KEY FEATURES OF THE UNDERSEA PLANT FOR HIGH CAPACITY AND FLEXIBILITY

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Abstract: Price, performance, and network availability are key metrics for both terminal and undersea equipment, but the inherent long life and inaccessibility of the equipment deployed undersea puts a premium on excellence in its design, manufacture, and deployment for the undersea equipment. This paper discusses the features that matter, the value of experience in bringing those features to new systems, and some past and expected changes in the way equipment is adapted for new applications not expected when systems are contracted.

1. INTRODUCTION

Advances in coherent transmission technology and silicon IC technology have led to fundamental changes in the undersea systems industry, changes that give system operators new features and much more value. Extra performance margin is available to apply to greater capacity, longer transmission distance, more complex network architectures, and cost reduction. Coherent detection improves available margin by allowing operation at lower Optical Signal-to-Noise ratio (OSNR) for a given bit error ratio, by as much as 1.5 dB. Soft-decision FEC is now generally available, with more than 1 dB improvement in Net Coding Gain over the best hard-decision FEC used in undersea systems. Coherent detection and high-power digital signal processors enable electronic dispersion compensation, polarization tracking, and PMD compensation. These features, in turn, enable transmission at higher baud rates, multi-level modulation schemes, and polarization multiplexing, giving us much higher capacity per fiber pair and reduced performance fluctuations from polarization effects (another dB of margin). Electronic dispersion compensation allows suppliers to build wet plant with high-dispersion fiber and no in-line dispersion compensation. This improves average span loss by more than 10% and suppresses penalties from fiber non-linearity (another 1 to 2 dB of margin). Finally, electronic dispersion compensation leads to simpler terminal equipment, especially in OADM networks with dynamic channel allocation (Switchable or Reconfigurable Optical Add/Drop Multiplexing (ROADM) networks).

These advances in technology, with ongoing improvements in fibers and filters, have made possible a 10-fold increase in undersea system capacity, and they have changed the design of the wet plant in fundamental ways. Price, performance, and network availability are still the key metrics for both wet and dry plant, but the inherent long life and inaccessibility of the wet plant equipment puts a premium on excellence in design, manufacture, and deployment for the undersea equipment.

2. OPTICAL PATH DESIGN

Optical path design balances transmission impairments and cost to meet customer requirements for capacity, reach, and performance margin. Low noise amplifiers are standard, but repeater spacing is still a key design parameter. Using available fiber and component technologies, polarization mode dispersion (PMD) is not a limiting factor for performance or capacity of current and next generation coherent systems. Fiber with low loss and/or large effective area is good for performance, but fibers with best-in-class values for these parameters are expensive, costing significantly more than the least expensive fiber being used in new systems. To optimize design for a given system, the purchaser needs to state their performance and capacity objectives clearly, and the supplier needs sophisticated and qualified design, manufacturing, and installation processes to deliver a compliant, cost-effective system.

Path design is complicated and difficult. Sophisticated modelling programs, specific to the physics of ultra-long-haul optical transmission have been developed through decades of research and qualified through extensive experimental work in the lab, and, most importantly, in deployed systems. Figure 1 illustrates a typical output from a typical design study.

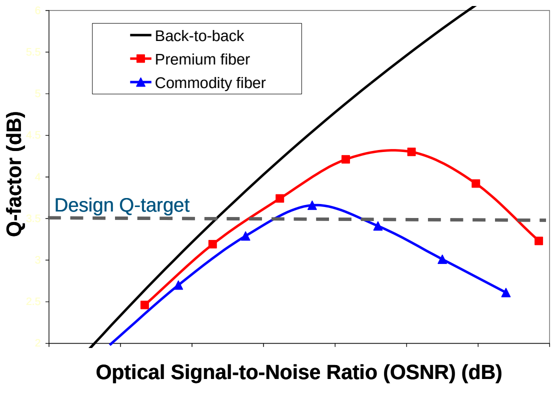

Figure 1: Designs of a transpacific link with premium and commodity +D fiber.

It shows transmission performance (Q-factor) vs. received Optical Signal-to-Noise Ratio (OSNR) for two path designs. The designs have the same length and repeater spacing, but use different fibers at significantly different price points. The dashed horizontal line is the design target (required Q to support the Performance Budget). As shown, both fibers can support the design (using the appropriate repeater output power), but the more expensive solution yields greater margin. The extra margin may be considered a greater opportunity for future upgrades, or evidence of an unnecessary initial cost.

Wide bandwidth and flat gain are essential for best performance in high capacity systems, and multi-tier schemes for gain equalization are necessary to manage gain shape. With well qualified models for fibers and amplifiers, required filters can be specified, but well controlled manufacturing processes with internal feedback and fast recovery are critical for success in setting design specifications and building to those specifications. One important step is having a short-interval fabrication process for high-reliability filters built to tight specifications. For example, TE SubCom does this using a dedicated fiber Bragg filter (FBG) manufacturing process with an interval as short as six weeks from specifications to delivery of certified parts built into a repeatered line at the factory. New systems, asking for more than 34 nm of equalized bandwidth, require tighter control of gain shape than yesterday's systems, especially for proposed systems having capacity greater than 8 Tb/s per fiber pair and lengths greater than 10,000 km. More aggressive maintenance strategies and/or embedded, controlled gain equalization will be needed, along with tighter control during system build and installation, to maintain transmission capacity over the life of the wet plant.

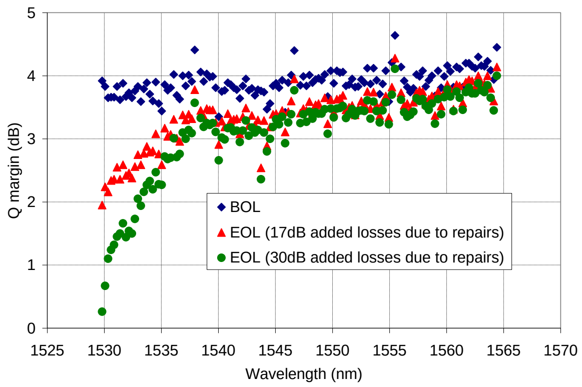

Figure 2: Performance degradation as a function of added path loss.

Figure 2 shows the affect on transmission loss to a 6500-km path transmitting 100 Gb/s channels. The loss added by ageing and repairs can easily exceed 30 dB. As discussed in the next section, compensating for this added loss requires an expensive maintenance strategy, expensive additional hardware in the wet plant, or both. Balancing path loss and path gain to keep gain shape flat can be accomplished using ship operations to add repair repeaters or to remove Line Build Out (LBO) optical attenuators, or by use of gain equalization equipment deployed in the wet plant that can be controlled from the terminals. The former adds cost primarily as operating cost, while the latter adds to the initial cost of the system (OPEX vs. CAPEX).

Optical Add/Drop Multiplexing (OADM) is required in many new systems. High efficiency in creating OADM bands (groups of channels supporting a single digital line section (DLS)) requires filters with narrow (in frequency) transitions from PASS to BLOCK. Filters based on Fiber Bragg Gratings (FBG) can define one or more OADM bands with guard bands less than 1 nm in width (125 GHz). In its newest developments, TE SubCom has qualified a ROADM technology for use in the wet plant. This qualified technology makes possible ROADM branching nodes with 40nm optical bandwidth, and much smaller guard bands between OADM channel bands. The ROADM gives the customer complete control of the channel allocation plan at each node, and it supports any channel spacing or channel modulation format. These features will be important in branched systems. The required capacity between stations over the life of the wet plant are sure to be different than the allocations planned when the system was built, and new customers may be brought into the system through added branches.

3. WET PLANT FOR FLEXIBLE HIGH CAPACITY SYSTEMS

Repeaters: Up to about 40 nm, the least expensive way to increase a system's ultimate capacity is to increase its bandwidth. For repeaters using Erbium-Doped Fiber amplifiers (EDFA), the limit comes from the shape of the EDF gain spectrum, as shown in Figure 3.

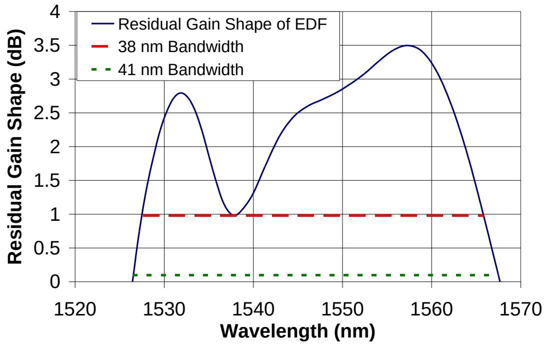

Figure 3: EDF Gain shape to be corrected by the gain flattening filter (GFF), for 38nm (dashed line) and 41nm (dotted line).

Figure 3 shows the increasing depth and steep edges of the gain equalization required for amplifiers with bandwidth greater than 28 nm. The widest bandwidth in a repeatered system deployed in a repeatered system is 41nm bandwidth, a practical limit on useful bandwidth for a C-Band EDFA. Precision build and athermal packaging are required to keep gain shape error within acceptable limits in the installed system.

Wider bandwidth and higher transmission capacity have renewed a demand for higher power from pump lasers. Current technology supports 500 mW from undersea qualified pumps, which supports more than 19 dBm output power from repeaters. Available pump power limits repeater spacing in some system designs. Two-stage amplifier designs allow higher output power than single-stage designs, but the higher noise figure of these amplifiers makes them attractive only in applications requiring very high repeater gain (>16 dB span loss).

Branching Nodes: The classic branching node is a 3-port body supporting electrical switching and spliced connections among cabled fibers. Branching products now support a host of features enabling complex architectures in the wet plant architectures, addressing an expanding range of needs in all undersea system markets. Key features are OADM functions and remote-controlled high-voltage switching. OADM branching nodes have been implemented in single body solutions and with the OADM functions in a body separate from the BU functions. The single body solution is simpler to build and to install. The two-body solution provides room for more complex functions and simpler sparing and OADM node maintenance since all BUs in a system can be of one design, and node-specific OADM features are defined in the separate body which can be added or changed after trunk installation with minimum impact on trunk traffic. If the customer chooses to change the OADM channel allocation at a branching node, the separate OADM body can be replaced without cutting the trunk cables at the PSBU, and the PSBU can ground the power conductor of the branch cable to allow safe marine operations on the branch without powering down the trunk cables.

Reconfigurable OADM nodes greatly enhance long term value of wet plant in a complex system. The channel plan at each node can be switched to accommodate changing traffic demands or to reassign channels to new branches, without replacing existing nodes. A limited degree of flexibility is possible using optical switches to select from a small set of filter options deployed in a node. The more complete solution is a ROADM node based on the wavelength selectable switch (WSS). This technology, widely used for ROADMs in the terrestrial network has now been qualified for deployment in undersea equipment. It makes possible extreme flexibility in OADM network channel allocation and simplifies OADM fault recovery by allowing optical channels and loading signals to be routed into segments as needed to maintain maximum capacity with least impairment. The power of this technology is discussed in detail in reference [1].

Dynamic Gain Equalization (DGE): New interest is being expressed by customers hoping to maintaining system performance over a 25-year lifetime without using repair repeaters. Path loss added by ageing and repairs changes gain shape through the wet plant, and something must be done to correct for the effects of the added loss. Controlled repeater output power has little value in managing gain shape. A DGE is any controllable equipment embedded in the wet plant by which an operator can change gain shape without a marine operation. A DGE, by any method, is useful if the technology is effective in correcting the gain shape errors that arise over a system's lifetime.

The obstacle to deployment of DGEs is cost. Adding DGEs to a system increases initial system cost in anticipation of cost savings and enhanced performance over the life of the system. Without DGEs, installed system gain shape must be managed as part of a wet plant maintenance strategy based on marine operations, filters, and repair repeaters. The cost of DGEs must be weighed against extra repair costs to maintain tight control of gain shape and the cost of capacity lost because of degraded gain shape while waiting for effective corrections to be implemented through marine operations.

4. CONCLUSIONS

Coherent transmission technology has opened a new era in undersea system design. Wet plant designed for this technology promises unprecedented value and flexibility if it is well designed, manufactured, and deployed. Systems designed and built by proven processes augmented by carefully selected and qualified innovations promise enduring value in the wet plant through multiple upgrades to the terminal products. Advanced OADM technologies, especially ROADMs, allow cost effective solutions for complex and changing networks while preserving value in the initial investment. Static channel allocations will be replaced by controlled allocations and, eventually, by dynamic allocation on wet plant shared by many users through many DLSs on few fiber pairs. Higher capacity per fiber pair and simpler path designs, tolerance to faults, and operator control of the optical features of the wet plant enable new system functions and reduce operating costs per channel

5. REFERENCES

[1] M. Enright, M. Manna, “Agile Undersea Networks Based upon Advanced OADM Technology” SubOptic 2013, Paris, France

