace on fiber cut & baseline trace run once repair is complete, in-service OTDR traces to check for fiber degradation versus baseline due to aging, are some of the key features.

Another design we incorporated in our network is reserving the shorter wavelengths or higher frequencies in the spectrum for longer transmission distances, due to their lower attenuation and better reach. This is because shorter wavelengths are less affected by fiber dispersion and absorption, allowing them to travel longer distances without significant signal degradation.

11. General Comparison between C only and C+L Systems

C+L system is more efficient than 2 x C system from a deployment perspective, as it requires to install and configure two independent systems.

C+L system has better utilization of fiber resources, as compared to 2 x C systems (two parallel C-band systems). Capacity can be scaled without the need for deploying or acquiring new fiber.

Receiver power sensitivity of C and L-band transponders are different. Output power of L-band transponders is lower as compared to C-band transponders. Although these are not substantial but worth mentioning them when troubleshooting sporadic optical routes exhibiting unexpected behavior.

L-band EDFA’s are less efficient and have increased noise figure penalty as compared to C-band. This is due to the insertion loss of splitter/coupler unit, which are used for multiplexing/de-multiplexing C and L-band signals.

L band is more sensitive to both micro-bends and macro-bends. which in some instances will warrant additional remediation efforts on fiber plant. In general, the requirements of OSP fiber [splicing, connectors] are same for both C+L and C only system.

L-band optical components, often pricier and less available than C-band parts, suffer from low production volumes and design complexities. Yet, as deployment of L-band systems increases, their costs are anticipated to drop.

C-band channels experience minor performance issues when near L-band channels, primarily due to Stimulated Raman Scattering (SRS). This effect is more noticeable in channels with shorter wavelengths.

12. Benefits of C-L Band CDC-F Systems

1. Increased transmission distance and larger DWDM transmission capacity. The C and L band operation at least doubles the number of channels present in a single optical fiber.
2. Higher baud rates and channel spacing can provide you with 400G, 800G and above.
3. In the initial phase in a C-L band DWDM network, deploy the C-band photonics with a C +L band coupler unit for in-service upgrade to L-band later, and reduce the initial deployment costs. As network traffic increases, add the integrated L-band amplifiers (comes with Optical Amplifiers (OA), Wavelength Selector Switch (WSS), and Optical Channel Monitors (OCM).
4. With faster SRS adjustment through SRS tilt control, system performance and flatness can be greatly optimized.

13. Conclusion

As bandwidth demand increases while transponder spectral efficiency gains become incremental, expanding the total amount of spectrum on the fiber by adding the L-band becomes an increasingly attractive option, especially in fiber-constrained environments.

This paper has reviewed the green field deployment of C-L CDC-F system for Rogers Long haul network. The advanced modulation schemes, in conjunction with coherent detection and digital signal processing, has proven to be the most economical solution for modern long haul optical networks. Not only does it have the required spectral efficiency, but it also delivers increased Optical Signal-to-Noise Ratio and decreased Bit Error Rate by effectively compensating for fiber impairments.

The new C-L CDC-F DWDM system demonstrates superb scalability and density. With newer generation DSPs in service cards, it can deliver 30-40% space savings and close to 30% reduction in power, on top of doubling the fiber spectrum with C + L bands. The system is also ready to support next generation modulations and automation to allow us to further scale it easily and economically. The latest coherent optical transceivers available in different form factors and capable of supporting multiple modulation formats, are designed to connect directly to the routers, without the need for additional intermediary interfaces.

C-L band Colorless-Directionless-Contentionless with Flexible grid (CDC-F) DWDM systems are revolutionizing the telecommunications industry by offering great levels of network agility, efficiency, and scalability. These systems provide a multitude of benefits, including the ability to seamlessly manage bandwidth through dynamic allocation, which significantly reduces operational expenses.

The flexible grid aspect of CDC-F ROADMs is particularly beneficial as it future-proofs networks against increasing data demands by accommodating larger passbands required by high symbol rate coherent modems. This adaptability is crucial for supporting the ever-growing need for data in our digital world, ensuring that networks can handle the traffic of today and tomorrow.

Additionally, CDC-F systems contribute to simplified network architectures, which streamlines operations and maintenance, leading to quicker service deployment and improved customer satisfaction.

In essence, C-L CDC-F DWDM systems are key to building a more robust, flexible, and efficient optical network infrastructure that can adapt to the evolving demands of modern communication networks.

Abbreviations

AR	Augmented Reality
ASE	Amplified Spontaneous Emission
BER	Bit Error Rate
CD	Chromatic Dispersion
CDC-F	Colorless, Directionless, Contentionless-Flex Grid
DSP	Digital Signal Processing
DWDM	Dense Wave Division Multiplexing
EDFA	Erbium Doped Fiber Amplifier
EOL	End of Life
FEC	Forward Error Correction
FWM	Four Wave Mixing
GFF	Gain Flattening Filter
GHz	Giga Hertz
ILA	In Line Amplifier
IROADM	Integrated Reconfigurable Optical Add Drop Multiplexer
IRU	Indefinite Right of Use
MCS	Multi Cast Switch
MPO	Multi-fiber Push- On/Pull -off
MSO	Multiple- System Operator
NE	Network Element
OA	Optical Amplifier
OCM	Optical Channel Monitor
OPEX	Operational Expenditure
OSC	Optical Supervisory Channel
OSNR	Optical Signal to Noise Ratio
OTDR	Optical Time Domain Reflectometer
PCT	Path Continuity Test
PMD	Polarization Mode Dispersion
ROADM	Reconfigurable Optical Add Drop Multiplexer
SPM	Self-Phase Modulation
SRS	Stimulated Raman Effect
VR	Virtual Reality
WDM	Wave Division Multiplexing
WSS	Wavelength Selective Switch
XPM	Cross Phase modulation

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