Spectrum sharing in subsea networks

Service description and deployment considerations for spectrum sharing

Application note

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Enabling spectrum sharing for submarine fiber cables

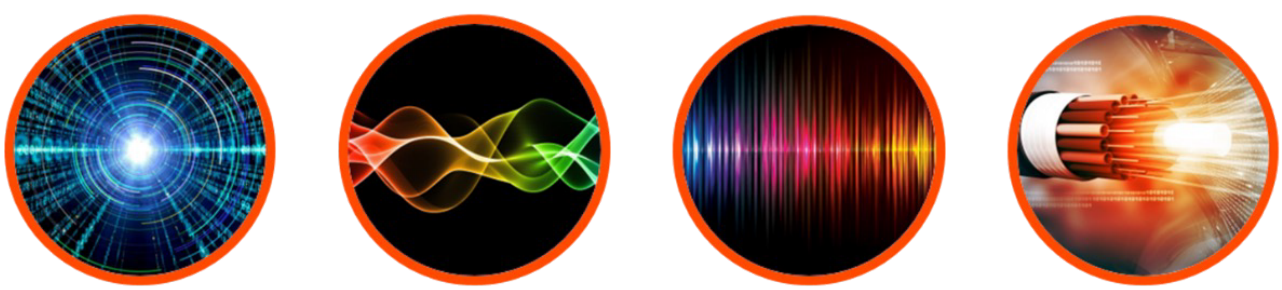
Introduction

Traditionally, subsea fiber optic cable systems were made up of a limited number of fiber pairs due to the complexity associated with armoring and protecting the cables for deep water deployment. Until recently, it has been the norm for the entire wavelength division multiplexing (WDM) transmission spectrum of an individual fiber pair to be operated and managed by a single operator, oftentimes known as a turn-key project, and lit using a common set of Submarine Line Terminating Equipment (SLTE) technologies and vendor.

More recently, Open Cable Systems (OCS) allow for the separation of the wet plant portion, comprising the subsea fiber cable and optical repeaters and known as an Open Cable Interface (OCI), and the SLTE, comprising the reconfigurable optical add/drop multiplexers (ROADMs) and transponders that transmit services across the fiber cable. This separation allows different network operators to use the same subsea fiber cable, and enables them to select the SLTE equipment with the best capacities and features required for their application, independent of the subsea cable ownership.

Over time, capacity per subsea cable has increased through the introduction of higher performance coherent transponders, improvements in optical fiber specifications, and more recently, improved cable designs using Space Division Multiplexing (SDM) containing a greater number of fiber pairs per cable. This has given rise to the creation of a new business model of selling spectrum within a virtual fiber pair, adding new options for selling subsea capacity in addition to traditional capacity sales such as bandwidth circuits, wavelengths and entire fiber pairs.

Figure 1: Different models for selling and consuming bandwidth on subsea fiber optic cables, including Virtual Fiber using Spectrum Sharing as a Service



Sub-Wavelength	**Wavelength**	**Virtual FIber**	**Dark Fiber/MOFN**
OTN/Packet/TDM	OTU/Ethernet	Spectrum (GHz)	Fiber pairs
Mbps - 10’s of GBps	100-800 Gb/s	100’s Gb/s - Tb/s	Tens of Tb/s

This Virtual Fiber or Spectrum Sharing service divides the optical fiber spectrum into “shares”, with each portion of the spectrum being used by different entities. In many cases, the users include the fiber pair owner and additional tenants, enabling additional revenue from leasing spectral space that otherwise would be unused by the fiber pair owner for extended periods of time. This helps the fiber owner obtain faster investment recovery whilst maintaining minimal impact to operational costs.

For users, or tenants, of Virtual Fiber capacity enabled by Spectrum Sharing, they benefit as follows ;

1), spectrum sharing allows access to subsea routes with heavy demand for a fractional investment compared to deploying a full cable system or purchasing a full fiber pair; and

2), spectrum sharing gives the tenant the flexibility to deploy the SLTE of their choice, in order to leverage the best and latest technology and thereby extract the maximum capacity or lowest cost/bit from the cable across the spectrum they are assigned.

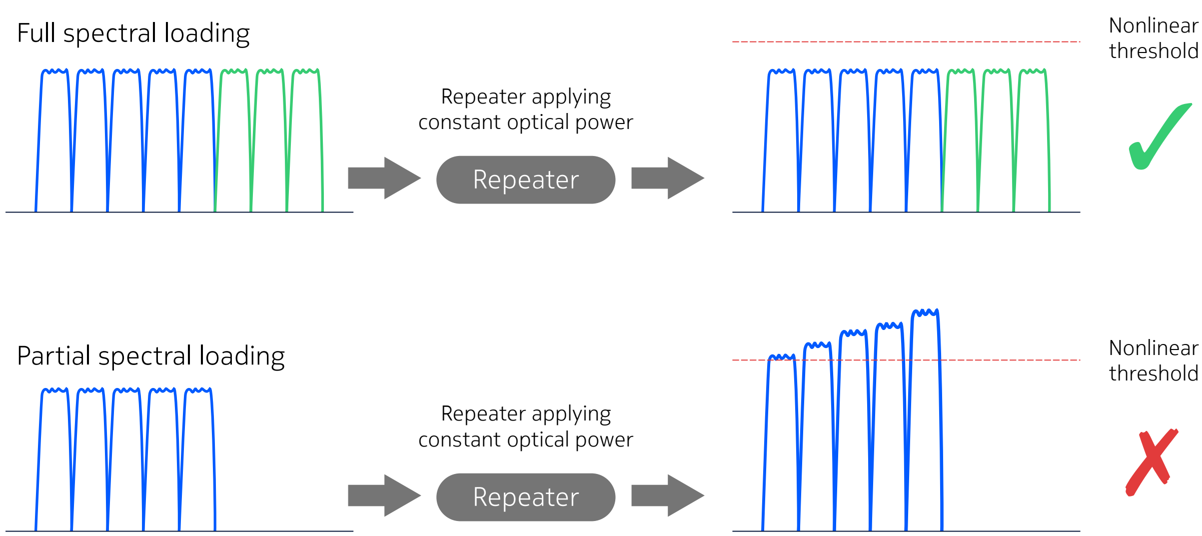
The Importance of Optical Power Management in Subsea Fiber Cables

The key principle enabling spectrum sharing and protection in subsea fiber optic cables is the fact that subsea optical repeaters operate with constant output power. The repeaters in a long-distance subsea fiber optic network utilize in-line optical amplifiers, for reasons mainly of equipment reliability and system stability. These repeaters operate in constant output power mode, with each amplifier maintaining a constant output power irrespective of a potentially variable input power. This is in contrast to terrestrial repeaters that tend to include automated power control protocols, in order to achieve as close to constant gain per channel as possible.

Constant power mode in subsea repeaters means that the optical power load in a given fiber pair must be maintained as close as possible to the optimum level for total optical power. This total power can be a combination of service wavelengths and/or amplified spontaneous emission (ASE), such that the spectrum is fully loaded. ASE is used to substitute for service wavelengths when these are not yet active, and often a fiber is initially loaded using only ASE optical power. As service wavelengths are added, the ASE spectrum is reduced to maintain the optimum optical power level across the spectrum.

In the event of the loss (either planned or unplanned) of transponder signals, the ASE can be quickly and automatically re-inserted to maintain optimum power levels, and thus is used to protect the shared spectrum.

Figure 2 The effect of partial spectrum loading in a subsea fiber optic cable

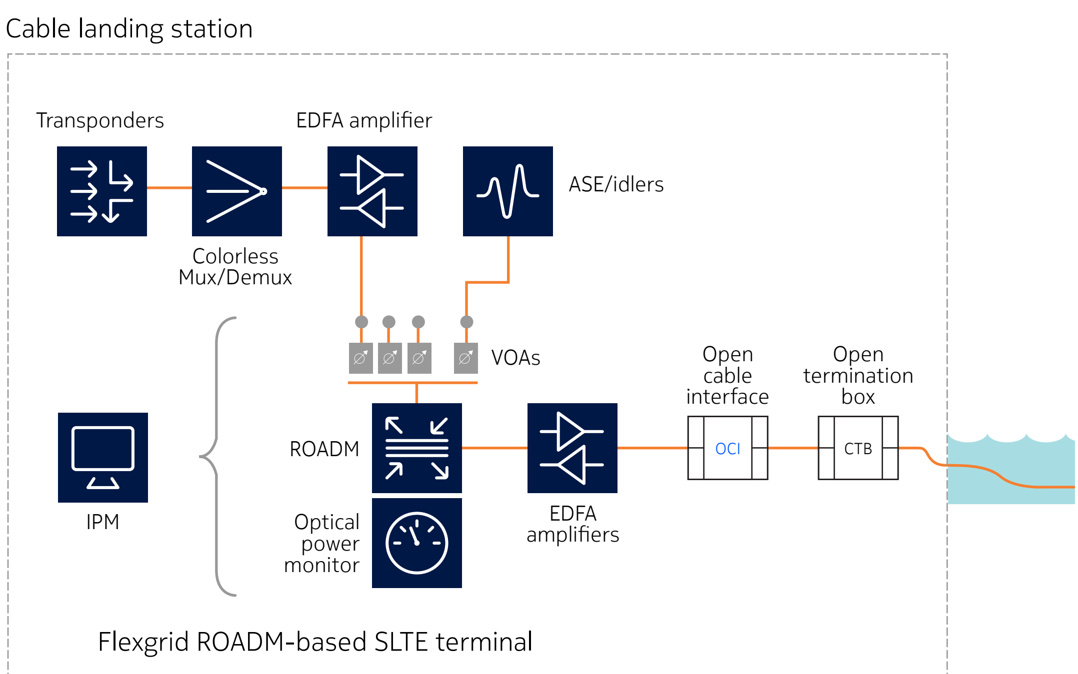


If optimum fiber spectral loading is not maintained when signals are lost, the service wavelengths will receive either too much or too little power because the repeaters will continue at the same total optical power level. An example of this is shown in Figure 2, showing the effect of a partially loaded spectrum. Too little power will impact channel power and subsequently Optical Signal to Noise Ratio (OSNR) and quality of the signal. Alternatively, too much power will result in nonlinear propagation impairments, also impacting the Q of the signal. Either condition could result in service outages to some or all of the other service wavelengths, depending on how much the payload wavelength power deviates from the optimum value.

Figure 3 shows the generic architecture of an SLTE with the typical functions of each block. The transponders carrying customer traffic are connected to the colorless mux/demux that provides the composite optical signal to the flexgrid ROADM SLTE terminal, which performs pre-emphasis adjustments and grooming of the optical spectrum. The combined optical signal from the ROADM then connects to the Optical Cable Interface (OCI), which acts as the demarcation point into the submarine wet plant.

The most relevant element for spectrum sharing is the C-band ASE idler generator that is permanently attached to one of the ROADM SLTE ports. This is used to provide ASE noise blocks in unused areas of spectrum.

Figure 3 SLTE generic architecture



The ASE idler generator can also be used to fill subsea line spectrum that is lost when a carrier or group of carriers are lost due to unexpected conditions, thus maintaining the stability of the subsea link by keeping the usable spectrum fully loaded. ASE insertion under these conditions is monitored and controlled by an Optical Power Manager (OPM) within the SLTE solution.

This architecture enables the fiber pair owner to sell portions of the spectrum, based on a Spectrum Management Block (SMB), as defined by the SubOptic Spectrum Sharing Working Group. This methodology ensures that the stability of the subsea line is managed as necessary.

This implementation architecture described above is what is referred to as spectrum sharing, with several users accessing the spectrum available on a single fiber pair under the constant power control of a Spectrum Manager Block.

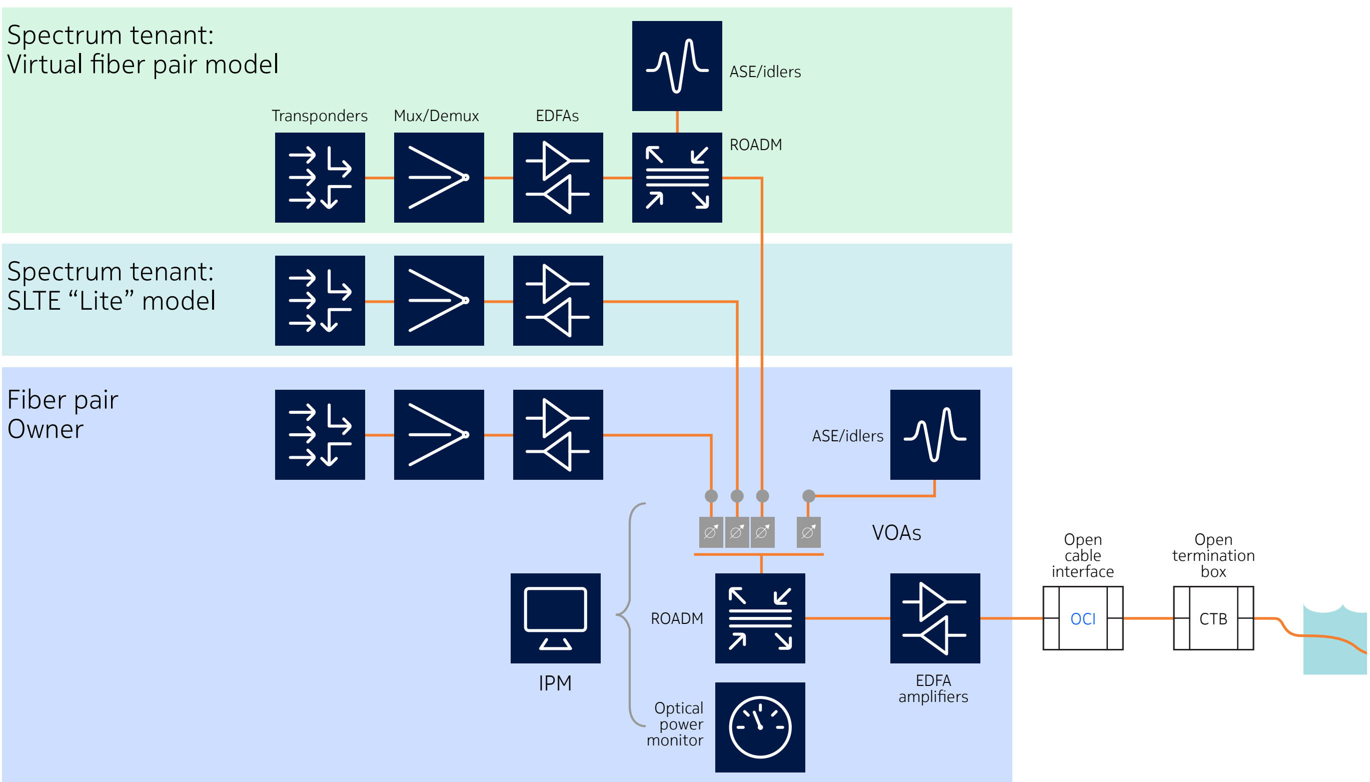
Types of Spectrum Sharing Models

There are two models for operators to offer the Spectrum Sharing services to other subsea capacity users; the Lite SLTE model, and the Virtual Fiber Pair model.

The first model, known commonly as the "Lite" SLTE model, is where the bandwidth customer, or tenant, accesses the existing SLTE terminal of the fiber pair owner using their own 3rd party transponders. The tenant transponders are connected to a colorless coupler/ROADM operated by the fiber pair owner, who then undertakes the optical power management of the SMB.

The second model, "Virtual Fiber Pair", connects a full SLTE terminal operated by the tenant, including transponders, muxes and ASE idlers, to one of the ROADM ports of the SLTE operated by the fiber pair owner. In this model, there are two independent levels of optical power management that must be managed; one protecting at the tenant level and one protecting the fiber pair. Figure 4 shows a fiber pair having both models, in addition to additional channels operated by the fiber pair owner.

Figure 4 Spectrum sharing models



The advantages of each model are the combination of cost vs flexibility. In the case of the "lite" SLTE model, less equipment is required from the tenant, so they can access subsea spectrum with a smaller investment, but at the sacrifice of flexibility during operation and provisioning where a dependence on the fiber pair owner for most actions is required. Conversely, the Virtual Fiber Pair model minimizes dependency on the fiber pair owner SMB for most activities, but requires the spectrum tenant to incur the expense of a full SLTE solution.

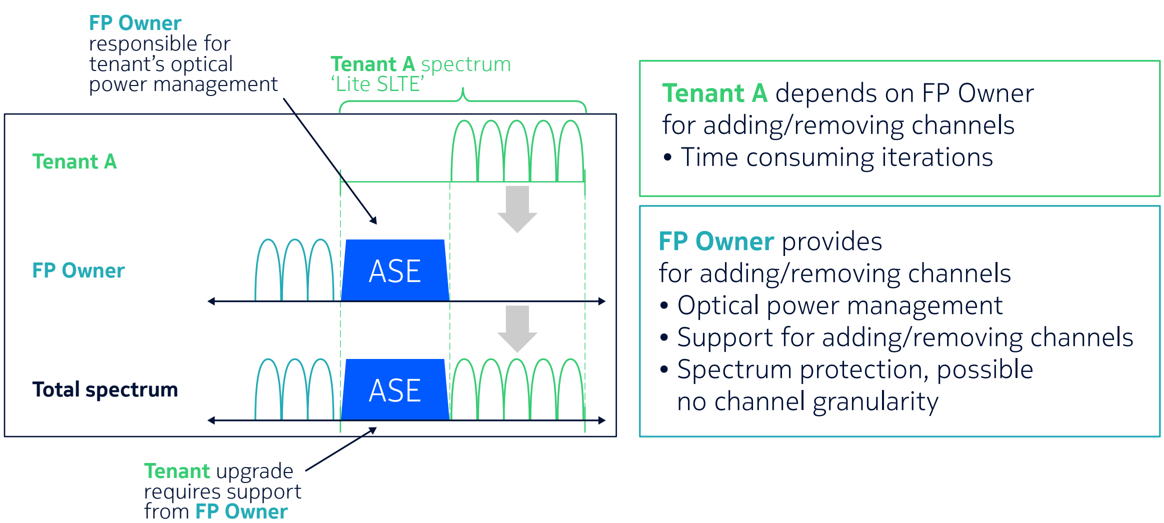
Adding and Protecting Channels

If the two models are compared for the cases where additional wavelength channels are added, or when channels fail and the spectrum needs to be protected, the advantages and disadvantages of each become clearer.

For the case of the "Lite" SLTE model, as shown in Figure 5, any upgrade of capacity will require intervention and coordination with the fiber pair owner manipulating the ASE block. When new wavelengths/channels are added by the tenant, the ASE provided by the fiber pair owner is reduced accordingly, and any other settings in the gateway ROADM are updated to support this change. This creates a heavy dependency on the fiber pair owner by the tenant, for all changes to their spectrum use. If not agreed upon properly, the lack of channel granularity on the spectrum protection may cause all tenant traffic to go down, even if only some channels have failed.

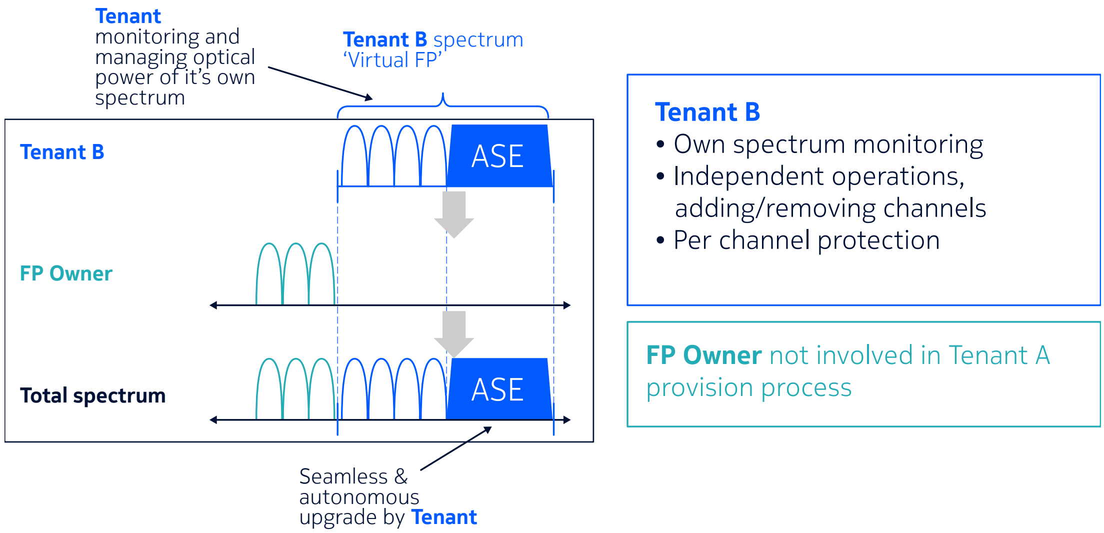
Similarly, protection of spectrum in case of tenant transponder failures relies on ASE insertion by the fiber pair owner, and requires careful agreement of protection protocols as part of the spectrum sharing service-level agreement (SLA).

Figure 5: Tenant channel additions in the SLTE "lite" model of spectrum sharing



The Virtual Fiber Pair model for spectrum sharing services ensures that activities such as channel additions or failures are independent of the fiber pair owner, and spectrum protection within the allocated band is managed by the tenant. Figure 6 shows how the tenant generates their own ASE blocks that can be adjusted as needed within their SLTE terminal.

Figure 6: Tenant channel additions in the virtual fiber pair spectrum sharing model



For protection of failed channels in the Virtual FP model, the spectrum protection via ASE insertion is managed by the tenant, and can be very granular to only the affected carriers.

Feature details of spectrum sharing

When establishing a spectrum sharing service, there are several specific topics related to the Spectrum Sharing SLA that require agreements between the fiber owner and the spectrum tenants. These are technical specifications which have dependencies on the spectrum sharing models used, the capabilities of the equipment in use, and ultimately who is responsible for which aspects of cable performance and operations.

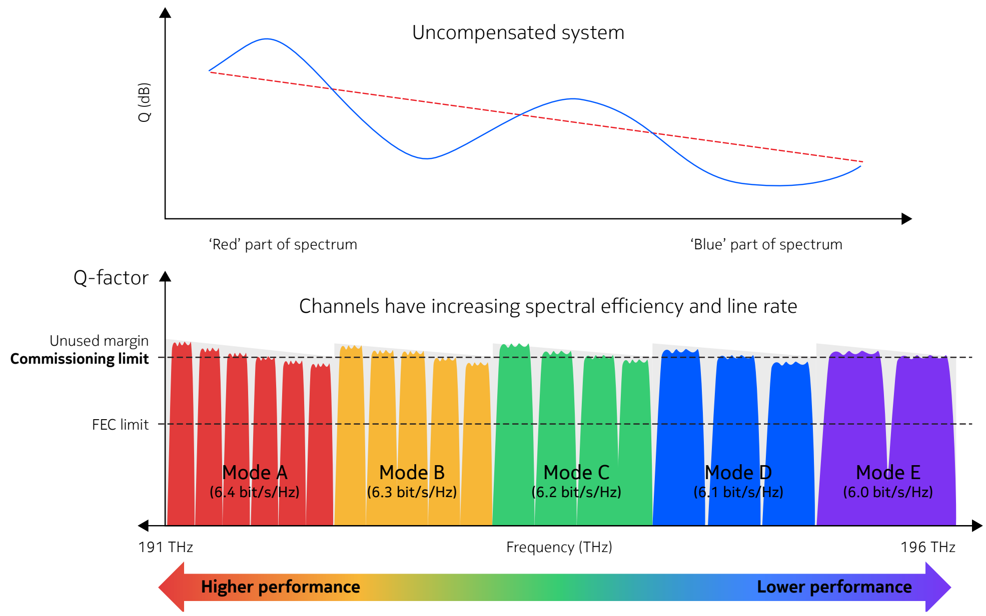
Spectrum allocation for spectrum sharing

A key question for cases where spectrum sharing is utilized between a fiber pair owner and one or more spectrum tenants is the spectrum assignment for each user.

Some relevant details to keep that the fiber owner and tenant(s) must consider when deciding spectrum allocation include:

1. There is no equal performance across the entirety of the fiber spectrum, as OSNR non-linear impairments vary across the C-band spectrum, and thus what portion is being used will influence transmission performance. For example, typically the red side of the C-band typically performs better than the blue side. This difference can be leveraged with coherent optics, using variable baud rates and shaped Probabilistic Constellation Shaping (PCS) to achieve the best possible capacity per wavelength across the spectrum portion, as shown in Figure 10.
2. Transponder technologies are constantly changing, so Non-Linear Compensation (NLC) performance and capacity projections could evolve over time for the spectrum that has been allocated.
3. Performance can be measured using attributes such as SNR and Generalized SNR (GSNR). However this requires the cable/fiber pair to be available to the user to perform these measurements and consumes time and resources, and may thus not be suitable metrics to decide spectrum assignment when a cable system is not yet ready.

Figure 7: Variation in transponder performance across C-band spectrum from red-to-blue



The simplest option for allocating fiber spectrum in spectrum sharing applications would be the simple division into two, or more, spectral shares, based purely on total spectrum available. Thus a subsea fiber cable having total spectrum in the C-band of 4500 GHz could be simply divided into two spectrum sharing portions of 2250GHz each. From a purely commercial perspective, allocating spectrum using fixed spectrum passbands based on GHz/THz might be simplest approach, but will not result in equal performance for each portion of the spectrum, in terms of transmission capacity.

Other options for allocating spectrum sharing include dividing the spectrum based on performance, either using capacity per wavelength/spectrum, or based on received SNR or GSNR. Figure 11 explains the four possibilities to measure and decide the exact division criteria for spectrum sharing, along with advantages and disadvantages of each approach.

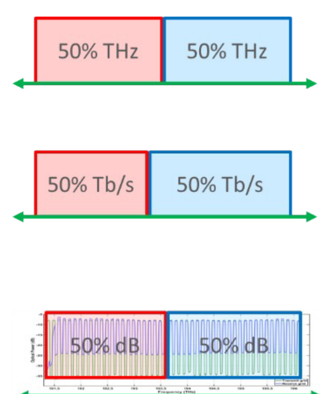
Figure 8: Examples of options for allocating spectrum in spectrum sharing applications

1) Dividing spectrum based on bandwidth (THz)
   +simplicity
   -unequal capacities

2) Dividing spectrum based on capacity (Tbps)
   +equal value
   -transmission technology dependent, difficult to assess

3) Based on equalized Rx SNR_{ASE} (dB)
   +transmission technology dependent, fast measurement
   -requires system to be RFS, does not take into account nonlinearities

4) Based on equalized Rx GSNT (dB)
   +transmission technology dependent, takes into account wet plant nonlinearities
   -requires system to be RFS, slow measurement, does not take into account NL compensation, conversion to capacity has a higher uncertainty



Allocating spectrum based on SNR or GSNR, as described in cases 3 and 4 in Figure 11, has been proposed by the Suboptic Spectrum Sharing Working Group as a means to predict and estimate capacities in an Open Subsea Cable. This relies on the measurement of SNR_{ASE} and GSNR during the acceptance testing of the wet plant using a combination of ASE and basic coherent modems, thus making it independent from the specific technology and features that each transponder vendor may have developed and might deployed by the different spectrum users.

However it should be understood that estimating the capacity performance for the entire fiber pair or a spectral portion using SNR_{ASE} and GSNR values might not always provide accurate capacity predictions, as more advanced and/or future transponders may have improvements and features that will provide better results. This could yield different capacity values in practice compared to initial estimates, especially if different vendors and/or technologies are used in different parts of the spectrum.

Spectrum monitoring

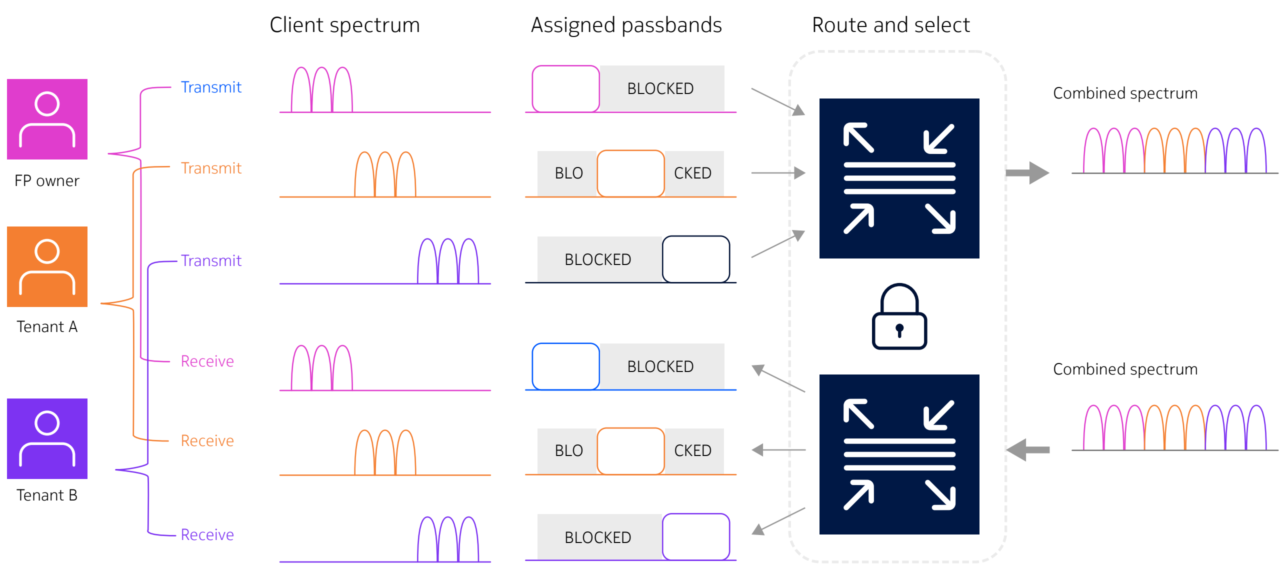
A key requirement for ensuring error-free operation of a spectrum sharing service is to measure and monitor the optical spectrum, and enable any needed actions by the power management controller. Spectrum monitoring is enabled by fast and high-resolution OCMs to quickly detect and react to spectrum changes. Without this capability, there are significant limitations regarding the precision to which spectrum can be assigned and the speed to which decisions for ASE insertion can be made in the event of faults.

This OCM capability must be deployed by the party responsible for protecting the spectrum in case of transponder failures, either the fiber pair owner in the case of the "lite" SLTE model, or by the tenant in the case of the Virtual Fiber pair model. In this latter case, the fiber pair owner would also deploy an OCM to monitor the spectrum they are using, and as back-up to monitor the entire spectrum on the fiber pair.

Spectrum security and privacy

Another important aspect of a spectrum sharing service is the security and privacy of each user's spectrum and associated data. Full separation of spectrum between each user/tenant is paramount, and requires that the fiber pair owner gateway ROADM has a route and select architecture, providing each user with controlled access and visibility to only their allocated portion of the spectrum, as shown in Figure 9.

Figure 9: Spectrum privacy with route and select WSS architecture



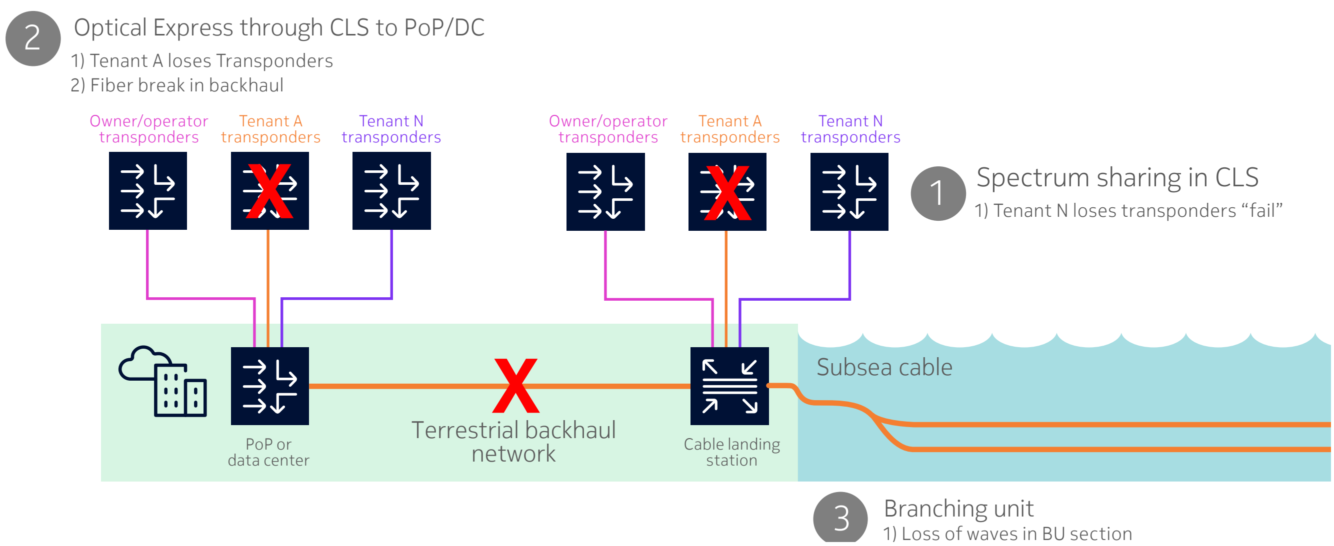
This route and select architecture enabled by the owner's ROADM also provides the additional benefit of protecting against frequency misconfiguration by any of the spectrum users.

Impact of submarine networks backhaul configurations

There are multiple ways in which the subsea traffic that is part of a Spectrum Sharing service may interact with the terrestrial backhaul fiber optic network, which is used to connect from the cable landing station (CLS) to a Point-of-Presence (PoP) or Data Center (DC).

Therefore an important aspect of spectrum sharing applied across end-to-end subsea-terrestrial networks is the ability to control and police the spectrum end-to-end, with the ability to intervene and restore performance in a diversity of possible subsea-terrestrial configurations. Figure 8 shows the possible scenarios in the CLS-PoP/DC configuration where spectral sharing would be required across both the subsea and terrestrial backhaul networks.

Figure 10: Submarine network optical paths complexity



The traditional scenario requiring spectrum protection is the loss of transponders at the CLS. As mentioned earlier, this requires quick ASE insertion for the failed spectrum into the subsea fiber to keep the surviving channels stable and operating at the correct power levels.

More recently, subsea fiber cables are increasingly providing high-capacity trans-oceanic connectivity between data centers spread across different continents. In this case traffic across subsea cables does not originate or end at a CLS; it flows end-to-end between data centers or PoPs that may be located meaningful distances away from a CLS. This leads to a change in the network architecture, where back-to-back transponders at the CLS are removed, and subsea traffic is transparently passed through in the optical domain at the CLS, directly into the terrestrial network fiber and all the way to the DCs/PoPs, in the process reducing the cost, space and power of transponders used at the CLS.

In this second case, where the transponders are located at the DC or PoP and connect to the CLS using a terrestrial backhaul network, in either protected or unprotected configurations, there are two possible failure scenarios if spectrum sharing is used. The first is due to transponder failure at the DC/PoP and which impacts specific wavelengths that connect to the subsea cable, and the second due to a fiber break in the backhaul, where all wavelengths that connect to the subsea cable will be impacted.

In both cases, it is necessary to provide ASE spectrum into the subsea cable to restore the failed carrier(s) and keep the subsea spectrum fully populated. This may therefore require ASE sources at the DC/PoP and CLS depending on the backhaul specific configuration for adding/dropping traffic.

A third case common in subsea networks is the use of branching units (BU), where carriers into the main subsea fiber trunk are lost due to failure from the BU section, which affects the channels active in the trunk. ASE spectrum insertion, either coming from the terminals or the BU's ROADM, should recover proper operation for the surviving traffic in the trunk.

Other factors that can influence failure recovery in subsea fiber cables that implement spectrum sharing include,

a) The complexities of terrestrial network operation, including potential failures across a wide range of network elements (ie: transponders, WDM muxes, ROADMs, ILAs, etc) as well as changes in non-linear impairements due to optical power, which can potentially impact transmission performance in other channels

b) Improper transponder configurations, for example where too high of an output power per channel can impact other portions of the spectrum by starving them of optical power, or where channel power is too low which then impacts transmission performance

c) Use of the latest generation of high-performance coherent optics operating at baud rates of 140Gbaud or higher. These provide continued increases in capacity per wavelength and lower power per bit, but require high stability, with typically lower operational margins, and also increase the spectrum use per channel. In this latter case, a failure or misconfiguration of one channel has a greater impact on overall spectrum use compared to prior coherent generations that required less spectrum per channel (ie: 50GHz/ch).

In view of these challenges, it is paramount that a very robust and reliable automated spectrum protection and restoration solution is implemented to enable correct activation and operationalization of Spectrum Sharing.

This can be simplified and automated using software planning tools, such as the Nokia Intelligent Power Manager (IPM) solution. IPM is a suite of software applications to support, without requiring additional hardware elements, the various aspects of network characterization, optimization, (re-)configuration and more. IPM provides the tools needed by both fiber pair owners and tenants that implement spectrum sharing according to the SubOptic recommended Spectrum Management Block (SMB).

Spectrum optimization

One additional functionality highly desirable when spectrum sharing is used is the ability to optimize the shared spectrum to obtain the best possible performance and capacity. This applies to both the fiber pair owner, who needs the capability to optimize the entire spectrum to provide an acceptable baseline usually agreed with the spectrum sharing tenant, and the tenant who seeks to maximize performance on their share of the spectrum.

This spectrum optimization is also facilitated through the use of software planning tools, such as the Nokia Intelligent Power Manager. In this case, IPM supports key functions such as spectrum viewing, Tx and Rx pre-emphasis settings for transponders, and performance per channel. Figure 9 shows a sample of the spectrum optimization graphical user interface, called Smart Optimize, available from the Nokia IPM tool.

Figure 11: Spectrum optimization GUI

Conclusions

As can be noted, implementing Spectrum sharing in a subsea fiber pair involves new implications not seen before in the subsea industry, ranging from engineering, deployment and daily operations and management (O&M). This document provides an overview of the key aspects of spectrum sharing, including different implementation models, technical requirements and important features, for both fiber pair owners providing a spectrum sharing service, and the tenants for such a service.

In the next section, we dive deeper into the details behind implementing spectrum sharing between parties, including all the specifications, rules and SLAs to be applied between the fiber pair owner and the future tenant(s). Clear definition of these attributes are a key part of a successful implementation of a spectrum sharing service for all the parties and groups involved, and also help frame the daily O&M actions and commitments needed for ongoing operation.

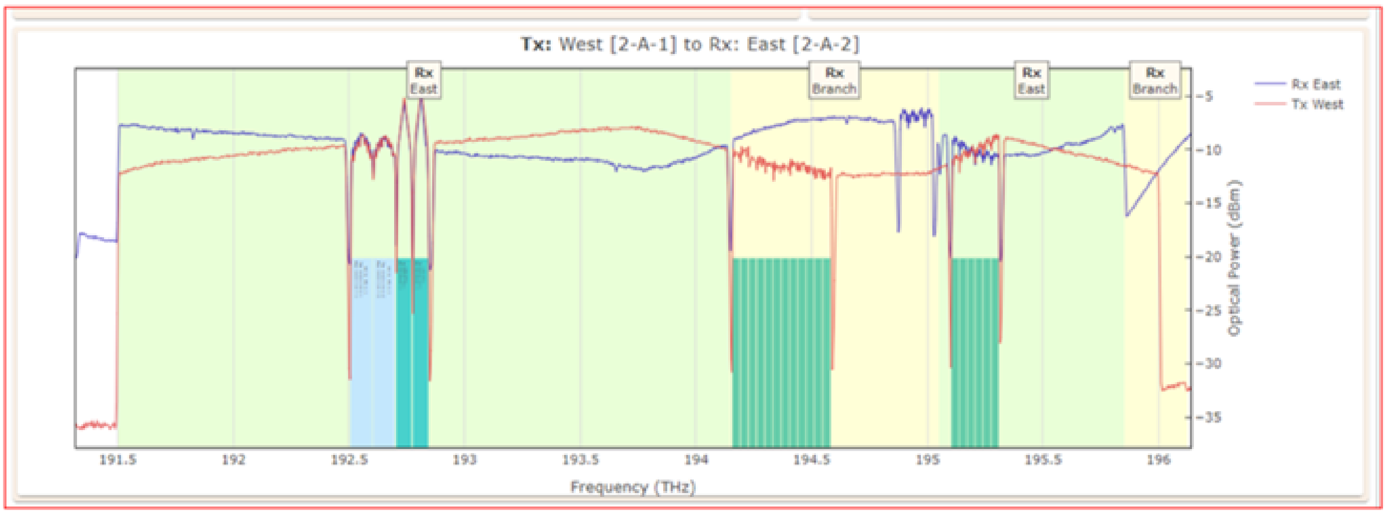
Practical implementation of spectrum sharing

Spectrum equalization

A first step needed to prepare a subsea fiber pair for use with a spectrum sharing service is to ensure the proper equalization of the spectrum at the gateway SLTE, in the line port of the ROADM , and usually located in the SMB, in order to optimize the performance. A suggested simple method for achieving this uses fiber power (P_{fib}) optimization, which equalizes the sum of Tx and Rx power profiles, and mirrors the Rx behavior when transmitting with a flat Tx profile.

The benefits of using P_{fib} as an optimization metric are lower nonlinearities, suitability with newer high fiber count SDM cables, and a good balance between simple and rapid optimization and accuracy. Figure 12 shows a fiber pair with P_{fib} equalization applied.

Figure 12 P_{fib} applied to fiber pair

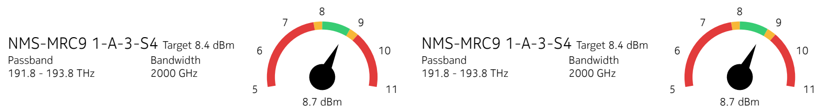


Power masks and thresholds

Another key element of offering a spectrum sharing service is the management of the expected power each tenant requires, such that the composite launch power to the subsea line is at the nominal level to enable the overall subsea fiber pair to operate with optimal performance. Once the spectrum allocation for a tenant is defined, a total input power must be provided by the fiber pair owner into the subsea fiber. This total power is usually formed by sum of spectrum slices enabled by the ROADM, multiplied by the Power Spectral Density (PSD) value for each of these spectrum slices.

Each tenant must ensure that the total power level of their spectrum slice is maintained with a combination of active service wavelengths and ASE blocks. In the case where the PSD value is not met, and is either too high or too low, ASE protection could be applied by a software-based power management tool. Figure 13 shows the way this is represented in Nokia's IPM for a sample spectral share.

.Figure 13 Tenant Input total power calculation



Total power by measured at the port where the tenant spectrum block is connected at each end of the link

Tenant input power = -13 dBm + 10log (2000/12.5)
Tenant input total power = 8.4 dBm

As can be noted in the figure, the total tenant power is calculated using the PSD specific to the target system, and the formula used is,

SMB Tenant Total Input Power= **PSD**+10log (**BW/12.5**)

Where;

PSD is defined by the fiber pair specific details and configurations. (For details on the PSD calculation see the SubOptic Spectrum Sharing white paper section 10)

BW is the tenant spectrum assigned (in GHz)

12.5 is the spectrum slice used by the ROADM, with 12.5GHz and 6.25GHz being the most typical values and which are defined by the ROADMs wavelength switching resolution.

If the system is already deployed, actual field data can be used to calculate the effective PSD, in a manner similar to the case shown in Figure 13.

Once the tenant's spectrum is inserted into the fiber and the ASE protection is enabled, software optimization tools such as Nokia's IPM, using the Smart Shield software application, can automatically monitor power levels and trigger ASE protection when thresholds are crossed. Power deviations in the tenant's share of the total spectrum could trigger ASE protection that will replace the entire tenant traffic, depending on the thresholds set.

As mentioned earlier, with the use of the Virtual Fiber Pair model for spectrum sharing, options exist to minimize cases where ASE switching is applied to the tenant's entire spectrum, and instead ASE switching can be minimized and only a failed channel/carrier can be replaced with ASE. Hold-off timers can be incorporated if multiple layers of ASE protection are available.

The tenant's spectrum share will not be restored to the subsea line until it has been thoroughly verified, to ensure that it meets the required target power and poses no risk to other spectrum users on the same fiber pair

As can be noted, the protection triggering thresholds are a fundamental value to be defined based on the expected behavior of the fiber pair. It should be noted that newer uncompensated cables are more tolerant to power per carrier changes compared to older fiber cable systems based on dispersion-managed fiber.

Figure 14 shows an example where the total fiber spectrum is split in half between two tenants, and shows

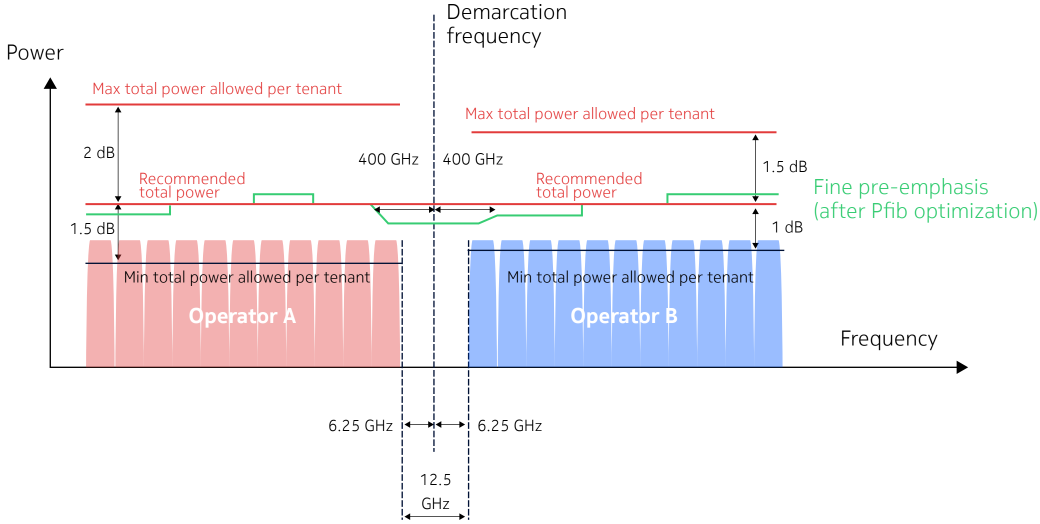
a) the target power per spectral share,

b) the fine pre-emphasis defined to provide the best performance on both ends,

c) guard bands

d) the upper and lower thresholds for the ASE protection.

Figure 14 Spectrum Power Control and Guard bands



This example reveals several noteworthy details. From a power perspective, the upper and lower limits are not the same since, as explained previously, the tolerance to change is smaller in the blue side of the band. From the separation perspective, it can also be noted that the pre-emphasis attenuation is increased in the guard band to minimize the impact of the neighboring carriers of the two tenants.

Guard bands

Guard bands are another important metric that must be considered and defined when setting up a fiber pair for spectrum sharing. Defining optimal guard bands will isolate interaction between tenants without sacrificing too much spectrum. Typically, the guard band definition depends on the type of fiber cable, based on either newer uncompensated or legacy compensated fibers, the type of modem, and ROADM technology used. Typically, a 12.5GHz guardband is sufficient to separate spectrum slices, but if the tenant and fiber pair owner use the same vendor, this could be reduced. For example, in a fiber cable using Nokia optical transport solutions across the entire spectrum, the guard bands between spectrum sharing slices can be less than 5GHz.

It should be noted that the SubOptic Working Group for Spectrum Sharing uses the term “Dead Bands” which, in practical terms, refer to the same definition as guard bands; namely spectrum areas that can’t be used for full or partial carrier/channel allocation.

Considerations for compensated fiber cables

The important issues mentioned previously require a more careful definition when older generations of subsea fiber cables are used to implement spectrum sharing. The chromatic dispersion compensation design of these compensated cables complicates the implementation of spectral sharing but does not prevent the cable owner from offering it. The definition of what spectrum areas are available for potential tenants becomes more complicated since the presence of older non-coherent (ie: OOK) carriers or Continuous Wave (CW) idlers could reduce the portions of spectrum available, in both size and number.

Additional specific design rules need to be agreed between both parties to guarantee the correct operation of the surviving carriers during channel/spectrum block protection events. Some relevant considerations and areas of required agreement between cable owner and spectrum sharing tenant include,

a) Transmission performance that varies based on which parts of the spectrum are used, requiring parties to agree on expected capacity projections.

b) Capacity projections will vary based on transponder technology used and corresponding NL impairment mitigation capabilities, which also requires parties to agree on capacity projections.

c) CW idler positions should be pre-defined and excluded from spectrum passbands.

d) Compensated systems are older and thus have a higher probability of having an impaired spectrum, for example due to gain tilt from fiber cable repairs that have occurred over time. These impacts should be considered in advance when considering new spectrum sharing deployments.

e) The fiber cable owner should confirm the presence of CW idlers at the edges of the shared spectrum, which may then require additional guard bands.

f) Upper and lower narrow thresholds for PSD or total power (compared to uncompensated cables) need to be defined, since even a small change in the tenant's shared spectrum could have an impact to the neighboring channels. This would also be very dependent on the spectral region affected.

g) The fiber cable owner could restrict the use of older transponders based on non-coherent carriers, in order to reduce stability issues

h) The fiber cable owner should block the zero-dispersion region since this is a critical part of the spectrum

i) Wider guard bands (dead bands) of 25GHz to 50GHz could required into order to best isolate different parts of the spectrum and to minimize cross-band interactions

j) Tenant spectrum reinsertion after a failure must typically always be done in a manual fashion due to the reduced stability on older compensated cable/fiber types

k) Tenant use of a full SLTE to provide partial ASE insertion could improve operations in these cable types, but will result in a higher cost per bit for the tenant due to the additional hardware required.

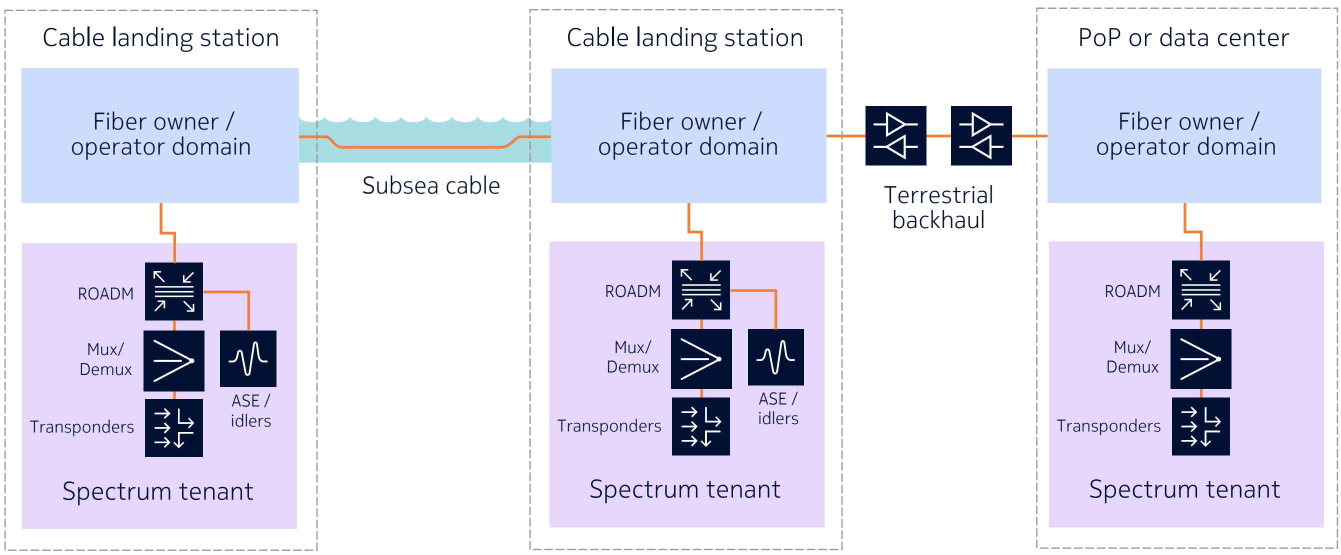
l) A useful option could be to further divide the shared spectrum assigned to the tenant through the use of narrower spectrum blocks, so that the impact of carrier failures is limited.

Special cases for spectrum protection

As was discussed in previous sections, a hierarchal order between the fiber cable owner and one or more shared spectrum tenants is required to prevent issues in spectrum protection for all users. The protection in cases where the subsea traffic by the tenant and fiber pair owner originates and terminates at the CLS is described above. In many cases however, protection requirements apply to more complex scenarios that include terrestrial backhaul links to DCs or PoP's, add/drop at the CLS, and more.

We explore below some of these typical use cases and discuss important details about each one.

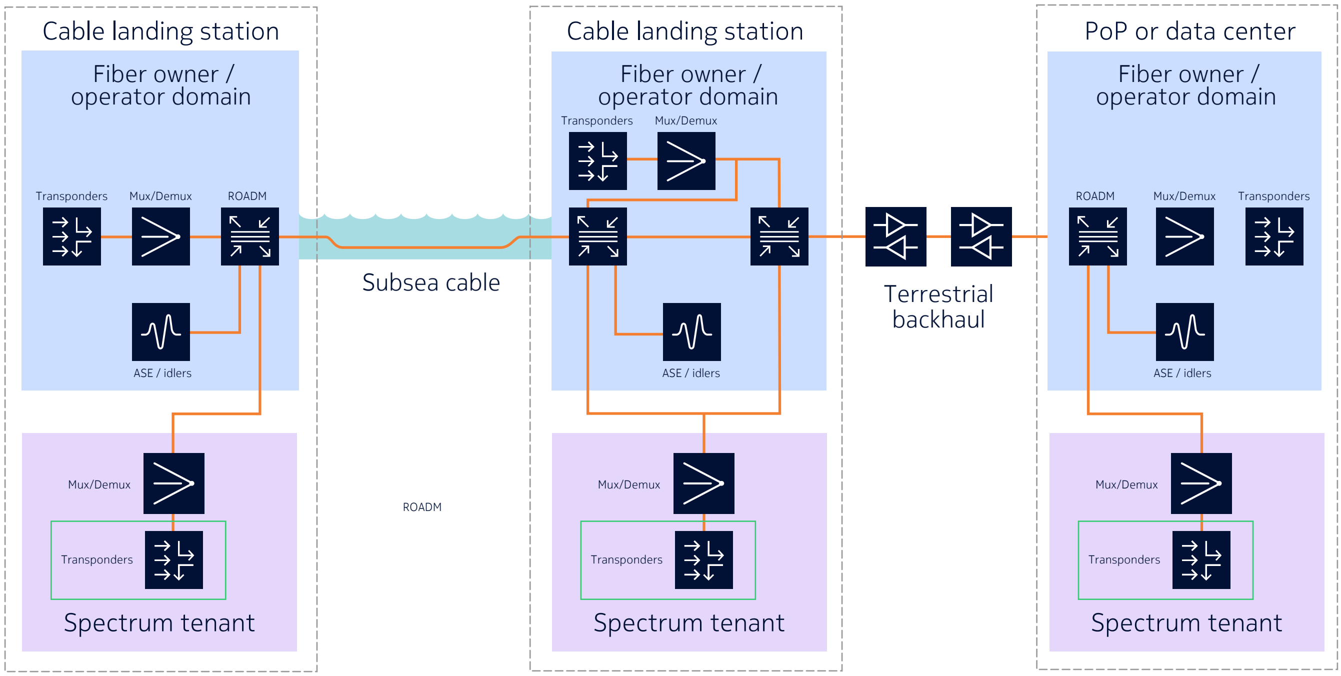
Figure 15: Tenant with full SLTE



When a spectrum sharing tenant deploys a full SLTE, the SLTE and transponders can come from any vendor and proper configuration must ensure that:

- Tenant line card failures are protected by ASE insertion from the tenant SLTE
- The fiber cable owner must monitor the complete spectrum blocks of the spectrum sharing tenant(s), and be prepared to replace these spectrum blocks with ASE in case power from the tenant exceeds upper thresholds, or fails to meet a minimum threshold
- Tenant can have full autonomy in managing their portion of the network under the SLA between the parties
- If the tenant's SLTE is from Nokia, Nokia IPM optimization and automation tools are available for use across the tenant's network domain
- Tenant configuration can include backhauls to DC/PoP locations

Figure 16: Tenant “Lite” SLTE with Nokia transponders



As shown in Figure 16, when the spectrum sharing tenant deploys Nokia transponders (circled in green) and allows the fiber pair owner access to them for O&M activities, the tenant does not see the owner's network and cannot access any of their network elements. From the SLTE point of view, these transponders are handled the same as the fiber pair owner's own transponders, which if using Nokia can also include use of the IPM optimization and automation software applications.

In this case, the fiber pair owner manages capacity optimization, pre-emphasis, channel plan creation, mode optimization, power targeting, and other important attributes. Additionally,

- The tenant transponder line cards are protected, in case of transponder failure, by ASE provided by the fiber pair owner's SLTE
- The tenant can fully manage the client services (ie: 100GE, OTU4, 400GE) carried over the system
- The tenant can monitor the optical performance of their own transponders.
- Tenant configuration can include backhauls if supported by the fiber cable owner's topology

Equipment management

Another aspect to be considered for both the fiber pair owner and spectrum tenant is how equipment from the tenant will be managed. The two primary options are where (1) the tenant gives the fiber pair owner management access to the tenant's transponders, and (2) when neither party (either the fiber pair owner, or spectrum tenant) sees the other party's network elements.

In the first case, the tenant can provide the fiber pair owner management access to their transponders. If the tenant's transponders are from Nokia, the fiber pair owner can utilize both Nokia's EMS and IPM automation tool to configure, optimize and manage the tenant's transponders. If the tenant uses third-party transponders and the fiber pair owner uses Nokia, then the tenant must provide view access to their 3rd-party EMS to the fiber pair owner, and Nokia's IPM will not be able to communicate or configure the transponders.

In that case, any power management actions (ie: channel insertion, re-insertion, etc) normally performed automatically by Nokia's IPM would need to instead be manually carried out by the fiber pair owner. Capacity optimization of the tenant's spectrum, for example reading transponder Q for establishing pre-emphasis, channel plan creation, mode optimization, power targeting, etc., would be performed by the fiber pair owner using third party EMS tools. Tenant transponder protection would be provided by ASE from the fiber pair owner SLTE. Meanwhile the tenant retains full management control of their digital client services (ie: 100GE, OTU4, 400GE) carried over the system and can also continue to monitor the optical performance of their transponders.

A second case occurs when transponders are sourced from any vendor, including Nokia, but the tenant does not provide the fiber pair owner access to them. In that case, the fiber pair owner monitors the tenant's spectrum blocks, and replaces complete blocks with ASE in case the tenant's spectrum power exceeds upper thresholds, or fails to meet lower thresholds. In this case, capacity optimization requires close coordination between fiber pair owner and spectrum tenant for all O&M activities including pre-emphasis, channel plan creation, mode optimization, power targeting etc.

Guidance on threshold settings for tenants and fiber cable owner

Depending on the different modes of connection between the spectrum sharing tenant and the fiber cable owner, different equipment settings are recommended. The tables below provide a summary for different use cases.

a) Fiber pair owner deploys Nokia SLTE and spectrum sharing tenant deploys Nokia full SLTE and transponders (Virtual Fiber Pair mode)

Attribute	Uncompensated SDM fiber	Legacy compensated fiber
Upper threshold for tenant spectrum block	0.8dB (1)	Each spectrum area requires analysis
Lower threshold for tenant spectrum block	-0.8 to -1.5dB (1)	Each spectrum area requires analysis
minimum guard band between tenant and fiber cable owner spectrum blocks	>2GHz	>2GHz (2)

Note 1: The exact threshold depends on several factors and could be revisited depending specific spectral sharing conditions, position, size, etc

Note 2: Additional guard bands could be required if CW idlers are present in the spectrum

b) Fiber cable owner deploys Nokia SLTE and spectrum sharing tenant deploys Nokia transponders (SLTE "Lite" mode)

Attribute	Uncompensated SDM fiber	Legacy compensated fiber
Upper threshold for tenant spectrum block	Defined by fiber cable owner	Each spectrum area requires analysis and setting by fiber owner
Lower threshold for tenant spectrum block	Defined by fiber cable owner	Each spectrum area requires analysis and setting by fiber owner
Minimum guard band between tenant and fiber cable owner spectrum blocks	>2GHz	>2GHz (1)

Note 1: Additional guard bands could be required if CW idlers are present in the spectrum

Spectrum tenant guidelines

Certain key technical parameters/topics that are essential in the definition of a spectrum sharing service between the fiber pair owner and the spectrum tenant should be included in the committed SLA between the parties. These include;

a) Target specifications for SNR and GSNR (average and worst case) for the tenant's cable system/fiber pair/spectral share
b) Tenant model type, either SLTE "Lite" or Virtual Fiber Pair, and associated definition of ASE responsibility and high-level upgrade sequence
c) Passband size (start/stop frequencies)
d) Guard bands, which must consider filter sizes and possible wet plant ROADM characteristics.
e) PSD value
f) Tenant total power for the assigned spectral share
g) Upper and lower power thresholds for tenant's spectral share used to trigger protection mechanisms
h) Spectrum protection triggering delay and recovery mechanism, either manual or automatic
i) Estimated spectrum capacity based on the selected transponder vendor, technology and features.

The technical topics above are mentioned in the Suboptic Spectrum Sharing WG recommendations set out in the Key Parameters Table (KPT), added in Appendix A. Figure 17 shows a suggested table that can be used and agreed between the parties involved to capture these KPI specs/topics.

Figure 17: KPT for spectrum sharing SLA definition

Nokia spectral sharing technical data and requirements FP/DLS#			
Assigned spectrum specifications	**Tenant 1**	**Tenant 2**	**Notes**
Assigned spectrum start/stop frequencies (THz)			Add additional columns if more than 2 tenants of FP owner
Guardband requirement on the spectrum edges (GHz)			If available and the spectral share definition is based in this value, common in recent D+ open cables
$GSNR_{AVG}$ (dB)			If available and the spectral share definition is based in this value, common in recent D+ open cables
$GSNR_{WORST}$ (dB)			6.25 / 12.5 GHz is the typical value
Spectrum controller ITU grid granularity (GHz)			Number of slices for the spectral share assigned multiplied by the PSD value
Recommended total power at the input port of the spectrum interface for the assigned spectrum			
Power spectral density (12.5/6.25 GHzgranularity (dBm)			
Maximum allowable PSD variation (dB) (+/-)			
Expected power at the output port (Rx of the spectrum interface for the assigned spectrum (dBm)			

Nokia spectral sharing technical data and requirements FP/DLS#	
Spectrum controller (SMB) settings	
Maximum total inpout power in the assigned spectrumbefore ASE power protection is triggered	
Minimum input power in the assigned spectrum before ASE power protection is triggered	
ASE power protection mode (auto or manual)	
ASE protection revertion upon restoration of power (auto or manual)	
Spectral controller (SMB) current attenuation setting	
Spectrum controller (SMB) protection active in the entire spectrum	
Tenant spectral share spec and channel plan (optional)	
Planned channel plan for the tenant spectral share (include edge frequencies, central frequency and channel width)	
Required passband per carrier (with or without GB's) (THz)	
10 GB/s or older technology carriers active in the spectrum (yes or no)	
Power optical manager with ASE protection used in the tenant SLTE (yes or no)	

Useful software functionality requirements

When selecting an optical power management tool, including Nokia's IPM, there are a few requirements that must be included in the software solution to enable easy initial setup and ongoing daily operations and maintenance. Examples of relevant functionalities desired in a power management tool include:

a) Spectrum view with a high level of granularity, usually better than 3 GHz, in order to have maximum level of resolution of carriers and edge areas.

b) Automated P_{fib} setup to expedite the pre-emphasis adjustment.

c) Generation, storage, and manipulation of fiber pair baselines allowing a comprehensive analysis of the evolution of the spectrum in normal and failed conditions.

d) Availability of different optical passband setup sizes so the spectrum protection can be applied to the maximum granularity possible, usually, channel level.

e) Configurable alarm and protection threshold settings so it can be adapted to any type of spectrum sharing configuration or cable system technology.

Acceptance Testing

Once the SLA has been defined and spectrum sharing deployed, the acceptance testing of the shared spectrum service is a key element needed to confirm the proper setting of ASE protection thresholds, and could help to fine-tune these in case the test cases show issues.

A summary of important test cases to consider as part of acceptance testing includes possible cases of carrier failure in the tenant spectrum, including the following considerations:

1) The testing protocol must include cases with total loss of light and partial loss of carriers in the fiber pair owner's channels as well as the tenant, and in cases of compensated cables, in different regions of the available spectrum.

2) If the fiber pair is newly provisioned, this can be accomplished when transponder signals from both the fiber pair owner and the tenant are available, as using only ASE would not provide a real testing of the behavior during failure.
3) If the fiber pair is carrying traffic, a Service Affecting (SA) Maintenance Window (MW) would need to be set up to verify the correct settings and operation. This could be a complex process but is the only viable way to verify the proper setup.
4) If any test fails, all thresholds will need to be analyzed between the parties to define adjustments to the settings and tested again until the required behavior is achieved.
5) For the case of the Virtual Fiber Pair mode, a subset of tests can be added to confirm that ASE/channel operations within the tenant spectral share have no effect on the other traffic across the fiber pair.

References

(1) Norris Richard, et al. Spectrum Sharing Working Group. May 2025, SubOptic SubOptic Resource | SubOptic

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(3) Kam, A. et al. Pre-emphasis-based Equalization Strategy to maximize cable performance. Suboptic 2019.

(4) Dass, R. et al. Translating GSNR into Capacity - SubOptic Open Cables Working Group White Paper 2023

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Appendix A: SubOptic Spectrum Sharing white paper recommended KPI tables

Spectrum Sharing Performance Key Parameters

Item	Spectrum characteristics key parameters	Example parameters
1	Spectrum bandwidth (GHz)	1000
2	Start & stop frequencies (THz)	192.5–193.5
3	Per FP spectrum allocation block diagram (Y/N)	Y
4	BoL GSNRAVG of the spectrum allocation (dB)	10.5
5	BoL GSNRWORST of the spectrum allocation (dB)	9.7
6	Ageing and repair margin over the life of the service (dB)	0.5
7	Dead band included in the user's allocation (Y/N)	Y
8	Dead band at each side of the allocation (GHz)	6.25
9	Total service dispersion (ps/nm)	7000

More detail for each of these parameters is defined below:

1. Spectrum bandwidth (GHz)

The total frequency allocation for the spectrum service in GHz. For example: 1000 GHz.

2. Start & stop frequencies (THz)

The start and stop frequencies for the spectrum service in THz. For example: 192.5 to 193.5 THz.

3. Per fibre pair spectrum allocation block diagram

The provider may offer to give the user information on where their spectrum service relates to other services on the same fibre pair. A spectrum allocation block diagram may be a suitable way to provide this information. Users are required to supply detailed spectrum allocation data to the provider but are not entitled to receive detailed information about the spectrum allocations of other users.

4. BoL average GSNR (dB)

The spectrum service Beginning of Life (BoL) performance expressed as average GSNR (dB). It is expected that performance will have some variation versus frequency so this parameter will be the average across the spectrum service frequency range as defined in points 1 and 2. The parameter will be from SMB port to SMB port and cover the entire end-to-end spectrum service.

5. BoL worst GSNR (dB)

The spectrum service Beginning of Life (BoL) performance expressed as worst case GSNR (dB). This parameter will be the lowest GSNR value within the allocated frequency range. The parameter will be from SMB port to SMB port and cover the entire end-to-end spectrum service.

6. Ageing and repair margin

The provider recommended ageing and repair margin in dB that a user should expect to impact their spectrum service over the IRU period. The user may or may not decide to implement this margin.

7. Dead band included

As defined in section Error! Reference source not found., there is always a small dead-band between spectrum services. This parameter identifies whether the dead-band is included in the user's frequency allocation or not. If it is included, then the user will not be able to place optical channels at the extreme edges of the frequency allocation. If it is not included, then the user will be able to place traffic channels at the extreme edges of the frequency allocation with no performance impact.

8. Dead band size

If the dead-band is included in the user's frequency allocation, this parameter defines its size in GHz and is the unusable space at the edges of the frequency allocation.

9. Total service dispersion (ps/nm)

The total Chromatic Dispersion for the spectrum service. The parameter will be from SMB port to SMB port and cover the entire end-to-end spectrum service.

Spectrum sharing operational key parameters

Item	Spectrum operational key parameters	Example parameters
1	PSD target at SMB input from user SLTE (dBm/ X GHz)	-10.0 / 6.25
2	Total power target at SMB input from user SLTE (dBm)	9.0
3	PSD target from SMB to user SLTE (dBm/ X GHz)	-16.0 / 6.25
4	Total power target from SMB to user SLTE (dBm)	3.0
5	ASE replacement mode (automatic or manual)	Auto
6	Automatic ASE replacement hold-off time (s)	60
7	Triggering condition for major alarm and for automatic ASE replacement (dB)	+/- 3
8	Triggering condition for minor alarm warning of power variation (dB)	+/- 2
9	ASE removal and spectrum service reinstatement mode (automatic or manual)	Manual
10	Automatic service reinstatement hold-off time (minutes)	30
11	Optional channel plan (User to Provider)	Y/N

More detail for each of these parameters is defined below:

1. PSD target at SMB input from user SLTE (dBm/ X GHz)

The Power Spectrum Density (PSD) per X GHz from the user's SLTE to the provider's SMB. This is a more granular power requirement specified per X GHz, therefore, independent of the total spectrum service width. The GHz is not defined in this document as it is vendor specific and will vary, however, it should be agreed between the provider and user when completing the table for their contract.

2. Total power target at SMB input from user SLTE (dBm)

The nominal total optical power that a user's SLTE should output into the provider's SMB. This power level will be in relation to the total spectrum service width as defined in Error! Reference source not found.. The thresholds for alarm conditions will be in reference to this parameter.

3. PSD target from SMB to user SLTE (dBm/ X GHz)

The Power Spectrum Density (PSD) per X GHz from the provider's SMB to the user's SLTE. This is a more granular power requirement specified per X GHz, therefore, independent of the total spectrum service width. The GHz is not defined in this document as it is vendor specific and will vary, however, it should be agreed between the provider and user when completing the table for their contract.

4. Total power target from SMB to user SLTE (dBm)

The nominal total optical power that the provider's SMB will output into the user's SLTE. This power level will be in relation to the total spectrum service width as defined in Error! Reference source not found..

5. ASE replacement mode

With automatic mode selected the SMB will replace the user's spectrum with ASE automatically when a major PSD violation is detected (as per line 6). With manual mode the provider will be required to act when the major alarm is detected and replace the user's spectrum with ASE.

6. Automatic ASE replacement holds off time (s)

If ASE replacement is set to automatic, the SMB will delay the ASE insertion for a defined number of seconds. This will allow the user to have some time to rectify any issues they have.

7. Triggering condition for major alarm and automatic ASE replacement (dB)

The maximum total optical power thresholds of the SMB input from a user's STLE with both positive and negative ranges. If the input total power from the spectrum user exceeds the upper or lower threshold it will trigger a major alarm and ASE replacement if it is set to automatic.

8. Triggering condition for minor alarm warning of power variation (dB)

Lower total optical power thresholds of the SMB input from a user's STLE with both positive and negative ranges. If the input total power from the spectrum user exceeds the upper or lower threshold it will trigger a minor alarm but no ASE replacement.

9. ASE removal and spectrum service reinstatement mode (automatic or manual)

Once the user has restored their input to the SMB, the SMB will remove ASE and reinstate the user's spectrum service. This can be done automatically or manually with the provider having the ability to decide if the service can be restored.

10. Automatic ASE reinstatement hold-off time (minutes)

If the service reinstatement mode is set of automatic, there is an option to hold off for a number of minutes. This will ensure that there are no fluctuations in the user's input, and it is sufficiently stable to be restored.

11. Optional channel plan

To aid the provider's understanding of how the spectrum users are loading their allocations, each user is given the option to provide a channel plan. This parameter is defined as optional and for the provider and user to agree on if it should be provided and the level of detail included.

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