MAXIMIZING THE CAPACITY AND CHANGING THE NETWORK TOPOLOGY OF EXISTING SYSTEMS

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Abstract: New technologies and sophisticated design tools allow the industry to extract new life from older undersea systems. The continued pressure to reduce the cost of adding capacity and the availability of newer terminal technology have combined to change the approach to upgrades and the way they are implemented. In many cases, this yields dramatic changes in system capacity and topology. Links originally designed for as little as 20 Gb/s per fiber pair are being upgraded to several times that capacity. In some networks implemented with several terminated links, it is now possible to bypass some of the intermediate termination points for some or all traffic on a fiber pair.

1. INTRODUCTION

Less than two decades after the first deployment of optically amplified fiber cable submarine systems the underlying technologies are reaching a mature stage and the basic layer physics are reasonably well understood. The two concurrent trends are driving the upgrade markets. On one side, extensive experience with operating submarine networks and changing patterns of worldwide demand for capacity push operators towards rethinking their network connectivity and capacity cross-sections. On the other side, the submarine system suppliers are aggressively introducing new technologies such as differential phase-shift keying (DPSK) modulation format [1,2,3], better Forward Error Correction (FEC) [4,5], and optical add drop multiplexing (OADM) in both terminals and wet plant. These advances allow for dramatic changes in connectivity and capacity in older systems.

When optical-amplifier-based transmission technology was being introduced, the optical path design was conservative to provide substantial performance margin. The extra margin was protection against possible defects in hardware, pitfalls in manufacturing, and incomplete understanding of the underlying optical propagation effects and impairments. This was especially true for the first system deployed with WDM and 10 Gb/s channels. As our understanding and manufacturing experience has progressed, this extra margin in deployed systems has been reallocated to support capacity upgrades well beyond the original design capacity or to allow changes in network topology to address emerging market distributions.

Another instrument that led to dramatic opportunities in the upgrade market is the improvement in computer-based system design tools. Better modeling algorithms, design practices, and overall accuracy allow for more accurate and detailed models of the optical paths as they were built [6], a better match to the performance of existing channels, and greater opportunity to expand capacity on installed paths using established and new terminal technology while guaranteeing acceptable transmission performance.

This paper reviews our recent experiences using modern technologies to upgrade the capacity and change the connectivity of existing legacy systems.

2. EXAMPLE I: MAXIMIZING THE CAPACITY OF A LEGACY SYSTEM

A typical request from a network owner is to increase capacity on an existing system. For this type of challenge the superior qualities of the RZ-DPSK modulation format, balanced detection, and advanced FEC are invaluable tools for multiplying system capacity without changing the wet plant. Each of these technologies gives the designer extra margin that can be used to add channels, to increase bit rates, or to extend the length of a digital line section (DLS). Modern terminal equipment brings more than 7 dB of additional margin to the system design process compared to the first WDM undersea systems. The real challenge is determining how much improvement is possible and making it happen.

Upgrades change the relative importance of different impairments that can limit performance. Systems divide roughly into two categories based on the relative contribution of impairments caused by nonlinear propagation. Optical signal-to-noise ratio (OSNR) dominates performance in linear systems, but channel power dependent effects cause significant penalties in nonlinear systems. An upgrade often changes the mix of impairments, and sophisticated modeling tools and experience are needed to manage the design change to yield a working system. A prime example of this is the wavelength allocation plan for the upgraded system. Failure to account properly for spectral hole burning or the interactions between channels of different formats and power levels can cause an upgrade to fail. However, these effects are well understood and simulation models can adequately capture the related physics [6].

Upgrading legacy wet plant to ultimate capacity using DPSK can be well illustrated by the following experiment. We use a straight line test-bed with a path design representative of the first generation WDM 2.5 Gb/s systems. The transmission path was originally designed to carry 8x2.5 Gb/s channels over 2,500 km. The testbed uses thirty-one EDFAs, pumped at 1480 nm, spaced at 82 km. The amplifiers operate at 7.5 dBm output power and have no gain flattening filters. The overall gain equalization plan is based on block equalization and results in about 7 nm of usable bandwidth. The dispersion map for the first generation WDM systems was based on non-zero dispersion shifted fiber (NZDSF) and block dispersion compensation with about 500 km period and an end-to-end path zero dispersion wavelength of 1561 nm. In this experiment we transmitted 5x2.5 Gb/s NRZ OOK channels together with 17x10 Gb/s RZ-DPSK channels and 1x10 Gb/s CRZ-OOK channel. The measured Q factors for all channels are shown in Figure 1. All 2.5 Gb/s NRZ and 10 Gb/s DPSK channels have adequate performance. However, the performance of the CRZ-OOK channel with comparable OSNR level is too low for sufficient system margin above the FEC threshold. Figure 1 clearly demonstrates that use of the DPSK modulation format allows for a dramatic system capacity increase beyond the original design capacity

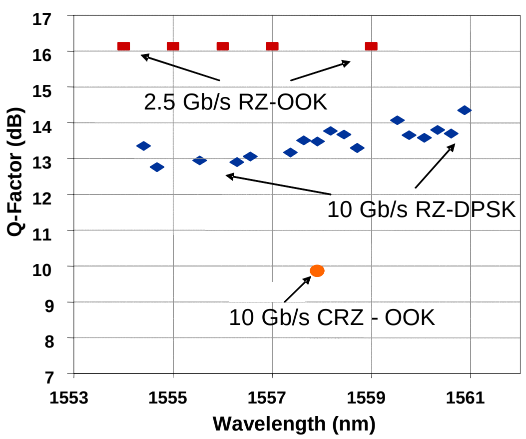

Figure 1. Performance of 5x2.5 Gb/s NRZ OOK, 17x10 Gb/s RZ-DPSK and 1x10 Gb/s CRZ-OOK channels in the transmission experiment using legacy test-bed.

3. EXAMPLE II: CHANGING THE CONNECTIVITY OF EXISTING NETWORKS

Another upgrade request that became quite common in recent years is the modification of the connectivity of an existing network while keeping or exceeding the capacity commitment for the original digital line segments (DLS). A dramatic example of this type of network reconfiguration is shown in Figure 2 where a few local DLS were interconnected to form an express DLS (from Station 1 to Station 4) almost 11,000 km in length while the length of each local path was shorter than 5,000 km. The original local DLS design targeted about 48x10 Gb/s capacity in 21 nm bandwidth and used first generation FEC. The dispersion map of the wet plant was based on Non-Zero Dispersion Shifted Fiber (NZDSF) with D=-2 ps/nm/km at 1550 nm and periodic dispersion compensation with Non-Dispersion Shifted Fiber (NDSF). The end-to-end zero dispersion wavelength of the path was at 1550 nm.

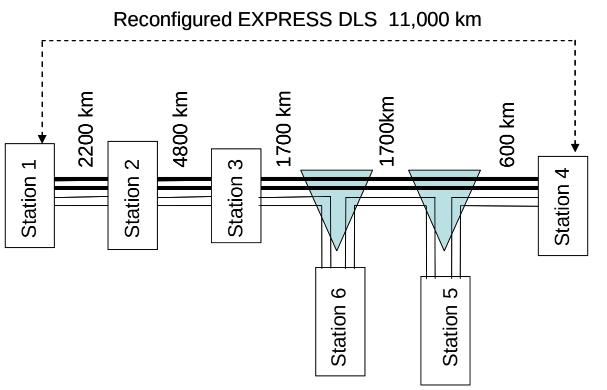

Figure 2. Schematics of an upgrade involving network reconfiguration from local DLSs to 11,000km express DLS connecting stations 1 and 4. The bold line indicates the reconfigures express DLS.

To address this challenge a multitude of issues must be taken into consideration. First of all the end-to-end performance should be explored to determine if there is enough margin on the concatenated path when advanced modulation formats (DPSK) and next generation FEC are applied. Second, the dispersion map and equalization plan of the concatenated segments must be tuned. Terminal line amplifiers were added as needed in the stations to cover the loss of additional components. The original 10 Gb/s CRZ-OOK channels which were re-deployed on the express path, was possible because each local DLS had been designed with some amount of unallocated margin which could be consumed in the reconfiguration. Furthermore, since the total final capacity is unchanged as a result of the upgrade proposal, the use of DPSK channels to replace the CRZ-OOK channels allowed for adequate OSNR for both the DPSK and CRZ-OOK channels. As a result, the performance of the re-deployed channels on the new express DLS decreased as compared to their performance on a local DLS. However, the overall performance is sufficient to ensure proper system operation over next 20 years. Figure 3 shows the simulated performance of the express 11,000 km DLS with 47xRZ-DPSK and 6xCRZ-OOK channels. The CRZ-OOK channels are configured at a higher OSNR to raise their performance to a level required by the second generation of FEC. The RZ-DPSK channels can operate at lower Q-factor without compromising system margin because this equipment is equipped with a more powerful FEC than the second generation FEC in the CRZ-OOK channels.

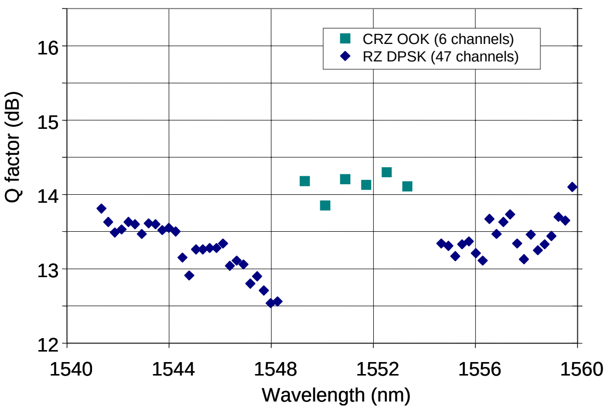

Figure 3. Simulated mean Q performance of an upgraded express 11,000 km DLS.

Besides computer simulations the design was verified in re-circulating loop experiments. The initial deployment used 6x10 Gb/s CRZ-OOK and initial loading equipment based on the addition of idler tones to manage the power distribution across the bandwidth and along the path. Figure 4 shows measured Q performance of the deployed 6 x CRZ-OOK channels over a few days. Note that after subtracting the budgeted 1 dB of manufacturing (i.e. the re-configuration implementation) Q margin, the measured performance shown in Figure 4 agrees well with the simulation prediction in Figure 3. Most importantly the large margin over the FEC threshold (8.6 dB) guarantees adequate operation over the life of the system.

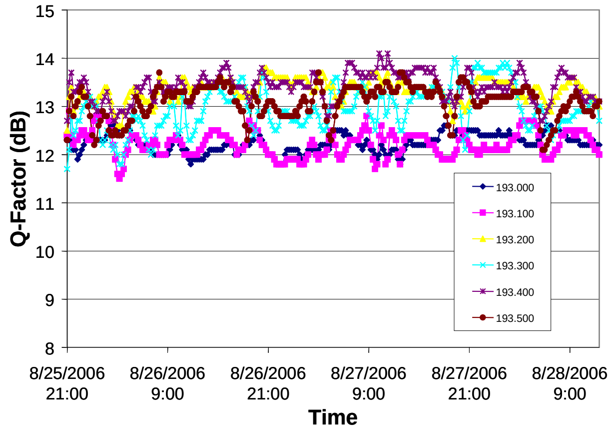

Figure 4. Measured Q performance of the initial 6x10Gb/s CRZ OOK channels on the upgraded express 11,000 km DLS. The insert shows frequecies in THz.

4. EXAMPLE III: NETWORK RECONFIGURATION USING DRY OPTICAL ADD DROP MULTIPLEXING (OADM).

Typically transmission systems are designed with line termination equipment that allows support for channel regeneration and re-transmission back into the network. The push towards cost effective and flexible upgrades calls for dry OADM functionality in such a way that it shall be possible to route one or multiple channel(s) without complete demultiplexing/multiplexing and regeneration in and out of a cable station. Ideally a fully reconfigurable OADM device is used. A simpler, though less flexible, solution is to add widely available channel selecting filters to the terminal architecture. However, in some cases this can limit the through capacity.

A simple implementation of the OADM functionality can make use of three port channel selection filters shown in the picture below. These three-port devices are typically thin film filters. Each has an input/output port, an add/drop port and an express port. The figure below shows the terminal station with only two of the N channels being dropped/added. Each add/drop channel requires two three port filters. Terminal line amplifiers (TLAs) are added to compensate for the loss of the filters. Additional TLAs may be needed depending on the number of add/drop channels.

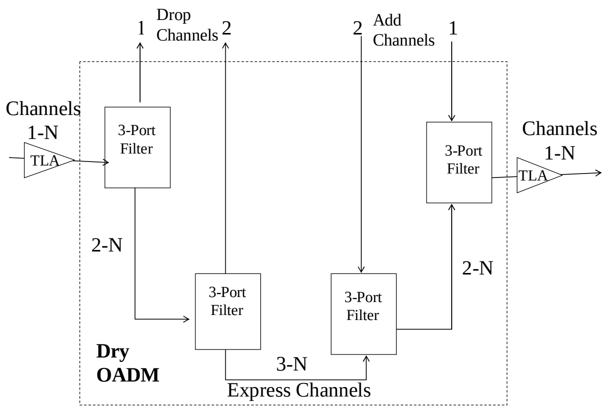

Figure 5. A simple implementation of OADM using 3-port channel selection filters.

The channel spacing of the add/drop channels is determined by the width of the channel selection filters and sufficient rejection of neighboring channel to avoid in-band cross-talk. Passing the express channels through both add and drop filters, as in the figure above, allows further rejection and interference between the add, drop and the express channels. Typically add/drop channel spacing is more than the spacing of the express channels. As a result the maximum capacity of the fiber pair is lower. This is typically acceptable since the add/drop channels propagate over a shorter segment before being received.

5. CONCLUSION

Rapid deployment of newtechnologies in submarine systems and maturity of understanding of the basic effects of the physical layer created opportunities to use performance margins of legacy systems and has spawned demand for dramatic capacity expansion and reconfiguration of existing networks. The few examples that this paper reviews give a sense of the scope of the new possibilities. Introduction of next generation advanced modulation formats, soft decision FEC, and ROADMs will enable another level of sophistication in network reconfiguration going forward.

6. REFERENCES

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