OVERVIEW OF SUBMARINE SYSTEM UPGRADES

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Abstract: Since the late 1990's, submarine optical cable systems make use of advanced technologies such as 10 Gbit/s high speed modulation, Dense Wavelength Division Multiplexing (DWDM) and Forward Error Correction (FEC). Most of the systems initially operate below the capacity they are designed for, allowing carriers to apply the well-known "pay-as-you-grow" concept. The original Supply Contract covers their progressive equipage commercially and technically (standard upgrades). When alternative technologies are used in the terminal equipment, they allow going beyond the designed capacity. Upgrades become challenging and depend on system design as well as actual margins.

1 INTRODUCTION

The first commercial application of the optical amplification technology in submarine systems dates back to the mid 1990's (e.g. TAT12/13 installation). Since then, the combination of optical repeaters and the wavelength division multiplexing technique firstly introduced on Sea Me We 3 in late 1999 allowed the cable owners to upgrade their systems up and sometimes beyond the capacity they were designed for, thereby matching with their customers demand. In less than 10 years, repeated submarine systems achieved multi-terabit/s capacities over thousands of kilometres making use of successive enabling technologies such as 10 Gbit/s data rate, chromatic dispersion management, enhanced FEC or advanced modulation formats. These capacities are most frequently greater than the carrier's customer needs by the time of putting the systems into service and upgrades may be used to balance supply and demand. This paper aims to specify the concept of upgrade, which can be standard or challenging. The trivial upgrade that consists in lighting a dark fiber is not adressed here.

2 THE CAPACITY EQUATION

As reported in many technical publications until years 2002-2004, most of the submarine laboratory experiments conducted by suppliers used to demonstrate greater capacities per fibre over longer distances. To our knowledge, the latest world record with adequate commercial margins was published in 2003 where 226 channels were transmitted at 10 Gbit/s over 7410 km [1].

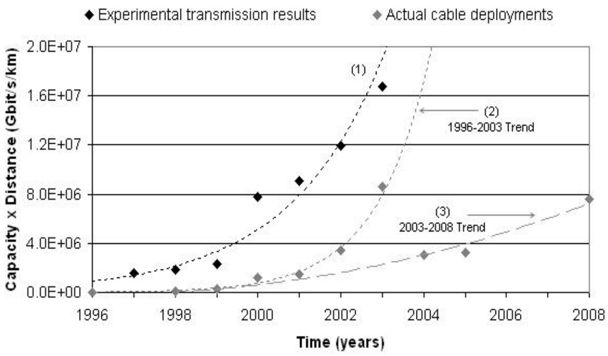

Figure 1 Laboratory results vs. designed capacity for actual cables (limited to C-band EDFA transmissions)

In parallel to these races for lab records, the transoceanic submarine cables actually deployed took advantage of the technologies developed by the R&D laboratories as shown in Figure 1. It is striking to note that even though the general trend of both curves (1) and (2) slightly differ, it has typically taken less than 3 years for lab demonstrations to become commercial until 2003. Since most systems are loaded in the range of 10-20% of their designed capacity by the time of their putting into service, capacity increases i.e. upgrades become ordinary steps during system life. They may involve repeated and unrepeated links located in any region of the world, systems designed for various bit rate and may imply the use of mature technologies as well as brand new ones. Indeed it is interesting to note that the race for lab records has transferred to the unrepeated market while some emphasis was put on optimization to lower the cost per channel in the repeated market (e.g. by increasing the repeater span) since the Telecom Bubble of year 2000. The same occurred in the field: a new trend (3) can be calculated in Figure 1 from 2003. According to many experts, the global submarine activity is now slowly recovering [2]. One specific factor that could help for such analysis is the growing number of upgrade contracts that are awarded since 2005.

3 UPGRADE DEFINITIONS

We define hereafter four notions relating to capacity that will be used throughout this paper. First, the maximum designed capacity (MDC) is the maximum capacity allowed by the original design of the system. We call "standard upgrades" the capacity increases that occur from the initial loading to the MDC using the contractually foreseen technologies. In opposition, upgrades that are performed with alternative technologies in the terminal equipment are called "challenging upgrades". Then the maximum capacity achievable after challenging upgrade(s) is named the "ultimate capacity" (UC).

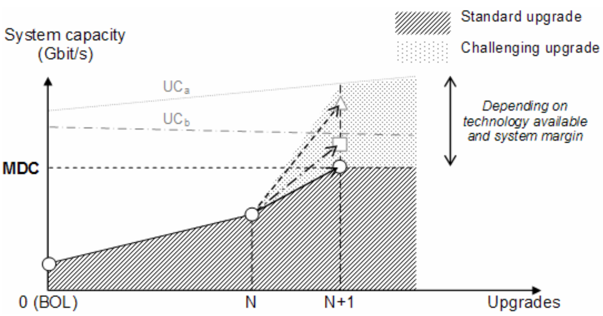

Figure 2 Upgrade and capacity definitions. UC_a (resp. UC_b) is UC when replacing (resp. keeping) the existing equipment.

By definition, UC is greater than MDC. Note that UC cannot be predicted as a single value because it depends on the choice of removing or not the existing terminal equipment to fully take advantage of new technologies (Figure 2). UC is also time dependent because it is based on technology improvements. It is basically limited by the design of the submerged plant. Note that curve UC_b in Figure 2 is deduced from curve UC_a and the actual system loading. For clarity purpose, curve UC_a was assumed quasi linear.

4 STANDARD UPGRADES

4.1 Power budget aspects

The computation of optical power budgets is crucial because it involves the responsibility of the suppliers to provide a system with adequate and guaranteed performances both at the beginning and at the end of life (25-year lifetime). In particular, it includes the commissioning limit that is the addition of the FEC Q limit and the various EOL margins. Depending on system's history (fibers/components ageing, pump failures/cable repairs occurrences), the commissioning limits should be redefined before each upgrade. This implies for people in charge of system maintenance to regularly record all events and set up a reliable data base. Note that by definition the commissioning limit is independent on the channel count and is used as a minimum target.

4.2 Progressive loading

Systems have a scalable and modular architecture and standard upgrades are planned by contract. Indeed, they may happen several times up to their MDC. No major issue is expected since the capacity is increased with a field proven technology already put in place in the existing equipment. An upgrade plan is sometimes attached to the contract as a guideline to define the sequence of channels to be added. In the case of large band systems, channels should be homogeneously distributed in the bandwidth to avoid SHB effect [3].

Standard upgrades may imply the modification of some settings e.g. pre-emphasis adjustment (automatic process done on-line), the characteristics of active equalizers incorporated in the wet plant and the loading tone(s) power if any. For the last item, the use of ASE sources was investigated to offer alternative solutions to typical techniques such as dummy lights and cross-patch configurations (one channel is traffic carrying in one direction and used as a dummy light in the reverse direction) [4]. The main advantage would be to decrease the number of loading tones.

It should be noted here that from a contractual point of view, nothing could prevent a given submarine supplier to make a proposal for upgrading a system it did not deploy initially. Indeed, provided the wet plant can still be monitored and supervised, competitive offers are to the benefit of the Purchasers. Integrating equipment coming from different suppliers induces some special rules in terms of responsibility and warranty. It also necessitates some equipment compatibility that could be controlled by standardization committees.

5 CHALLENGING UPGRADES

When discussed within consortiums, the feasibility to upgrade a system beyond its MDC is usually debated before achieving it. Two main driving factors may motivate the system owners: optimizing the current system CAPEX and anticipating the need for a new system in time. Then it became common through the years to request UC studies to the original supplier(s) of the system, in parallel to the work undertaken by the technical group of the consortiums themselves. However, it remains the Purchaser's responsibility to decide when performing challenging upgrade(s) if there is a possibility to do so.

5.1 Data collection

The first step in the process of determining the UC is to collect as much as possible information on the system.

Obviously actual data are preferred to estimations based on Contract figures. It should include but not limited to (i) optical spectra at transmitter and receiver (pre-emphasis setting, end-to-end gain shape, channel spectrum spread and optical signal to noise ratio performances), (ii) SLD data (chromatic dispersion map) and (iii) Q factor performances over time (Q distribution shape, system stability, average margin to FEC limit or updated commissioning limit).

5.2 Estimation of available margin

The data collection aims to assess in detail what is the overall margin on the system and how it could be used to increase the capacity. Margin is the real critical issue of challenging upgrades. Three types of margin should be considered here: (i) the 1 dB EOL margin that is often required by Purchasers in the original Power Budgets, (ii) the unallocated and "security" margins accounted for in the Power Budgets and (iii) the margin that comes from the wet plant when comparing the assumptions made in the Power Budgets and the actual figures measured during the equipment manufacturing. Regarding the latest type of margin, it has been calculated on one recent cable that the difference between the worst case approach (Power Budget) and the statistical approach (average of actual data) was between 0,5 dB and 1 dB for the repeater noise figure.

5.3 Estimation of the Ultimate Capacity

The second indicative tool that can be used to assess the system UC is the calculated line Optical Signal to Noise Ratio (OSNR). Indeed, we implicitly refer to it in the first line of the Power Budgets when calculating the Mean Q factor [5]. It allows evaluating various system configurations depending on the current/new channel features. Then the best scenario is evaluated through Q penalty estimations based on linear and nonlinear propagation effects.

5.3.1 Channel properties

One technique to increase the overall capacity is to increase the data rate of some (or all) channels by replacing transponders in the terminal equipment. In some cases, it may be necessary to modify the bandwidth of optical filters or Mux/Demux within the existing terminal to deal with the new channel bandwidth. The OSNR sensitivity always increases linearly with the bite rate and propagation effects become more impacting, most of the time being the limiting factors to the data rate increases. However, other techniques described in the following can be applied to relax the new constraints put on the channels. A fundamental channel feature is the modulation format. Until 2006, all formats used for submarine transmission belonged to the On-Off Keying (OOK) family. Many studies have been reported during these five past years on Differential Phase Shift Keying modulation format (DPSK) [1] [6]. In combination with balanced detection and optical preamplifier DPSK has a better receiver sensitivity in back-to-back configuration compared to OOK (about 3 dB). As far as upgrades are concerned, DPSK can allow reducing the channel power to limit the nonlinear penalty. Other formats are also under investigation and coherent receivers seems to be of interest again especially for 40 Gbit/s transmission [7]. Another central aspect of transponders since late 1990's is their error correction capability. For example, second-generation versions such as Slim, Enhanced or Super FEC provide a Q limit threshold gain of about 3 dB at BER = 10^{-13} compared with the well-known standardized RS(255, 239) [8]. In the early 2000, researchers started to focus their studies on soft decision, which third FEC generation is based on, and signal processing. The most studied ones are low-density parity-check codes (LPDC) and block turbo codes. Mitsubishi experimentally demonstrated in 2006 that the latter type offered 10,1 dB net coding gain at 12,4 Gbit/s [9]. The compromise to find is always to minimize redundancy and optimize performances.

5.3.2 Channel position in spectrum

When the end-to-end ASE gain shape and the margin of existing channels allow it, some extra channels may be inserted in the terminal equipment. In that case, more efficient FEC and modulation format can be used to relax the requirement on the receive Q factor for the new channels. Their receive OSNR can be decreased, what typically arises when channels are added, without affecting the BER after correction. The loading scheme becomes a vital management. The two extreme solutions are either to leave the channel spacing as it is and extend accordingly the bandwidth or to keep the bandwidth unchanged and modify the channel spacing. Most of the time, both solutions are used in a complementary way. Then the penalties associated to the accumulation of chromatic dispersion for the new channels, their relative power and their spacing can be estimated by means of engineering rules established with laboratory experiments and/or numerical simulations. This is represented in Figure 3 and Figure 4 where the Q factor penalty is the difference between the transmitted Q and the Q factor in back-to-back configuration at same received OSNR. These curves depend on many parameters such as modulation format and fiber type.

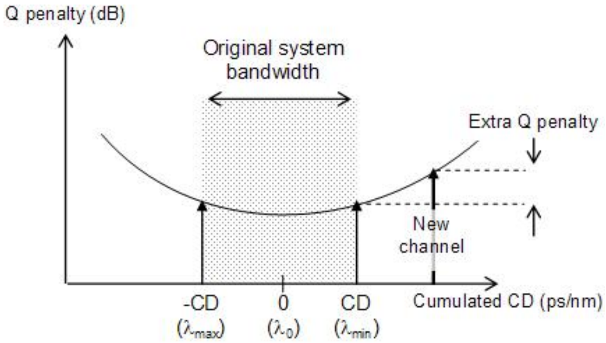

Figure 3 Q penalty as a function of accumulated CD for 10 Gbit/s OOK system

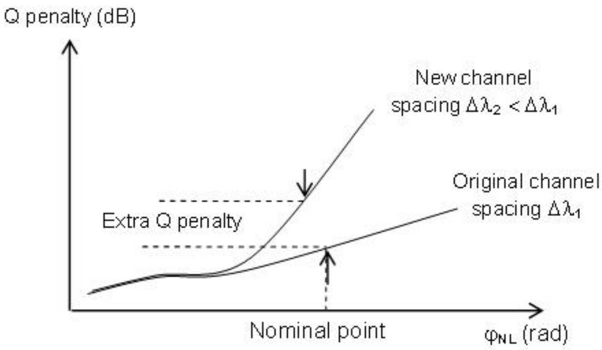

Figure 4 Q penalty as a function of the nonlinear phase noise and the channel spacing

Note that in practice couplers are used to connect the old equipment (existing channels) and the new one (added channels). The proportion of old equipment to keep in the stations should be investigated in terms of capacity and footprint.

5.3.3 UC estimation

Even if sufficient OSNR margin permits going beyond the MDC, some engineering issues may prevent it. Therefore, the owners undoubtedly prefer the tenderers to test on site the UC they can achieve to make their decision. If this option cannot be exercised, from traffic reasons for instance, the two basic remaining solutions are numerical simulations and lab experiments. Simulations can reproduce many different scenarii to increase the capacity when modifying the various terminal equipment features. However, they always need to be validated through experiment or field trial. Two types of lab experiments do exist: full straight-line test-beds and recirculating loops. Loops are cheaper and more flexible than deployed test-beds but their polarization behaviour is quite different as compared to real systems. Also some corrective factors must be defined to address the OSNR and nonlinear phase differences mainly due to the existence of a "dead span" that includes as a minimum a coupler and a switch. In any case, the system owners usually do prefer suppliers to minimize assumptions and calculations.

5.3.4 Discussion

In practice, the propagation of 10 Gbit/s signals over 2,5 Gbit/s WDM designed systems is usually feasible with still sufficient EOL margins. However, impacts due non-linear effects, cumulated chromatic dispersion and polarization impacts (e.g. Q fluctuations over time [10]) are clearly issues for higher bit rate such as 40 Gbit/s. Table 1 reports some challenging upgrade that could be performed on some cables co-owned by France Telecom.

System	Length	MDC	UC	Gain
A (1996)	6300 km	16×2,5 G	20×10 G	× 5
B (2001)	7400 km	16×10 G	50×10 G	× ~3
C (2004)	5000 km	64×10 G	102×10 G	× ~1,6

Table 1 Upgradability of real systems (UC was estimated by suppliers when removing all existing equipment)

The idea that any system is purchased for a certain cost per bit but may be automatically upgraded beyond its MDC is largely disseminated those days. We have to bear in mind that the ability of any system to overcome its design limitations is not a contractual obligation. The extra capacity is a non-automatic tailored bonus.

Whatever the upgrade type we consider, the wet plant must be very reliable since design changes occur in the terminal stations only. The common denominator of all new technologies is the risk assessment, specifically in terms of quality and reliability, which remains critical. Generally speaking, we observe that the spreading of challenging upgrades greatly slows down the natural occurrence of new cable deployments. This should not compromise the continuous exploration needed to anticipate the technological challenges that will be required by the future growths in traffic demand.

6 CONCLUSION

We have defined two types of submarine system upgrades. Standard upgrades are planned in the original Contract and no specific issue is expected (ordinary and foreseen steps). On the other hand, challenging upgrades are non-automatic, might be risky when involving new technologies but can lead to some substantial CAPEX gain. Purchasers must follow-up the latest technological improvements to assess the potential ultimate capacity of their own systems, in anticipation of the future demands of their customers.

7 ACKNOWLEDGEMENTS

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