UPGRADE OF SUBMARINE SYSTEMS: NEW OPERATIONAL ASPECTS AND OPPORTUNITIES OF NETWORK EVOLUTIONS

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Abstract: For a while, upgrading a system simply meant to increase its capacity by adding more channels in the line optical spectrum. Nowadays, since the spectrum of some systems is already fully populated by waves, the upgrades actually involve the replacement of the existing waves. That implies traffic manipulations and a close operational relationship between the Purchasers and the provider. While such upgrades are made possible by the extra optical margins provided by new technologies, these margins can also be used to upgrade the system in other ways than the capacity, by modifying the network topology. In parallel, the upgrade can also happen at the service level.

1. THE MANYFOLD MEANINGS OF "UPGRADE"

To "upgrade" a system may have manyfold meanings. While it could mean straight additions of waves, it may also involve elaborated traffic operations to optimize the system bandwidth. Upgrading a system may also mean the evolution of the network configuration. All of that is enabled by the amazing continuous technology improvement: indeed, who would have planned, while first WDM systems were originally designed for 2.5Gbit/s, that coherent transmission would allow them to carry 40Gbit/s and 100Gbit/s per channel?

2. ENABLING TECHNOLOGY

2.1. From design to ultimate capacity

Any WDM (Wavelength Division Multiplexing) amplified system is originally designed to be upgradable from its first installed capacity to a so-called design capacity, by adding more and more channels. This design capacity assumes the use of technology which is existing or foreseeable when the system is implemented. However, over years, new technologies become available and allow to increase the possible maximum capacity over the installed cable: new technologies make possible to consider higher bit rate and closer spacing between waves. In a word, a better spectral efficiency is made possible.

2.2. Spectral Efficiency: the relevant indicator of achievable capacity

Since the system bandwidth is fixed by the repeater amplifiers, the improvement of the achievable capacity is obtained by the combination of the bit rate transported by each carrier and by the spectral spacing between these carriers. A relevant criterion is the spectral efficiency, which corresponds to the bit rate transported in a given spectral slot. The spectral efficiency has been increasing over years as shown in Table **1** with some combinations of bit rate and channel spacing.

Carrier bit rate (Gbit/s)	Carrier spacing (GHz)	Spectral Efficiency (bit/s/Hz)
10	50	0,2
10	33.33	0.3
40	50	0,8
40	33.33	1.2
100	100	1
100	80	1.25
100	50	2
100	40	2.5

Table 1: Spectral Efficiency of several transmission solutions

However, the seek for larger spectral efficiency is quite greedy in terms of optical performance margin. Indeed, increasing the bit rate does increase the OSNR (Optical Signal to Noise Ratio) requirement in a straight way. Similarly, packing closer the channels means larger non-linearities which have to be compensated by some margin. Closer spacing may also means the use of modulation formats with closer modulation states (Quadrature Phase Shift Keying vs Binary PSK for example), which also increase the need in terms of performance. Let us briefly review the drivers to obtain these better performances out of an existing laid cable.

2.3. Drivers for larger performance from an installed cable

The main drivers to be able to increase the bit rate per channel and to pack them closer are listed hereafter [1]:

- new modulation formats : modulation formats have evolved over time to be able to mitigate the impairments. Phase modulation formats (with a constant amplitude) and smart polarization multiplexing are now commonly used to minimize the non-linearities occuring within the optical fiber.
- advent of coherent detection combined with advanced digital processing : this has been a tremendous revolution in the recent years and has been introduced with 40Gbit/s channels. This technology provides high performance and high robustness against transmission impairments. In particular, the tolerance to Polarization Mode Dispersion is quite beneficial for an installed system to be used for very high bit rate.
- new generation of FEC (Forward Error Detection): beyond the turbo-code which brought large improvements in the last decade for 10Gbit/s systems, a new revolution is provided by the practical realization of soft decision FEC for high bit rate transmission. Indeed, the electronics is now able to feed FEC with digitally sampled detection, which allows FEC to provide a soft decision involving probabilistic algorithms.

Figure **1** depicts the principle of the improvement of the achievable capacity over a given installed cable. With a constant technology, the cable system margin which would be necessary to upgrade to a larger bit rate would linearly grow vs the targeted bit rate. However, the figure shows that, due to numerous technology improvements, the actual requested margin is actually lower.
Therefore, the extra margin observed after the original implementation can translate into a significant increase of the design capacity.

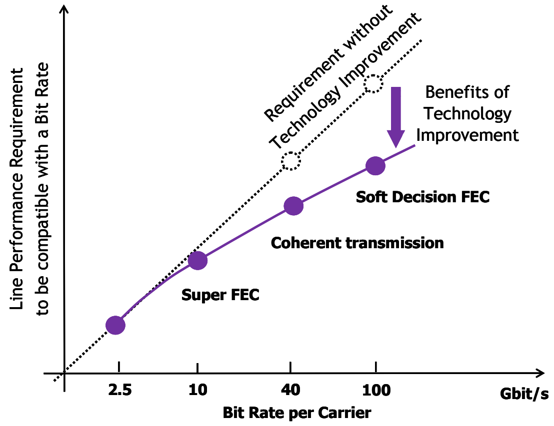

Figure 1: Upgradability of installed systems thanks to technology improvement

3. NEW PROCESS FOR CAPACITY UPGRADE

3.1. Traditional situation

From an operational point of view, increasing the capacity by adding more waves in the frame of the original design is relatively straight. That does however require some due precautions to ensure a smooth loading of the line when the channel count is increased but there is no traffic manipulation since the existing waves are not affected.

3.2. Fully loaded systems

3.2.1. Step by step process

Principle

The matter is quite different when the system has already been heavily upgraded and its optical spectrum is full of waves. When technology allows to replace the former waves by waves at a higher bit rate or by waves more closely spaced, then it is necessary to remove the existing waves which are already carrying traffic. That implies to migrate the traffic of the existing waves to new waves, in a step by step process, along the implementation of the new waves

Step by step description

As an example, let us consider the typical case of Figure **2**, when the spectrum is already full before the upgrade starts.

This figure represents the case when former waves are replaced by waves at a higher bit rate and the same spacing. The same principle would apply if the new waves would be more closely spaced.

The ratio between the former and the new spectral efficiency is defined as to be $K_{SpecEff}$. For example, when moving from 10Gbit/s spaced by 50GHz to 40Gbit/s spaced by 50GHz, $K_{SpecEff}$ = 4.

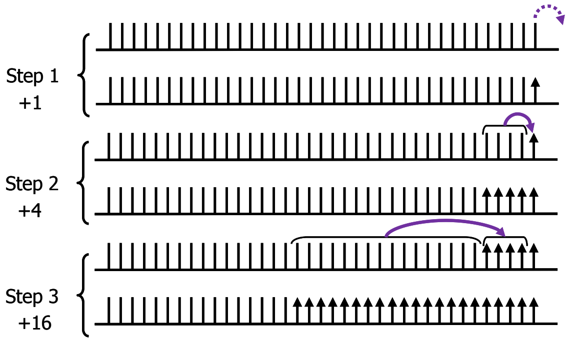

Figure 2: Spectral representation of the step by step capacity increase with traffic migrations. New waves are represented by an arrow.

Priming the pump

In order to prime the pump of the process and to implement a first wave with a high bit rate, it is necessary to remove a former wave. Its traffic has then to be rerouted to an alternate resource. Different options can be considered: implementation of a temporary wave out of the nominal spectrum, use of resources on another fiber pair, reallocation of the traffic of this wave to other waves thanks to traffic regrooming.

Traffic migrations

Once the first wave of the new type is implemented, the traffic of former waves can be transferred to this new wave. The count of waves which can be transferred is at maximum $K_{SpecEff}$. In practice, it may be less than $K_{SpecEff}$ taking into account the multiplexing structure and the band transitions. In order to migrate the traffic in a smooth way, the Purchasers may use a N+1 SDH or implemented network protection.

Addition of new channels

After this first step, more new channels can be implemented and, once that is made, the traffic of former channels can be transferred to the new channels.

Planning optimization

Operations such as traffic migrations may require to plan operational windows with some due notifications. For the sake of a resilient and optimum Plan of Work, the Purchasers and the provider may set up protocols based on several possible windows and some possible optimization of the commissioning periods.

Migrated Traffic and Net Capacity

Since some existing traffic has to be migrated, the net added capacity is less than the physical added capacity, as written below:

$$NetCapacity = AddedWaves - MigratedTraffic$$

Or, in other words, taking into account the ratio $K_{SpecEff}$ (ratio of spectral efficiencies before and after the upgrade):

$$NetCapacity = AddedWaves \cdot (1 - \frac{1}{K_{SpecEff}})$$

Keeping the same example of $K_{SpecEff}$ =4, that means that the Net Capacity is 75% vs the Added Waves capacity.

Count of steps

After N steps, the net capacity increase (the unit is the carrier bit rate after the upgrade) is growing like:

$$CapacityIncrease \approx K_{SpecEff}^{N_{steps}-1} - \frac{1}{K_{SpecEff}} \approx K_{SpecEff}^{N_{steps}-1}$$

In other words, the necessary count of steps is in the range of:

$$N_{steps} \approx \frac{Log(CapacityIncrease)}{Log(K_{SpecEff})} + 1$$

This is a general expression. In practice, the count could be reduced if more than one channel can be initially replaced to prime the process, or increased if there are some constraints related to band transitions when removing old channels.

4. TOPOLOGY UPGRADE TOWARDS WAVELENGTH PASS THROUGH

The extra margin provided by the new technologies can also be used in order to modify the network topology, in particular the wave connectivity and transparency.

As illustrated in Figure **3**, in the case of an express and an omnibus fiber, all waves of the omnibus station are usually terminated in a WDM terminal. It could be of interest to allow for some waves to pass through these stations without electrical regeneration.

The advantage is to create an express traffic over the omnibus fiber with no need for intermediate transponders. This can be beneficial to protect the traffic of the express fiber pair, or to further increase the express traffic if the express fiber is already full. From a networking standpoint, channels can also be used to connect intermediate stations while skipping some others.

In comparison to the express fiber pair, extra optical margin is requested on the omnibus fiber pair to implement an optical pass-through from end to end, due to the extra length of transmission in the branches.

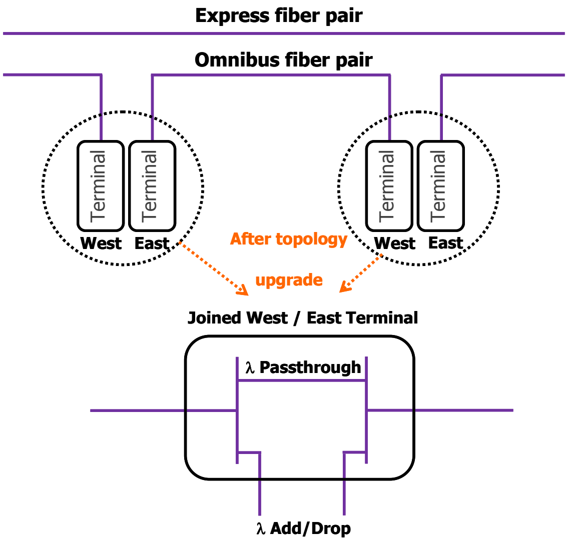

Figure 3: Moving to a wavelength passtrough in intermediate stations

From an operational point of view, this modification requests to join the two West and East terminals of an intermediate station into a single terminal. The traffic may be rerouted over the express fiber during the modification of the terminals.

In order to optimize the network connectivity, wavelength reallocation may also have to be considered.

5. TOPOLOGY UPGRADE TOWARDS PoP TO PoP

Another way to implement additional optical pass-through is to remove the electrical regeneration in the cable landing stations so that a PoP (Point of Presence) to PoP transmission is achieved, as shown in Figure **4**. Again, that requests optical margin to allow for the additional terrestrial transmission.

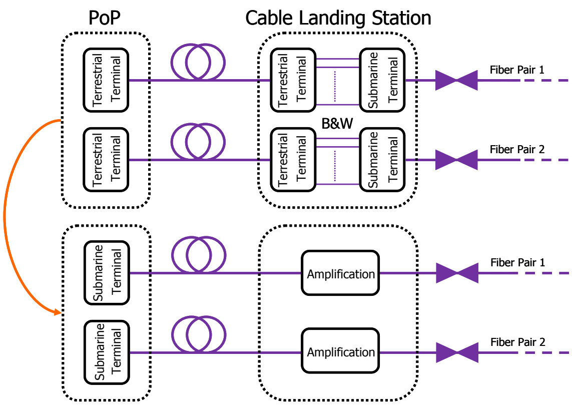

Figure 4: Moving to a PoP to PoP configuration

This modification of topology would require opening the whole WDM line when the terminal of the cable station is replaced by an optically transparent scheme. To make it practically acceptable for the traffic availability, one may proceed fiber pair per fiber pair and use protection mechanisms between the fiber pairs.

6. SERVICE UPGRADE TOWARDS 100GbE

Looking at the "upgrade" of the network in a broad manner, this should also encompass the evolution of the services.
This is particularly relevant since the features of the service layer may be more and more distinguished from the physical characteristics of the transmission layer.
Indeed, for a long while, the transmission layer and the service and client layers have been aligned : 2.5Gbit/s waves were used for for STM-16 service, 10Gbit/s waves for STM-64 services etc.
There is however no reason for the bit rate used at the client side to match the line rate which allows to optimize the spectral efficiency of the cable.
Therefore, adaptation devices may be used to ensure the match between the optimum line bit rates and the client bit rates.

That leads to the concept of a superchannel as to be a set of subcarriers transporting a service at whatever line bit rates.
As an example, Figure **5** shows the implementation of a 100GbE client interface adaptor over waves carrying 40Gbit/s. The implementation of this 100GbE client interface can be made independently of an upgrade of the line.

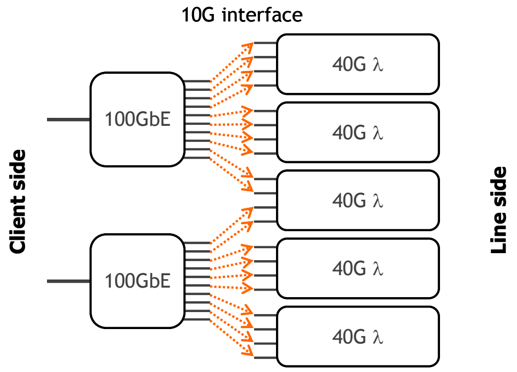

Figure 5: 100GbE client service implementation

7. FUTURE PROSPECTS

The asset of installed cables is quite valuable and the advent and the prospects of new technologies allow them to be used far beyond the original design, both in terms of capacity and in terms of topology. That may however require stringent modification of their configuration. Since these systems may be heavily loaded with traffic, that involves a tight relationship between the provider and the Purchaser to prepare smooth and efficient operational procedures.

8. ACKNOWLEDGMENT

We are grateful to the Sea-Me-We 4 Consortium for the joint experience in achieving large upgrades involving coordinated traffic manipulations.

9. REFERENCES

[1] G. Charlet et al., "Technological Challenges for Field Deployment and Upgrade of Multi-Terabit/s Submarine

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