HANDBOOK

# Open Submarine Cable Channel Planning

## Applications and Considerations

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## 1. Introduction to Channel Planning for Open Submarine Cables

### 1.1 The Critical Importance of Channel Planning

Historically, optical networks used a fixed-grid spacing that dictated channel placement. Available bandwidth was split initially based on filter technology limits and each channel had to match each allocated spectrum slot.

Following the introduction of Dense Wavelength Division Multiplexing (DWDM), the definition of specific slots within the bandwidth was extended to a grid based on 12.5 GHz, as defined in ITU-T G.694.1 “Spectral Grids for WDM Applications: DWDM Frequency Grid” recommendation. In this recommendation, the frequency grid, anchored to 193.1 THz, supports a variety of channel spacings ranging from 12.5 GHz to 100 GHz. For example, for channel spacings of 25 GHz on an optical fiber, the allowed channel frequencies (in THz) are defined by $193.1 + n \times 0.025$, where $n$ is a positive or negative integer including 0.

This ITU-T recommendation was further enhanced to include a ‘flexible grid.’ The motivation for the introduction of this flexible grid was to allow mixed bit rate or mixed modulation format transmission systems to allocate frequency slots of different spectral widths. In this flexible grid scheme, channel widths of $n$ x 12.5 GHz could be accommodated. For example, a mix of channels at 37.5 GHz and 50 GHz could be selected and allocated anywhere in the allowable optical spectrum.

This initial flexible grid system was suitable for transponders based on Intensity-Modulation Direct Detection (IMDD) technology and Submarine Line Terminal Equipment (SLTE) with fixed Multiplexer/Demultiplexer (MUX/DEMUX) structures, which also led to fairly simple channel planning. However, it was still anchored to a specific frequency and a slot width granularity of 12.5 GHz, which is simply unsuitable once coherent optical detection technology was established in SLTE modems.

The introduction of coherent optical technology led to two major changes. Coherent transponders can tune to the frequency of interest while rejecting other signals in the electrical domain without requiring optical filtering, which enables the optical MUX/DEMUX infrastructure in the SLTE to move to a truly gridless technology. This in turn allows modems operating at different bauds (symbols per second) to coexist in the same MUX/DEMUX structure.

Once the ability to manage any baud was ensured, modem development looked to maximize the baud with each generation, increasing the potential line rate and reducing the cost per bit. Furthermore, recent generations of coherent modems are capable of selecting the baud, improving total capacity or spectral efficiency and further reducing the cost per bit.

While the move to true flexible-grid (also referred to as flexgrid) architectures and increasingly higher bauds provides the benefits of higher line rates, improved spectral efficiency, and a lower cost per bit, it also comes with significantly increased complexity in planning the placement of the channels in the available optical spectrum. Fixed-grid channel planning could be done manually via simple spreadsheets, but flexible-grid technology has introduced complexities in channel planning related to both varying spectral occupancy requirements from different transponders, as well as filter impact rules based on the MUX structure and photonic equipment. As a result, channel planning on modern submarine networks requires more sophisticated tools to maximize spectral efficiency and validate rules imposed by the SLTE.

This handbook explores the concepts and considerations required in channel planning for a modern flexible-grid submarine network.

### 1.2 Channel Planning Terminology

As most modern submarine cables use flexible-grid photonics systems, much of the terminology used in channel planning is aligned to the ITU flexible-grid recommendations outlined in ITU-T G.807. Prior to discussing channel planning concepts, it is useful to review the terminology used.

The ITU recommendation outlines the concept of a Media Channel (MC) and a Network Media Channel (NMC), which define the optical path through a system and the location of channels within that path.

An MC describes the allocation of spectrum in a transmission fiber. The width of an MC can be expressed by two edge frequencies. In real-world examples, these edge frequencies are each aligned with the resolution of the Wavelength-Selective Switch (WSS) controllable elements, often referred to as ‘pixels.’ In many WSS implementations, the WSS is defined in 6.25 GHz increments. This constraint will be explored later in channel planning optimization.

The NMC is the allocation of spectral width within an MC in which the signal is confined. Each MC can accommodate multiple NMCs. NMCs within an MC are routed together from the multiplexing node to the demultiplexing node. There is normally a one-to-one correspondence between signals (i.e., modems) and NMCs.

The MC and NMC concepts are illustrated in Figure 1-1 which shows how a 35 GBaud channel would be mapped to NMCs and MCs.

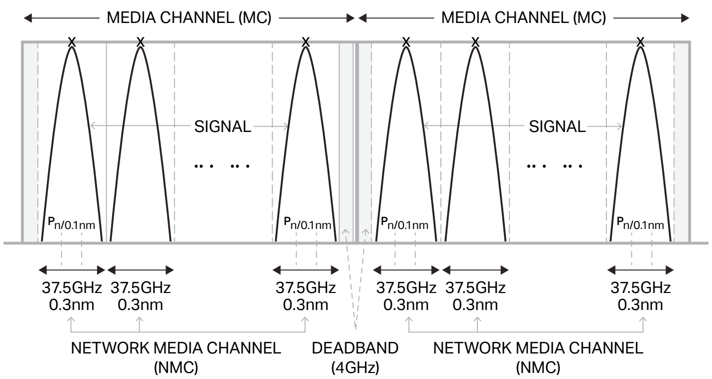


*Figure 1-1. Flexible-grid definitions*

In addition to ITU definitions, there are a few other useful concepts related to channel placement, including guard band, channel spacing, and dead band.

Guard band is the space between optical channels required by link engineering for considerations such as cross talk and other WDM effects. Channel spacing is the space between two neighboring channels' center frequency, which is marked with Xs in Figure 1-1. Notice that channel spacing may vary even with the same channel type due to the presence of guard band and/or dead band.

In fixed-grid systems, the filter shape dictated the size of channel that could be placed in the filter. This left gaps in the spectrum where channels were not placed due to the detrimental effects of the filtering. In flexible-grid systems, the size of the filter is adjustable using the WSS, but filter roll-off effects are still experienced at the edges of the defined bandwidth. This spectrum is referred to as 'dead band.' The size and number of dead bands is defined by the MC provisioning and the WSS specifications, and must be accounted for when planning channel placement.

## 2. Channel Planning for a Point-to-Point Link

### 2.1 High-level Process

The planning of capacity is an important component in the design and operation of submarine cable networks. It requires the specification of the operating spectrum of the fiber pair and the allocation of channels within that spectrum to plan, visualize, and deploy submarine network solutions. There are two types of cable states for channel planning exercises: a greenfield cable state and a brownfield cable state. The latter is typically more complex as existing optical channels must be considered in the process.

The channel planning process for both greenfield and brownfield cables can be divided into three steps: mapping the network topology, creating routes (flows) over the topology, and populating the routes with traffic (channels).

The mapping of network topology defines the relationship between terminal sites (such as the Cable Landing Station [CLS], Point-of-Presence [PoP], or data center), fiber pairs, and undersea Branching Units (BUs).

Flows are created based on the topology, including how spectrum is routed at any BU on the path. The optical path flows of the flexible-grid architecture thus define the traffic sub-network connection groups.

Optimized channel planning focuses on populating the spectrum with channels while minimizing wasted space and maximizing space that could be converted into spectrum for additional channels. Any unused space remaining is called 'unallocated spectrum.'

### 2.2 Point-to-Point Channel Plan Example

The following example outlines the channel planning process for a fictious point-to-point greenfield system.


*Figure 2-1. Point-to-point submarine cable example*

As it is a point-to-point system, there are no considerations required for BUs and all spectrum is available between site A in Halifax to site Z in Lisbon. This example assumes an operating bandwidth from 191.325 THz to 196.125 THz.

In a simple fixed-grid configuration, the channels would be placed based on the predefined grid between the start and stop frequencies of the submarine cable. Using ITU terminology, this would be defined as a system with a number of MCs that each contain a single NMC.

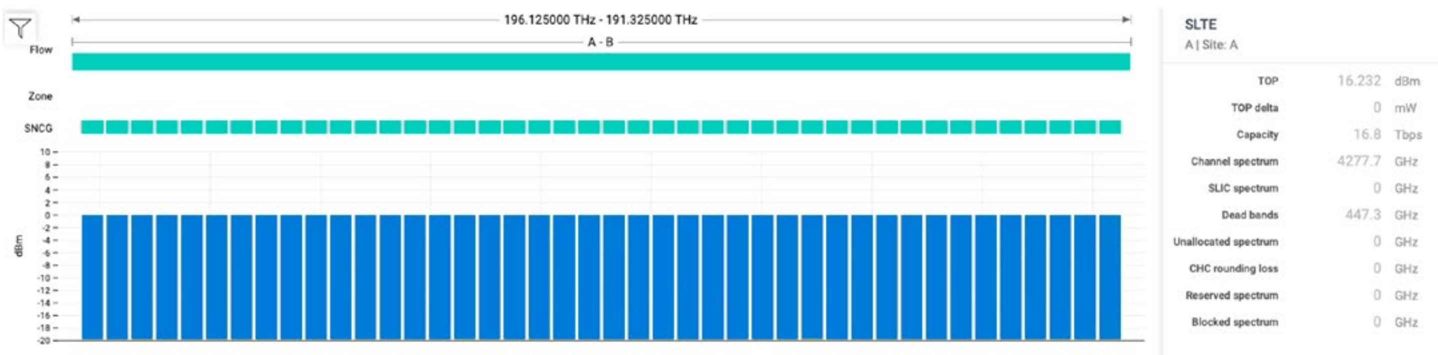


*Figure 2-2. Fixed-grid channel plan*

In this configuration, 42 channels can be placed in the spectrum but the use of the fixed filter results in unused spectrum from the filtering shape (i.e., dead band). To improve the total capacity, a flexible-grid MUX is used to reduce the dead bands and allow more channels to be added.

To reduce the number of dead bands, channels are grouped together to have multiple NMCs in the same MC. This uses the same flexible-grid filter for multiple channels and minimizes the number of times spectrum must be allocated to dead band. While the most efficient solution would be to have all NMCs in the same MC with any dead band at the very edges of the spectrum, the MUX structure and channel routing options may limit the ability to do this.

When grouping channels into an MC, the selection of start and stop frequencies for the MC and the alignment of those frequencies to the SLTE must be taken into consideration. The selection of an MC edge that is not aligned with a WSS pixel resolution may create a tiny amount of 'wasted' space, called 'rounding loss.' These wasted spaces accumulate with the number of MCs or instances of edge frequency alignment with WSS pixel resolution.

Figure 2-3 illustrates an example of a channel plan that does not take wasted space into account. While the total number of channels is increased over the fixed-grid case, the amount of waved spectrum—in dead bands, unallocated spectrum, and Channel Controller (CHC) rounding loss—results in a total decrease from the theoretical maximum number of channels.

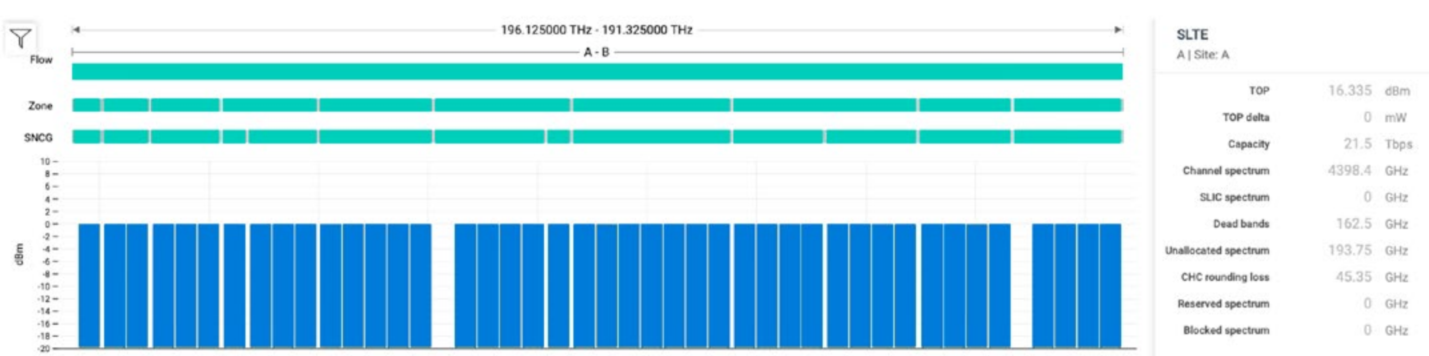


*Figure 2-3. Flexible-grid channel plan*

When taking into consideration the constraints of dead band and WSS granularity, the available number of channels that can fit within the available optical spectrum is no longer a quick division between bandwidth and channel spacing; the flexible channel plan optimization is focused around minimizing those wasted spaces by varying channel grouping and the type of baud within the group.

By using an intelligent routing algorithm, a channel plan can be found that minimizes the impact of all these control points and results in a solution that maximizes the total capacity, as show in Figure 2-4.

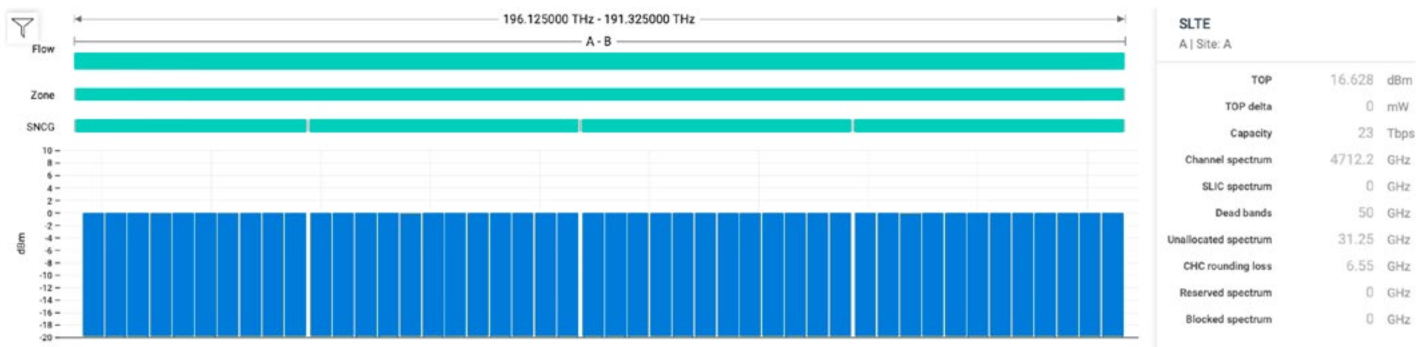


*Figure 2-4. Optimized flexible-grid channel plan*

## 3. Network Considerations

### 3.1 Power Management

Examples in this handbook consider full-fill channel plans, but consideration must be taken for power management in cases where the entire optical spectrum is not filled with channels.

For today's dispersion uncompensated networks, amplifier-shaped Amplified Spontaneous Emission (ASE) is normally used for power management. ASE can be shaped to represent a channel and have the same NMC definition as a traffic channel when creating an MC. The channel-planning exercise, including ASE, is akin to the exercise with full-fill traffic channels, where ASE is placed to fill empty spectrum. This will result in a channel plan that consists of MCs with traffic and separate MCs with power management. Over time, as traffic grows in size and composition, MCs will change with the reduction in ASE holding MCs.

In dispersion-compensated networks, high-power idler channels are often used for power management in addition to ASE. In many cases, these idler channels remain even at full-fill system conditions. This will result in a combination of MCs containing traffic channels, MCs containing ASE, and additional MCs containing high-power idlers. In this case, NMCs that are used to define the high-power idlers will be based on the specification of the idlers. The spectral occupancy and placement requirements for the high-power idlers may result in spectrum lost to dead bands, unallocated spectrum, and CHC rounding loss.

### 3.2 The Impact of Branching Units

#### 3.2.1 Branching Unit Primer

Modern submarine cable systems may incorporate undersea BUs to provide optical add/drop capabilities on branches connected to a high-bandwidth 'express' path. This allows the sharing of a fiber pair between multiple landing points in an efficient way.

From a channel planning perspective, BU devices in the submarine cable create multiple optical paths or flows between the end points in the system. As illustrated in Figure 3-1, some BUs provide traditional fixed-path filters while other BU devices provide Optical Add/Drop Multiplexer (OADM) filters to allow the sharing of a fiber pair between express and branch paths.

Traditionally, the OADM filters used thin film technology for fixed-width filters for branches, which resulted in spectrum filter ratios for branches and did not allow for changes if traffic demands changed over the lifetime of the cable system. The next generation of BUs provided optical switches to allow a few predetermined branch filter ratios that could be selected depending on capacity needs.

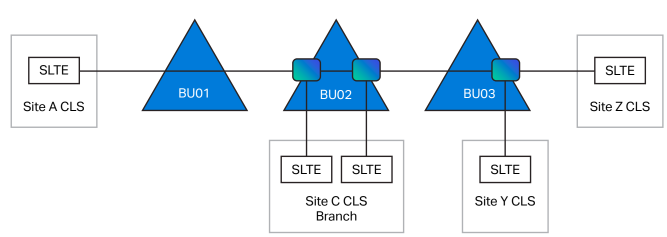


*Figure 3-1. Example submarine cable with 3 BU devices*

Modelling of the BUs in planning tools is required to ensure that the maximum number of channels can fit into the allocated flow frequency ranges. An additional challenge has been the emergence of higher baud transponders, for which some fixed OADM filter widths—chosen 10 to 15 years ago—may not support efficiently.

With the advent of high-reliability, undersea-qualified WSS devices, new BUs may be equipped with one or more WSS devices. This allows for fully reconfigurable spectrum allocation among the trunk and various branches to allow for changes in spectral range allocation among branches, and also allows for future transponder technology innovation. The use of WSS in BUs can make a simple asymmetric add WSS solution, a more complex symmetric add/drop solution, or an even more complex true three-way add/drop solution, shown in Figure 3-2.

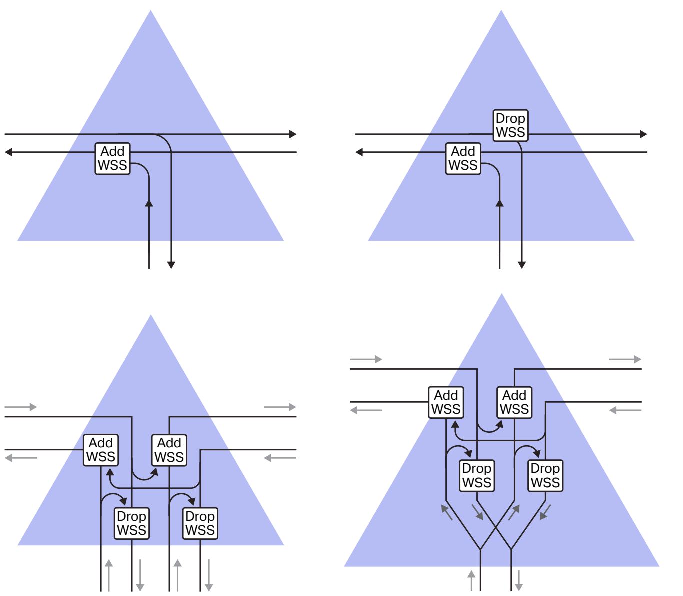


*Figure 3-2. New BU variants using reconfigurable WSS technology*

While WSS devices do not have a perfectly square filter shape, their filter shape is much sharper than older OADM BUs that used Thin Film Filter (TFF) or Fiber Bragg Grating (FBG) technologies. Therefore, lost spectrum due to dead bands are smaller with WSS filter devices than previous generations of filters, which improves the overall spectral efficiency of the submarine cable system.

### 3.3 Branching Unit Channel Plan Example

The following example outlines the channel planning process for a fictious system between Halifax and Lisbon with a branching unit that goes to Land's End.

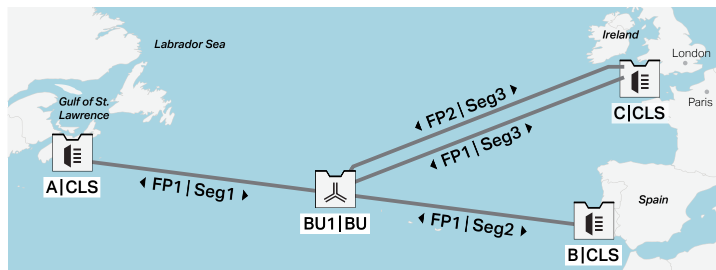


*Figure 3-3. BU submarine cable example*

In this submarine cable system, the spectrum that goes along the branch has to be taken into account when doing the channel planning. In this example, the repeater bandwidth stays the same as in the point-to-point example (191.325 THz to 196.125 THz) but frequencies between 192.894 THz and 194.175 THz have been configured at the WSS BU to be connected to the branch.

As with the point-to-point case, creating as few MCs as possible will minimize wasted spectrum. The existence of the BU will dictate how few MCs can be created. The dead bands created by the BU WSS filter further decrease the remaining useable spectrum. Alignment of the BU filters to the granularity of the SLTE WSS provisioning is also important in maximizing the available spectrum for channels. The alignment of the MC edges with the WSS pixel resolution and combined with an inefficient channel-fill algorithm can result in a valid, but non-optimized, channel plan, as shown in Figure 3-4.

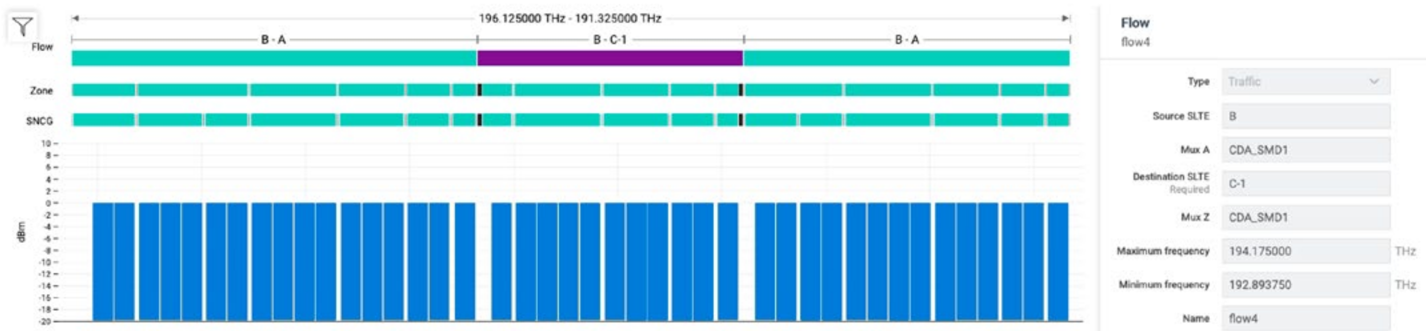


*Figure 3-4. Undersea submarine cable BU channel plan*

By using a more efficient channel-fill algorithm and aligning the WSS edges and dead bands, between the BU WSS and the SLTE WSS the amount of overall wasted optical spectrum can be minimized.


*Figure 3-5. Optimized submarine cable BU channel plan*

## 3.4 The Impact of Spectrum Sharing

### 3.4.1 Spectrum Sharing Considerations

As with the BU example, the use of spectrum sharing increases the number of filter points forced on the spectrum, which results in spectrum being lost to dead bands as each spectrum user is allocated separate MCs to ensure security and privacy in their spectrum.

While the same MC and NMC terminology can be used for spectrum sharing, the definitions slightly change. In spectrum sharing, the intent is that the spectrum provider does not have knowledge of the content of the spectrum used by the purchaser. As a result, the NMC is not defined as the content of a photonic channel (i.e., wavelength) but instead of a spectrum channel, which can contain an arbitrary spectrum fill.

In the simplest configuration, the spectrum provider assigns a single MC with a single NMC that the spectrum user fills as per their requirements. Options—such as the ability to support in-service expansion, contraction of spectrum, or allocation of spectrum over branching units—will increase the complexity of the spectrum provisioning. This may result in the spectrum provider defining the spectrum in terms of multiple NMCs.

#### 3.4.1.1 Spectrum Sharing with Multiple NMCs per MC

If the spectrum allocation is expected to change over time, the spectrum may be configured with one MC per customer with multiple NMC or multiple MCs per customer, each with one NMC. When an NMC is added or taken out of an MC, it will not impact the remaining NMCs and the MC width will be adjusted seamlessly to the new conditions. Channel planning must be performed to account for all the NMC/MC options 1, 2, and 3, as illustrated in Figure 3-6.

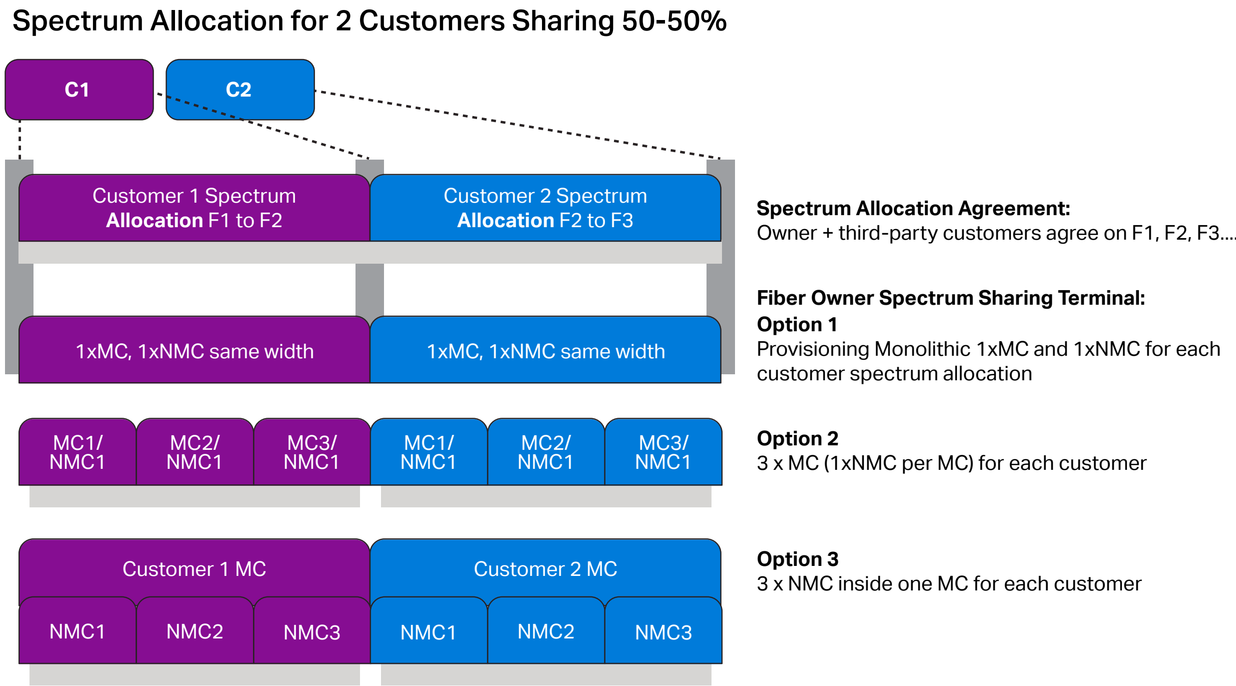


*Figure 3-6. Spectrum sharing allocation options: 1) single NMC/MC, 2) multiple single NMC/MC, 3) multiple NMC/MC*

## 4. Conclusion

Part of the activity of maximizing spectral efficiency in submarine cables is effective channel planning. With the advent of flexible-grid photonic equipment and variable baud modems, the complexity of channel planning has increased. Understanding how spectrum is allocated and what physical constraints must be adhered to is useful in developing channel-planning algorithms. The resulting channel-planning algorithms can be used to maximize the number of signals that can be placed on a submarine cable, whether that link is point-to-point, via a BU, or over shared spectrum. In short, improved optical submarine channel planning leads to an optimized return on investment of submerged network assets—the prime business goal of all cable operators.

Was this content useful? Yes No