FLEXIBLE ROADM NETWORKS: NEW ASPECTS OF COMMISSIONING, OPERATION & MAINTENANCE THROUGH PROJECT EXAMPLES

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Abstract: Subsea flexible networks are now becoming operational with the implementation and commissioning of the first flexible networks based on reconfigurable submerged units such are Reconfigurable Optical Add/Drop Multiplexers (ROADM). This paper reviews how Operation & Maintenance benefit from the new characteristics of such flexible networks and also discusses the practical optimization of the commissioning for systems with multiple possible configurations.

1. THE PATH TO FLEXIBILITY

Before being optically flexible, submarine networks have first evolved in terms of topology, from point-to-point to more complex network architectures. They have also evolved in terms of transparency with the advent of optical add and drop of waves in submerged units. They also became electrically reconfigurable in terms of powering, to be robust against cable breaks and shunt faults.

The optical flexibility, which is addressed in this paper, is hence more than a specific feature: it is a further dimension in the way to operate and maintain the networks, interacting with the other important characteristics of modern networks.

2. NETWORK CONFIGURATIONS AND OPERATIONS

2.1. Submerged nodes and related network configurations

A fundamental step in progressing from simple point-to-point networks towards more advanced topologies was the advent of Full Fiber Drop Branching Units (FFD-BU) which allowed topologies based on a trunk and branches. As shown in **Figure 1**, the principle was to separately route a Fiber Pair (FP) to a branch while sharing a common cable and common repeater housings. Along with the fiber routing, such BU also introduced a possible reconfiguration of the electrical powering of the network, as we will discuss later in this paper.

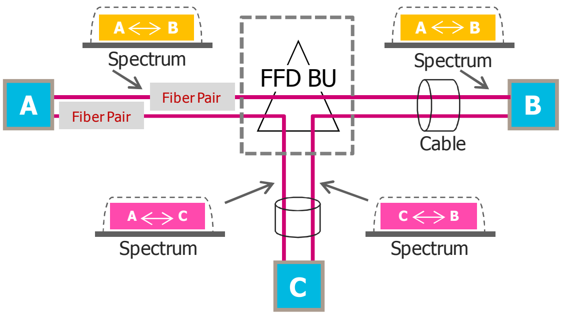

Figure 1: Full Fiber Drop Branching Unit (FFD-BU) principle

A further step came with optical transparency. The first practical versions of Optical Add and Drop Multiplexing BU (OADM-BU) were implemented in a few submarine networks in the late 1990s. The principle was still a trunk and branch topology but the routing in the Branching Unit was achieved at the wave level instead of the Fiber Pair level, i.e. within a

Fiber Pair, some waves of the trunk could be dropped to a branch.

As a main benefit, it was no longer necessary to dedicate a full FP to the branches and the same FP could carry both express traffic and omnibus traffic. Waves on a given Fiber Pair could be separately routed without being electrically regenerated, hence the term optical transparency was used.

In the first implementations of the late 1990s, the configuration of such OADM functions was fixed in terms of added and dropped optical spectrum bandwidth. Mature and reliable technology has now allowed more advanced units which are Reconfigurable OADM (ROADM) to be implemented in actual projects. The fundamental principle of the OADM or ROADM unit, in terms of spectrum bandwidth manipulation, is however the same and is depicted in **Figure 2**.

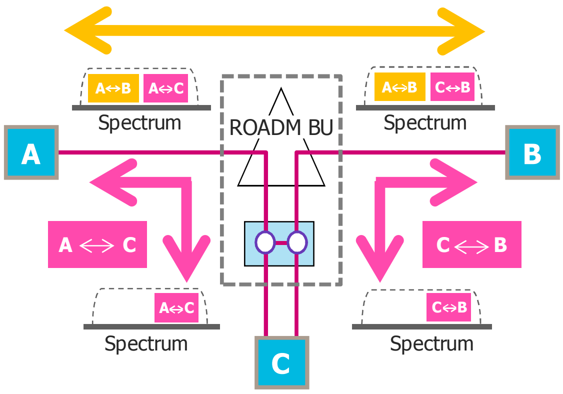

Figure 2: Reconfigurable Optical Add/Drop Multiplexing (ROADM-BU) high level principle

The ROADM BU has brought major improvements in terms of reconfigurability and functionality.

Typically, for systems currently being implemented, as illustrated in **Figure 3** to **Figure 6,** the ratios of spectrum bandwidth being added/dropped can be varied across the following values:

- A first value of Add/Drop of a part of the spectrum, which we denote X% A/D, to indicate that some ratio of the spectrum bandwidth is added/dropped to the branch.
- A second value of Add/Drop of a part of the spectrum, which we denote Y% A/D.
- A bypass of the spectrum through the ROADM-BU (that means 0% A/D), which can be useful when the branch does not yet exist, or in case of failure on the branch.
- A full Add/Drop of the spectrum from the trunk to the branch (that means 100% A/D), which can be useful in case of failure on the trunk.

Figure 3 and **Figure 4** depict the configurations for X% and Y% A/D.

Figure 5 and **Figure 6** depict the configurations for the cases when all the spectrum is bypassed or is added/dropped by the ROADM-BU.

For the sake of clarity, the spectrum in the branch is only depicted for one direction, as shown by the vertical arrow.

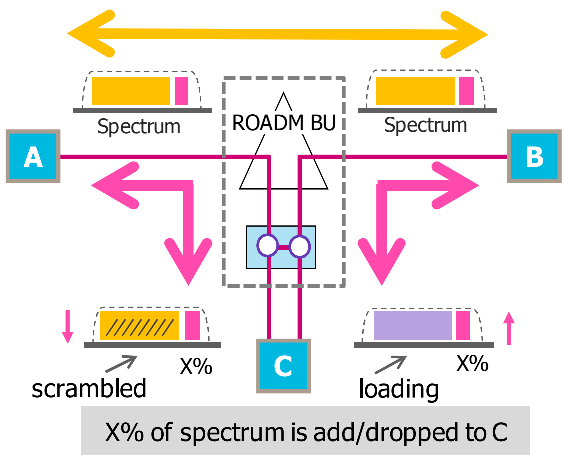

Figure 3: ROADM-BU configuration with X% A/D

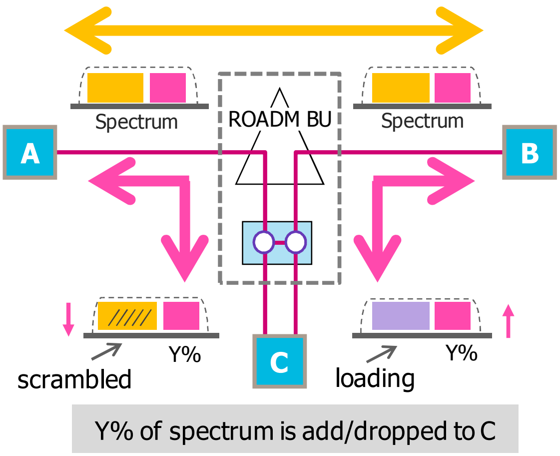

Figure 4: ROADM-BU configuration with Y% A/D

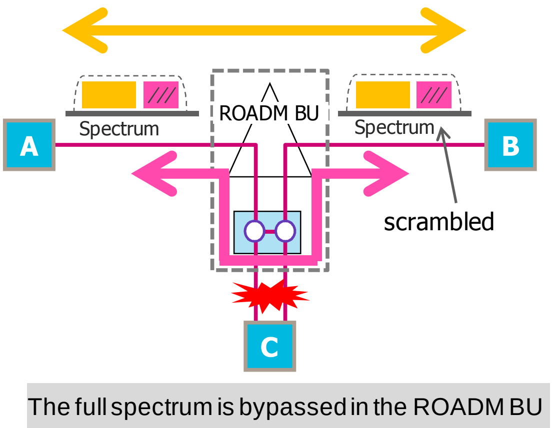

Figure 5: ROADM-BU with bypass configuration (for example in case of branch break)

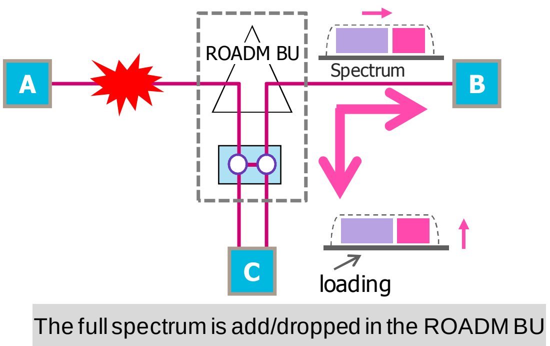

Figure 6: ROADM-BU with full add/drop configuration (for example in case of trunk break)

Two important aspects related to the ROADM-BU nodes are depicted in **Figure 3** to **Figure 6**:

- The confidentiality is ensured, that means that the waves reaching a station are scrambled when they are not dedicated to this station.
- The spectral loading of the system is constant, that means that, in case of cable break, the surviving area of the network still receives a fully loaded spectrum, thanks to the ROADM-BU reconfiguration.

2.2. ROADM-BU network topologies based on recent project examples

Recent ROADM-BU networks have featured numerous different topologies mixing ROADM-BU and FFD-BU.

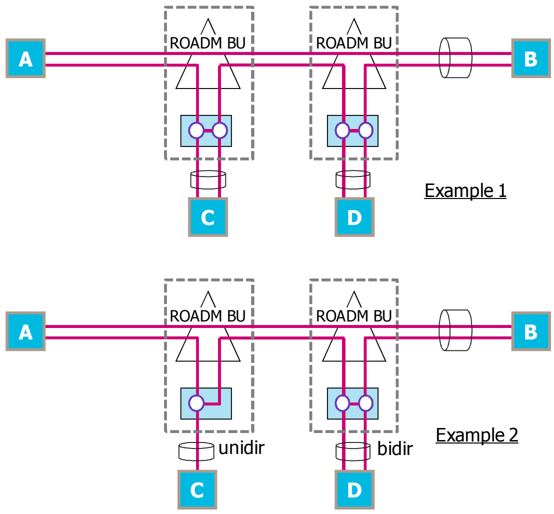

Figure 7: ROADM-BU network configurations – Examples 1 and 2

The most current approach is a trunk with branches as shown in **Figure 7**. This figure also illustrates that the connectivity between the branch and the trunk can be bidirectional, as shown in the Example 1, or unidirectional, as per Example 2. Indeed, in the unidirectional case of

Example 2 in **Figure 7**, station C is related to station A, but not to station B.

A more complex configuration, extracted from a network being implemented, can also be considered, as depicted in **Figure 8**. It can be commented as follows:

- Some of the ROADM-BU units are unidirectional: the stations C and D are not in relation to each other but each of them is in relation with both stations A and B.
- Both FFD-BU and ROADM-BU are used: the benefit is to optimize the cable and repeater housing count by using common cable in branch sections.

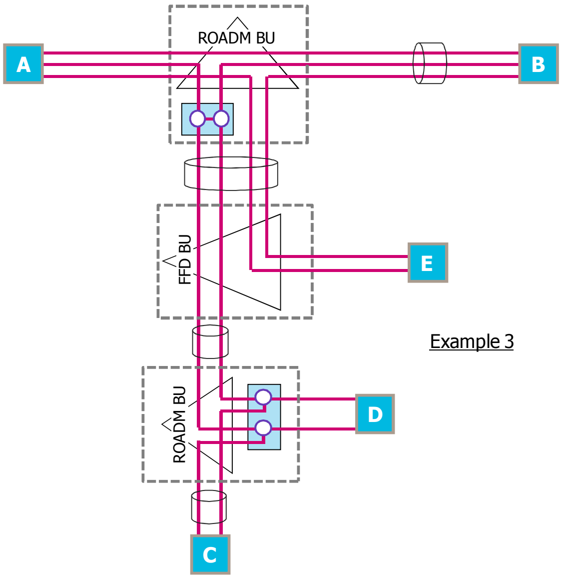

Figure 8: ROADM-BU network configurations – Example 3 (Branch on Branch)

2.3. Benefits and operation of a flexible Add/Drop bandwidth

Reduced forecast constraints

From a traffic standpoint, the obvious benefit of being able to vary the bandwidth allocated to a branch station is to be able to adapt to the traffic need.

This allows the use of the cable asset to be optimized without a difficult initial forecast about the spectrum to be allocated to the branch.

Possible protection

The 100% ratio may also be used to provide an escape or protection route to the traffic in case of an issue on the normal route of the traffic. This application, as for any dynamic use of the variable A/D, would mean that the adequate resources are present in the terminal stations, in terms of transponders and waves.

As a note, the bandwidth being add/dropped is usually gridless, that means it is not related to a specific grid of channels or to a specific transmission technique. The translation of add/drop bandwidth into waves and traffic can thus vary in time depending on the transmission technology used. This is of particular interest where the concept of spectrum engineering is used to optimize the use of the bandwidth.

Varying the wave count without contention

When the spectrum being allocated to a branch is varied, two practical aspects are of operational interest:

- The waves already commissioned should not need to be recommissioned at a different wavelength. That means that the increased spectrum being added and dropped should still include the previously added and dropped spectrum, to prevent contention.
- If it is desired to vary the add/drop spectrum to a branch, when allowed by the network configuration, it may be possible to vary this spectrum independently of another branch.

For example, if there are two ROADM-BUs on the same Fiber Pair, as depicted in **Figure 9**, an efficient way to allocate the channel wavelengths is to use an extremity of the spectrum for each branch. Then, the spectrum allocated to each branch can grow without having to change the wavelength of the already installed channels. Furthermore, the add/drop spectrum for each branch can be varied independently of the other branch.

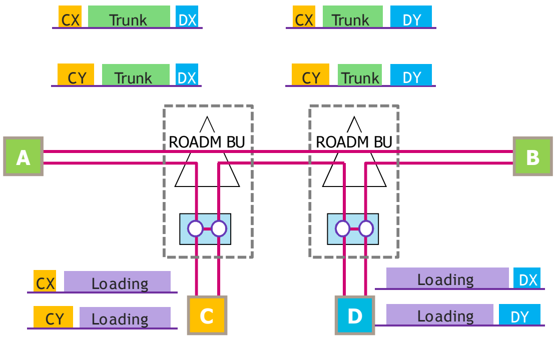

Figure 9: ROADM spectrum allocation – Example 1

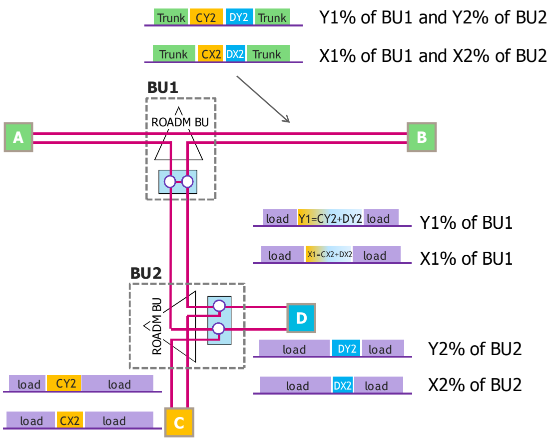

Figure 10: ROADM spectrum allocation – Example 2

The second example, given in **Figure 10**, is a branch on branch configuration with cascaded ROADM-BU. It is still possible to ensure that the increase of the allocated spectrum (to C or to D) does not induce any recommissioning of installed waves. As a remark, since two ROADM-BUs are cascaded and if the first ROADM-BU1 has two settings of Add/Drop (X% and Y%), then the setting of the second ROADM-BU2 has to vary in a simultaneous manner (X% of BU1 has to be used in conjunction with X% of BU2, Y% of BU1 has to be used in conjunction with Y% of BU2).

The wave allocations described in **Figure 9** and **Figure 10** are examples. For each network, this would be optimized and designed according to the topology and the desired spectrum bandwidth settings per branch.

Sharing a flexible count of waves between routes and network owners

Sharing a flexible count of waves for different routes may mean different arrangement on network owner side.

- When there is a single owner of the network asset, who is selling capacity for different routes or destinations, this flexibility can be used in order to allocate the waves and deploy the equipment where it is the most relevant according to the traffic needed.
- In the case of multiple owners, where each owner has the rights for a given amount of waves in the network, some rules have to be defined about the management of the wave count and the spectrum bandwidth. Different models could be imagined and recent experience of large consortiums over extended networks have shown that such an arrangement could be defined and agreed for ROADM-BU based networks.

For the latter case, an example of possible arrangement is given as follows. Let us assume that 320 waves can be shared among a given count of owners, on a set of Fiber Pairs (FP). Let us also assume, for the sake of simplicity, that each owner has a branch connected to this set of FP, identical in terms of design, where the smallest add/drop value is 5 waves (X%) and the largest add/drop value is 15 (Y%). Then, a possible arrangement could be that each owner has the same rights in terms of sum of waves on the trunk and on its branch. The maximum count of waves on the trunk for each owner is then depicted in **Figure 11** for two cases: the small A/D X% and the large A/D Y% .

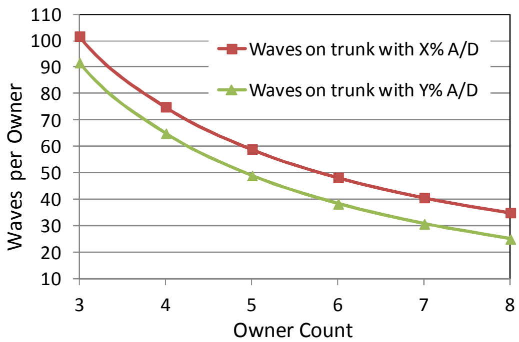

Figure 11: Example of calculation of rights of waves per owner in a theoretical network case

Therefore, when an owner would change the spectrum being added/dropped in its branch by a ROADM-BU, the rights for capacity of the other owners should not be altered. This means that, for example, if a owner would decide to add more waves on the branch by using a larger spectrum bandwidth, then it should be compatible with the count of waves which this owner is already using on the trunk.

This is only an example to illustrate the possible type of arrangements. Of course, many other approaches could be foreseen.

Facilitating network topology evolution

One of the benefits of the ROADM-BU flexibility is also to allow the bypass of a branch which is not yet laid. Unlike with usual FFD Branching Units, a branch can be added at a later stage of the network life, without a major disruption of the traffic on the related Fiber Pair. The benefit is illustrated in **Figure 12** and in **Figure 13**. When a ROADM-BU is already installed, the branch can be connected to the already-installed tail with a moderate impact on the trunk traffic since it is bypassed in the ROADM-BU for the main part of the operations.

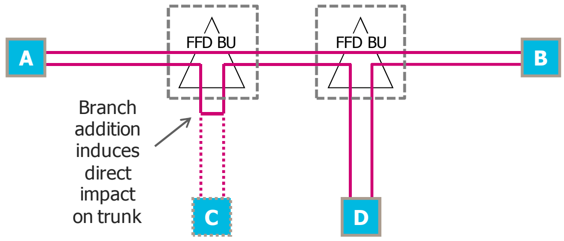

Figure 12: Adding a branch on a spur already equipped with a FFD-BU.

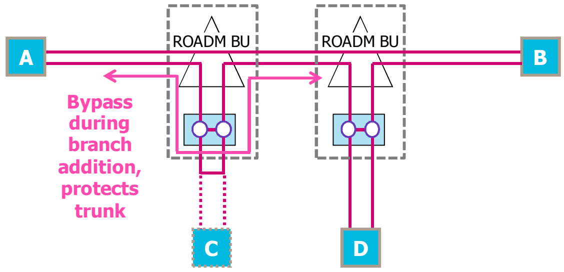

Figure 13: Adding a branch on a spur already equipped with a FFD-ROADM.

3. NETWORK RESILIENCE AND MAINTENANCE

Transmission resilience

In the same way as networks are electrically resilient against shunt faults and cable breaks thanks to BU electrical reconfiguration, the optically flexible networks have introduced a design and a flexibility allowing the resilience of the traffic not directly involved in a break.

This has required some specific care since a particularity of systems based on ROADM is that all waves in the comb do not have the same origin. Therefore, if there were no specific resilience mechanism, a problem somewhere in the network may affect the composition of the spectrum being transmitted and may hence affect the transmission.

Therefore, it is key that the system would allow, in case of fiber break, for the missing part of the spectrum to be compensated. The enabling resilience mechanism is twofold:

- The spectral wave loading of the system is homogenous in any part of the network. That means that a part of spectrum coming from a direction can replace the spectrum coming from another direction.
- The reconfiguration of the ROADM allows the spectrum coming from a faulty part of the network to be replaced by the spectrum coming from another area.

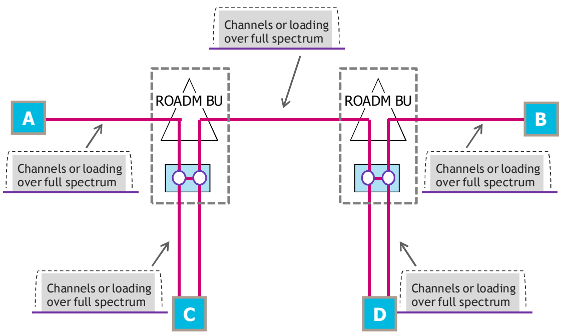

Figure 14: Homogeneous spectrum load in a ROADM-BU based network

Namely, as depicted in **Figure 5**, in case of branch failure, the ROADM can go into bypass mode, which allows the part of the spectrum coming from the branch to be replaced by the equivalent part of the spectrum coming from the trunk stations. This means that dummy channels coming from the trunk stations, which were anyway already present before the break, would replace the spectral load coming from the branch.

In a similar way, in the case of trunk failure depicted in **Figure 6**, the ROADM could be used in Full Add/Drop mode so that the spectral load coming from the branch would replace the load lost on the trunk, thus preventing any impact on the traffic coming from the branch.

Maintenance operations combining electrical and optical reconfigurations

In case of cable damage, either shunt fault or cable break, it is common to reconfigure submarine networks in the electrical domain [1]. Branching units are switched in order to power a branch where there is a shunt fault, or switched in a different way to isolate a part of the network before a ship repair.

When ROADM-BUs are used, optical bypass and full Add/Drop reconfigurations can also be used in combination with the electrical reconfiguration for a further resilience.

For example, in the branch-tree configuration shown in **Figure 15** and **Figure 16**, following a cable break, the branching unit is electrically switched to allow the electrical powering from the other side of the branch-tree. Meanwhile, the ROADM is also optically switched to the Full Add/Drop setting so that the lost spectrum previously coming from station C is replaced by the spectral load launched by station D.

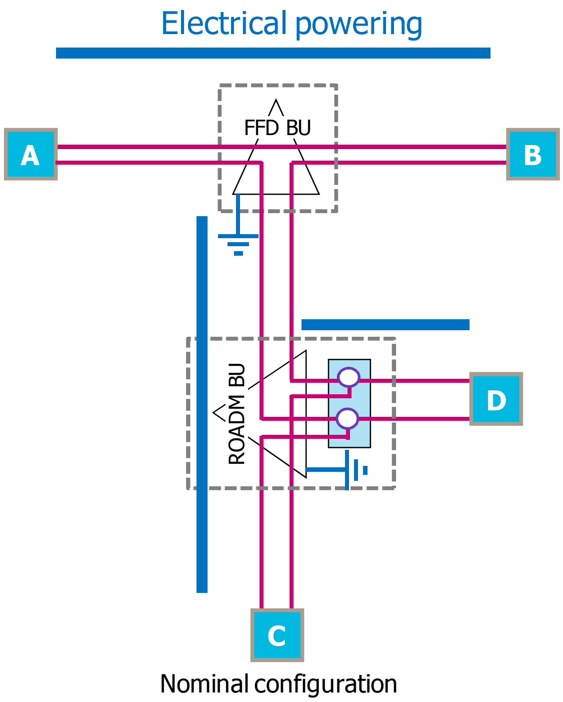

Figure 15: Combined electrical and optical reconfiguration – Nominal case

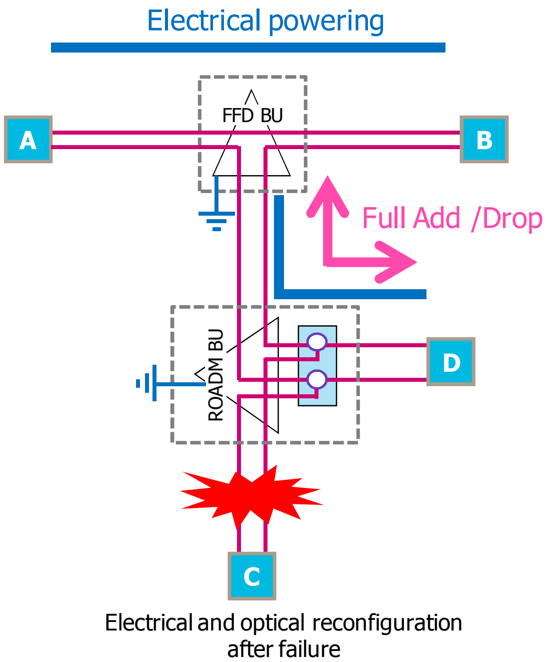

Figure 16: Combined electrical and optical reconfiguration – After reconfiguration

4. DESIGN VALIDATION AND SITE COMMISSIONING

4.1. Any-to-any transmission design

It has been common practice for submarine systems to run a significant design review programme, including laboratory demonstrations, before a new system is manufactured and laid. This is because submarine systems are usually at the state-of-the-art, because of their cost and obviously because applying a correction on a submerged plant is not practically possible. The additional benefit of a thorough design review in the case of a flexible network, is that it provides confidence that, based on the principles of the design, all the different configurations of the system would work properly, whatever the channel routing and channel path.

Actually, the recent evolution of the transmission technology has made flexible systems easier to design and to validate. As discussed hereafter, it is now possible to achieve "any-point-to-any-point" transmission design. This is of great help to optimize the on-site test plan during the commissioning.

Homogeneous optical fiber

Until a few years ago, one of the most demanding areas in terms of design and manufacturing was the management of the fiber in terms of chromatic dispersion along the line. Complex dispersion mapping was necessary to optimize the performance. In this context, it was quite challenging to use different paths or to mix, in the same fiber, channels having a different path in terms of chromatic dispersion map.

Fortunately, with the advent of coherent transmission combined with advanced data processing, the transponders are now able to deal with the uncompensated chromatic dispersion of standard fiber over more than 10,000km. This means that the fiber is now of the same type over the whole network and hence, whatever the path, the transmission would be of the same type.

Additionally, one of the benefits of the modern transponders is their tolerance to PMD (Polarization Mode Dispersion), which also makes less relevant the long term test of various paths.

Gain flatness management

So that the transmission performance could be guaranteed whatever the path selection, it is also necessary that the gain flatness across the spectrum is designed accordingly.

Each possible path is composed of different segments. Thus, by ensuring the flatness of each segment, the combination of segments will always result in a flat overall path. Practically speaking, this means that the gain flatness is designed and checked in relevant equalization blocks, such as the principle illustrated in **Figure 17**.

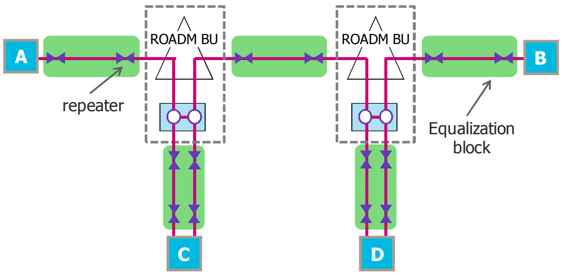

Figure 17: Gain flatness management principle

Homogeneous spectrum loading

As previously discussed to ensure the resilience, in any part of the network, the spectrum is homogeneously loaded with either traffic channels or loading dummy channels. Therefore, whatever the add/drop configuration in the ROADM-BUs, the transmission conditions are the same for the channels.

Network performance design

As for any submarine system, the design should make sure that all paths have the adequate performance. Already for systems with FFD-BUs, the repeater spacing had to be designed to deal with the longest path, since the location of the repeater housings was common to Fiber Pairs having paths of different lengths. This remains necessary and the design has to be further achieved, at channel level, for the channels which can experience the longest path.

4.2. Site validation

Structure of tests

One could be fairly concerned by the amount of tests that a flexible network may mean on site and by the practical difficulty to test different configurations.

Fortunately, as previously discussed, this is facilitated by the transmission design which is homogeneous in spectral and spatial terms and this is anticipated by the early phases of laboratory design demonstration. Also, when there are several ROADM-BUs on a Fiber Pair, all possible setting combinations may not be relevant and some analysis allows the tests to be optimized.

Transmission performance tests

Since the transmission across different paths of the network is over a homogenous medium, the most relevant validation of the transmission performance is over the longest path.

The transmission performance is hence verified between the two most distant stations being related and is also verified between each pair of stations exchanging traffic, to check that all the terminals are correctly set.

These verifications are achieved with the ROADM-BUs in the nominal configuration (X% A/D), which is the first setting being used for the initial traffic, so that installed channels are available to test the performance.

For the second (usually larger) ROADM-BU add/drop settings (Y% A/D), it is checked that the installed channels are still satisfactorily transmitted. Thanks to the homogenous design, the transmission would be equivalent for the further channels which would be installed in the larger add/drop spectrum bandwidth.

For the bypass and for the full add/drop ROADM-BU configurations, it is checked that the transmission is correct over the remaining relevant paths, in the relevant configurations as discussed below.

Network functional tests

During the commissioning, it is verified that the network can be operated as expected in terms of BU electrical switching, ROADM optical switching, wet plant interrogation and control. By design, the control operations on each element are independent. However, all combinations, in terms of optical ROADM configurations, may not be relevant. Hence, the transmission checks would focus on the adequate combinations.

For example, for the case of a branch on branch with ROADM-BUs, such as the one of **Figure 10**, **Table 1** shows all the possible combinations of optical configurations.

BU1	BU2	#	Description	Comment
X% A/D	X% A/D	#1	Nominal case 1	Nominal case where transmission is tested
X% A/D	Y% A/D	#2	Not appplicable since BU1 and BU2 are cascaded and have related configurations	NA
X% A/D	Bypass	#3	Cable break between BU2 and D	Transmission to be checked
X% A/D	Full A/D	#4	Cable break between BU2 and C	Transmission to be checked
Y% A/D	X% A/D	#5	Not appplicable since BU1 and BU2 are cascaded and have related configurations	NA
Y% A/D	Y% A/D	#6	Nominal case 2	Second nominal transmission case to be checked, equivalent to #1
Y% A/D	Bypass	#7	Cable break between BU2 and D	Equivalent to #3
Y% A/D	Full A/D	#8	Cable break between BU2 and C	Equivalent to #4
Bypass	X% A/D	#9	Cable break on BU1 branch	Test cases which can be regrouped as identical since BU2 configuration has no influence (#9, #10, #11, 12 are identical)
Bypass	Y% A/D	#10		
Bypass	Bypass	#11		
Bypass	Full A/D	#12		
Full A/D	X% A/D	#13	Cable break on trunk	Test cases which can be regrouped as equivalent since BU2 configuration has little influence (similar spectrum for #13 and #14)
Full A/D	Y% A/D	#14		
Full A/D	Bypass	#15	Several cable breaks, not likely applicable	Not practically relevant
Full A/D	Full A/D	#16		

Table 1: Combinations of ROADM BU optical switch configurations in a branch on branch such as in Figure 10

Some combinations can be regrouped as equivalent and some combinations may not be relevant: for example, when BU1 is in bypass mode, BU2 configuration does not matter since the branch is isolated from the trunk. The transmission tests would focus on the nominal case while the ability to transmit in the cases corresponding to resilient modes would also be checked.

This is only a particular example but shows that the test plan should be based on an analysis of the network topology and flexibility, to be optimized and relevant.

5. CONCLUSION AND FUTURE PROSPECTS

Large scale multi-thousand kilometre networks using ROADM-BUs are now being implemented with topologies and functionalities such as the ones described in this paper.

New concepts are now available for the operation and maintenance of such networks. It is possible to change the bandwidth allocated to each branch, without channel contention; also, it is possible to use the optical flexibility in combination with the electrical reconfiguration for improved resilience in case of cable break.

Thanks to the design and with some forethought about the relevant combinations of configurations, these networks can be tested in an optimum way.

Regarding the future prospects, looking at terrestrial systems [2] provides a useful hint, even if one should keep in mind that some requirements may be different, like the dynamicity. Once the needed technology will reach the submarine reliability standards, the trend will continue towards more advanced flexible submerged units. Technologies such as the Wavelength Selective Switch will allow the flexibility to be improved by managing even more settings for new cross-connection nodes while maintaining the gridless features.

Even with these new technologies, the aspects of the transparent flexible networking which were reviewed in this paper will still be relevant, in particular the need for any-to-any transmission design and for resilience against cable break involving electrical and optical reconfigurations.

These further features will require, on the Purchaser side, to further look for new ways to arrange the ownership and the rights in the network and will also require, in the commissioning phase, to analyse the network topology and functionalities to optimize the test plan as well as make it practical. Also, as discussed in the paper [3], such highly flexible networks will require a full eco-system in terms of agile colourless terminals, working along with the flexible wet plant with an advanced network management software to get the full benefit of their functionalities.

6. ACKNOWLEDGMENT

We are grateful to the **SEA-ME-WE 5 Consortium** for the joint experience in the implementation of one of the first flexible ROADM-BU network with adjustable spectrum bandwidth allocation across the network.

7. REFERENCES

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